RECENT DEVELOPMENTS IN QUALITY CONTROL: AN INTRODUCTION TO "TAGUCHI METHODS"

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Abstract

This paper discusses a set of ideas which have come to be known as "Taguchi Methods". It firstly suggests that the decline in U.S. industrial power, coincident with Japanese takeover of world markets, is the fundamental reason why American manufacturers have been, receptive to quality control ideas emanating from Japan. It sets out Taguchi's philosophy of off-line quality control, i.e. design the product: to be insensitive to normal manufacturing variation, component deterioration and environmental variation, and illustrates this with one of Taguchi's best known case studies. It then shows that the statistical experimental designs (orthogonal arrays) advocated by Taguchi are superior to the traditional engineering approach of investigating one parameter at a time. Some experimental design ideas introduced by Taguchi are described. In particular, his use of "inner' and "outer" arrays and the distinction he draws between "control" and "adjustment" factors are illustrated by examples from the literature. Finally, his performance measures, which he calls "signal-to-noise ratios", are described and related to his concept of a loss function which is fundamental to his philosophy of quality engineering.

Introduction

My title today is "Recent Developments in Quality Control" However, what I want to do is not to review the quality control area broadly but rather to discuss a set of ideas which have come, to be known as "Taguchi Methods" and which have received a great deal of attention in the statistical and quality engineering journals of late. The ultimate .reason for the recent resurgence of interest in quality control in the West, I believe, lies in Japanese success in world markets. I attended a seminar in Nottingham in March 1988 on "The Statistician's Role in Quality Improvement". There were two Speakers. The first, Dr.Henry Neave, who is Director of Research of the British Deming Association, opened his presentation with a "Quality Quiz" (1). One of his questions, shown in Figure 1, referred to the fact that Japan holds more than half the world market share in a significant number of products.

The second speaker, Professor George Box, who is Director of Research at the Centre for Quality and Productivity Improvement of the University of Wisconsin at Madison. also opened his presentation with a list (given in Figure 2) of products the US worldwide .manufacturing share of which slipped by at least 50% between 1974 and 1984 (2).An important part of this share has gone to Japan.

Quality Quiz

Which country has more than half of the world market share in the following products?

Shipbuilding
Motor
Cycles
Zip
Fasteners
Pianos
Colour Cathode Ray (TV) Tubes
Cameras
plain Paper Copiers
Hi-Fi
Electronic Typewriters and
Calculators
Artificial Leather
Robotics

Figure 1: A quality quiz with an obvious answer

In all these, industries U S. worldwide manufacturing share slipped by at least 50% 1974-1984.An important part of this share has gone to Japan.

Automobiles	food processors
Cameras	microwave ovens
Stereo Components	athletic equipment
Medical Equipment	computer chips
Colour TV sets	industrial robots
hand Tools	electron microscopes
Radial Tyres	machine tools
Electric: Motors	

Figure 2: the decline of U.S. industrial power

The American motor companies, in particular, were extremely worried by these developments and went to Japan to find the magic formula. There they discovered Statistical Process Control (SPC), the Deming philosophy, Quality Control, Circles, Just- in-Time manufacturing etc. In the course of their investigations of Japanese manufacturing practices, about 1982, Ford came across the work of an engineer called Taguchi. They asked Taguchi to train their suppliers in the US in the use of his methods. By 1984, sufficient progress bad been made to set up an annual symposium where case studies are presented. on the implementation of "Taguchi Methods" in the supplier companies. In opening the 'first of these symposia L.P Sullivan of the Ford Motor Company made these comments (3):

"In the early 1960_s.a result of Dr. Taguchi's work, Japanese engineers embarked 0n a steep learning curve in the application of experimental design methods to improve quality and reduce cost. Through our ,investigation we became c:onvinced that a significant reason for the Japanese cost and quality advantage in the late 1970_s and early 1980s was due to extensive use of Quality Engineering method".

He presented a diagram, shown in Figure 3, which he said was developed in discussions with Japanese supplier Companies.

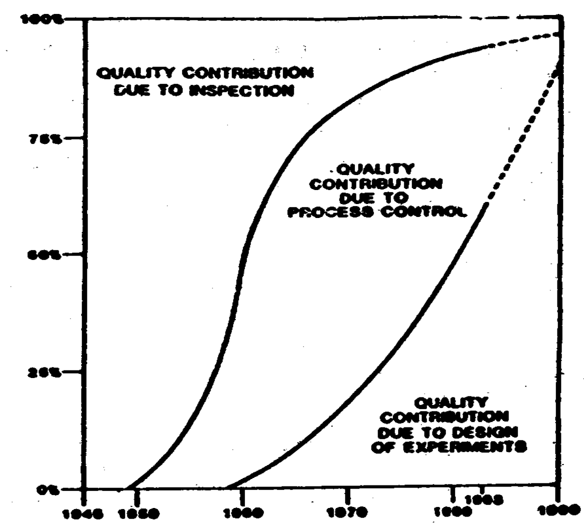


Figure 3: Use of quality control techniques in Japan.

The diagram shows that before 1950 quality was assured by inspection of products after they were made. This, of course,' is highly inefficient in that not only is money spent on producing defective items but more money must be spent in repairing or replacing them. During the 1950s and early 1960s, under the influence of such as Deming and Ishikawa, this, gave way to Statistical Process Control whereby the process is monitored using statistical control charts to ensure that bad products are not made. This simply means that at regular intervals during production a sample of the product is checked and a decision is taken on whether the process is working as it is supposed to or .whether something has gone wrong. The latest phase in Japanese quality techniques which Sullivan describes as "contribution due to design of experiments" derives, from Taguchi's influence; its projected growth is staggering.

The Taguchi approach to Quality Engineering is, perhaps best understood by contrasting it with the currently dominant Statistical Process Control (SPC) which Taguchi calls "on-line quality control"

SPC (on-line quality control)

Find and eliminate "assignable causes" so that the process remains in statistical control and the product remains within specification limits.

Taguchi philosophy (off-line Quality Control)

Design the product and the process so that the product's performance is not sensitive to the effects of environmental variables, component deterioration and manufacturing variation.

Figure 4: On-line versus Off-line Quality Control

Figure 4 sets out the contrasting approaches whereas SPC attempts to control quality by ensuring that the production process remains "in control" the Taguchi approach is to design a robust product i.e. one whose functional performance will be insensitive to normal manufacturing variation. An example which is quoted extensively in the Taguchi literature will serve to illustrate the difference between the two philosophies of quality control (4,5,6).

In the 1950s the Ina Tile company in Japan faced a serious problem with a new $2 million tunnel kiln, purchased from West Germany. The problem was extreme variation in the dimensions of the tiles that were being backed in the kiln. Tiles towards the outside of the stack tended to have- a different average and exhibited more variation than those towards the inside of the stack, see Figure 5. The cause of the variation was apparent uneven temperature distribution inside

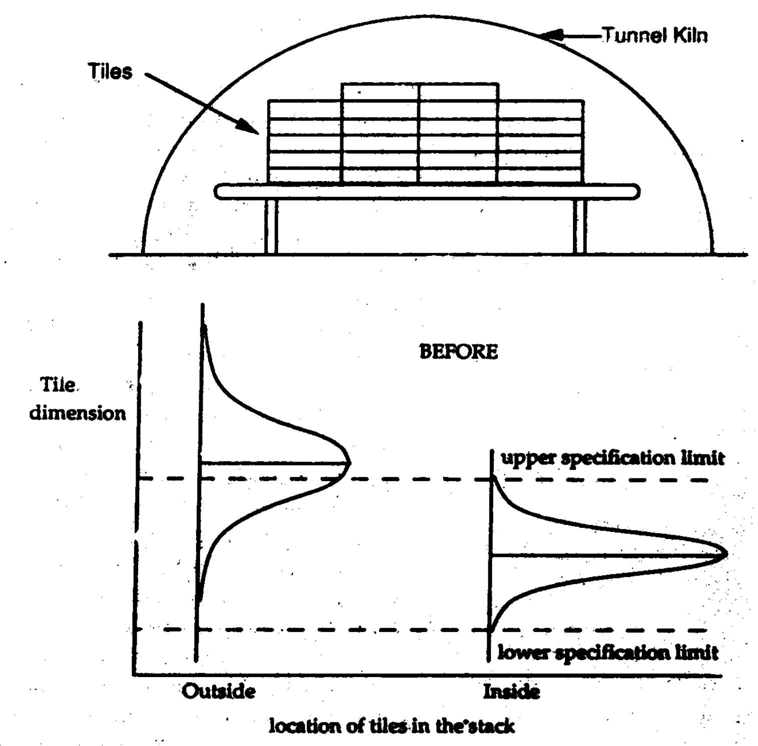


Figure 5: The Ina Tile Co. Problem, Tile Distributions

the kiln. This resulted in a high rate of defectives, of the order of 30%. A traditional SPC approach would be to attempt to rectify the cause of the problem i.e. to control the temperature 'distribution within the kiln. It was estimated that this might cost in the region of $500,000. Taguchi's approach was different - he suggested changing the composition of the raw materials to try to reduce the effect on the tile dimensions of the temperature variation in the kiln.

A brain storming session involving the production engineers and chemists identified seven factors which might be varied. After laboratory investigations, a production scale experiment was carried out using the factors shown in Figure 6.

The experiment consisted of eight runs at different combinations of the seven factors: how seven factors can be investigated in only eight runs is something we will discuss later. The experiment suggested that the first factor i.e, lime content was the most important and when this was changed from its current level of 1% to 5% the defectives rate dropped from around 30% to about 1%; the distribution of tile dimensions after the change is shown in Figure 7.

1. Content of a certain lime		
	A_1 = 5%	A_2 =1% (current level)
2. Fineness of the lime additive		
	B_1 = coarse (current)	B_2=finer
3. Agalmatolite content		
	C_1. = 43%	C_2=53 %(current)
4. Type of agalmotolite		
	D_1. =. Current	D_2 = new
5 Charge quantity		
	E_1' = 1300kg	E_2 =1200kg (current)
6. Content of waste return		
	F_1. = 0%	F_2 = 4%(current)
7. Feldspar content		
	G_1. = 0%	G_2 = %5(current)

Figure 6: Factors in Tile Experiment

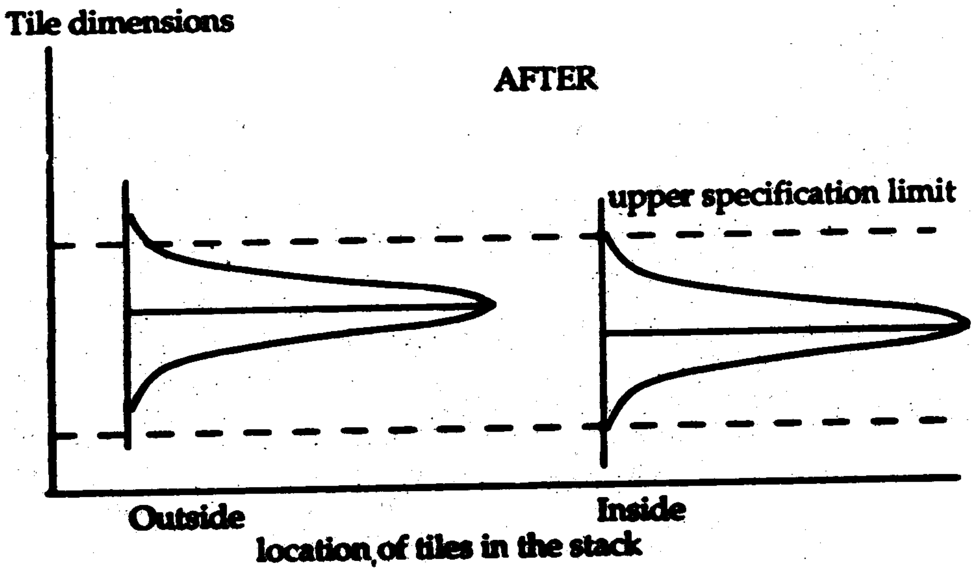


Figure 7: The distributions after raw material change

As well as solving the problem very cheaply - lime was the cheapest input - the experiment had a very useful secondary result, It was found that the amount of agalmatolite was not a critical factor and could be reduced without adversely affecting defect rate. Since this was the most expensive raw material in the tile, large savings accrued. It seems to me that this secondary result is of general interest as it is usually the case that experiments are conducted to identify what we might call active factors rather than passive factors such as agalmatolite level in this example. Taguchi makes the following comment:

"Through production field experiments - those experiments using actual production equipment and production output progress is likely, with many benefits such as gains of millions and lens of millions of yens having been reported it is not an exaggeration to say that most of these benefits come from the discovery of factors that do not affect quality very much but make a big difference in cost when levels are changed (4)

Quality Engineering

The Taguchi philosophy then is to design products and by implication to design the processes that deliver these products in such a way that normal manufacturing variation (or noise, as he calls it) does not affect the performance of the product. He would see three phases in the engineering optimization of a product or a process:

System Design
Parameter Design
Tolerance Design.

System Design is the creative phase where knowing what our product is required to do we select the appropriate technology to do it, assemble the raw materials and/or components into a prototype and specify a manufacturing process which will deliver products to customers.

Parameter Design is an experimental phase where the outputs from the system design phase is optimized by systematic experimentation. That is, the product and process parameters are systematically varied until a product results which has high functional performance and has minimum variability in this performance.

Tolerance Design is required if, after the parameter design phase, the product is still too variable .i.e. the process capability is poor. Tolerance design requires the use of higher quality inputs - either better grade components or raw materials or higher precision machinery.

There is nothing special about phases one and three. Indeed Taguchi argues that in the USA, in particular, the tendency has been to employ only these two phases in product development, ignoring what he calls 'Parameter Design'. Thus, he argues the response to low product quality levels, has been to throw money at the problem through use of higher grade components and machinery; This will very often be an expensive option. What is different about the Taguchi approach is the Parameter Design phase; most of the rest of this lecture will be concerned with the associated ideas.

Experimental Design

If Taguchi's approach to Quality Engineering is to be implemented successfully it will require study of many factors which may affect the performance of a product or a process. Accordingly, it will be critical to design experiments in such a way as to maximise the amount of information that can be gleaned from a given experimental effort. I would like, therefore, to discuss briefly the question of efficiency in experimental design. First I will illustrate what has been traditionally taught as the "scientific approach" to designing experiments. I will then contrast this with a more efficient approach using what are called factorial designs and then discuss how Taguchi's designs are related to these.

Scientists and engineers are usually told that the way to conduct experiments is to investigate one factor at a time, holding everything else constant. This as we shall see is highly inefficient. Suppose we went to investigate the effects on the performance of some system of varying three parameters A, B, C each over two levels. We arbitrarily call the two levels "low" and "high” In an investigation of a chemical process, for example, the levels" of A might be low and high temperature, those of B two different catalysts while the levels of C might be long and short reaction times. A Traditional approach to the investigation might proceed as follows. Hold Band C at their low levels and take a couple of observations at low and high A. We suppose now that high A is better. Hold A high C low and take a couple of observations at low B and high B. Suppose that high B is better. Finally, hold A and B high and take a couple of observations at low and high C. figure 8 illustrates the experimental sequence.

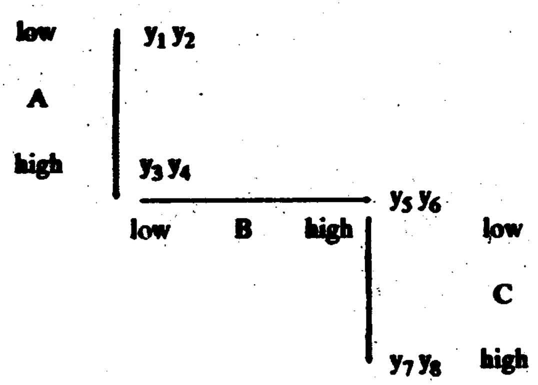


Figure 8: tradition experimental investigation of three factors

To measure the' effect of changing any factor we compare the average, performance at the high level of the factor with the average performance at the low level. Thus:

$$effect\ of\ changing\ A = \frac{y_3 + y_4}{2} - \frac{y_1 + y_2}{2}$$

Each, effect is measured by comparing the average of two observations with the' average of two others.

Consider an alternative experimental strategy where we investigate all possible combination of the levels of the three factors. Since we have three factors, each at two levels this requires 2 x 2 x 2 = 8 experimental runs. These may be represented by the eight, corners of a cube as shown in figure 9.

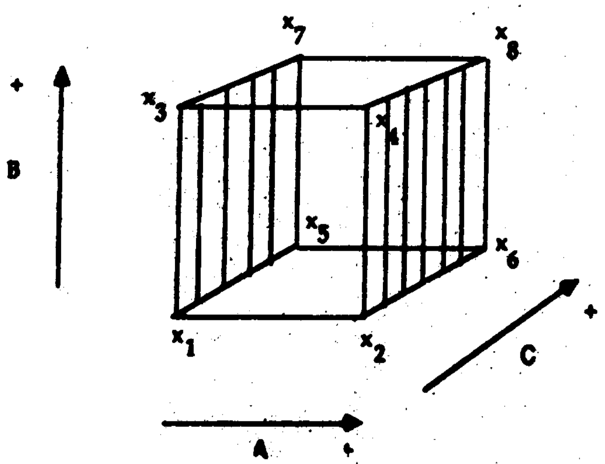


Figure 9: a factorial design for three factors (- is low + is high)

The four points on the, left hand side (LHS) of the cube are identical to their counterparts on the right hand side (RHS) except that A. is at its low level on the

LHS and at its high level on the RHS. The effect of changing from low to high A can be measured, therefore, by comparing the average yield on the RHS with· the, average-yield on the LHS:

$$\text{effect of chaging A} = \frac{x_2 + x_4 + x_8 + x_6}{4} - \frac{x_1 + x_3 + x_7 + x_5}{4}$$

Similarly, the effect of changing B involves a comparison of the average yield on the base of the cube with the average yield on the top; to measure the effect of changing C we .compare the average yield on the front with the average yield on the back of the cube.

In all .cases we compare the average of four observations with the average of four. This is clearly more efficient than the traditional approach, which, given the same number of observations for the overall investigation, measures the effect of changing each factor by comparing the average of two with the average of two. The second strategy - called a factorial design - is highly efficient in its use of the experimental data: all the observations are used in each comparison. This contrasts with the traditional approach which, uses different subsets of the data depending on the comparison being made and, in effect, throws away half the data in making any individual comparison.

Interactions

The factorial design, as well as being highly efficient, has another property which is easily seen from considering the previous example. Suppose We ignore C and follow through the traditional approach of' investigating one factor at a time. Figure 10 shows a possible outcome to such an investigation.

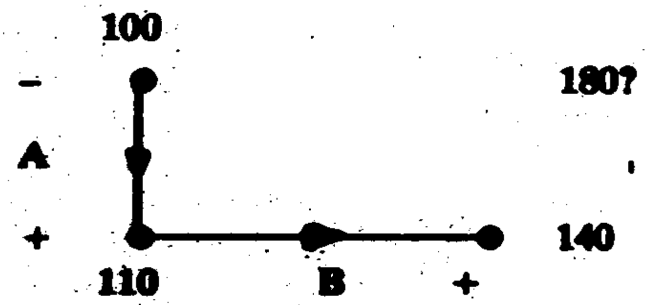


Figure 10: An interaction effect may be present

At low A, low B we get an average yield of 100 units; this .improves to 110 when we change to high A which keeping B low. When' we now change to high B, there is a further improvement to an average yield of 140 units. The experimenter would probably feel happy with the outcome of the investigation: yield has been improved by 40% from the current level of 100 obtained at low A, low B. However the combination of A low, B high has not been investigated and it could well be that if it had, an average yield of say 180 units would result: changing from low to high B when A is high increases yield, by 30 units; changing from low to, high B when A is low increases by 80 units. This is what statisticians call an interaction effect i.e. the effect of changing one factor depends on the, level(s) of one or more other factors. Experience shows that interactions are common and should not be ignored. The factorial strategy is not only efficient, in the sense discussed above, but is designed to detect interaction effects if they occur. Obviously the traditional strategy of investigating one factor at a time would have led us to the optimum if we had happened to investigate B first. But it is unsatisfactory that the outcome of our investigation should depend on our haphazardly picking the right sequence for investigating the factors, Such an approach can hardly be called "scientific"

Orthogonal Arrays

Taguchi recommends the use of what he calls orthogonal arrays for designing experiments. In fact he has published a book full of these arrays; so that the investigator can select an appropriate design to meet the experimental needs (7). To illustrate the relationship between these arrays and traditional factorial designs we return now to the tiles experiment discussed earlier, In this experiment, as you will remember, there were seven factors, each at two levels, Taguchi specified the eight runs as shown in Figure 11 where (+, -) label high and low levels of the factors respectively. The matrix of signs is the orthogonal array; the seven factors have been labeled A-G. Each row specifies an experimental run; thus ,run 1 requires A low, Blow, C low, D high, E high, F high, G low. The runs are presented here in a standard order; in practice the run order should be randomized. To see where this particular design comes from we focus on the first three columns of signs. When we compare the triples of signs in each of the eight rows with the triples (representing the levels of A, B, C respectively) labelling the corners of the cube in Figure 12 .we see that they are, in fact, the same.

The array simply collects the labels on the corner of the cube into a convenient table. Consider the column of signs under C; if we regard these as ± 1, multiply by the column of results (X) in the table, and divide by 4 we get the effect of changing from low to high C.

Effect of changing C

$$= \frac{(\times_5+\times_6+\times_7+\times_8)-(\times_1+\times_2+\times_3+\times_4)}{4}$$

This is simply the difference between the average response at the back of the cube and the average at the front. Multiplying the column of signs under A by the X's and dividing by 4 compares the average response on the LHS with that on the RHS;· the effect of B is calculated similarly. So,

Run no	A	B	C	D	E	F	G	Results
1	-	-	-	+	+	+	-	X_1
2	+	-	-	-	-	+	+	X_2
3	-	+	-	-	+	-	+	X_3
4	+	+	-	+	-	-	-	X_4
5	-	-	+	+	-	-	+	X_5
6	+	-	+	-	+	-	-	X_6
7	-	+	+	-	-	+	-	X_7
8	+	+	+	+	+	+	+	X_8

Figure 11: the experimental design for the tiles problem

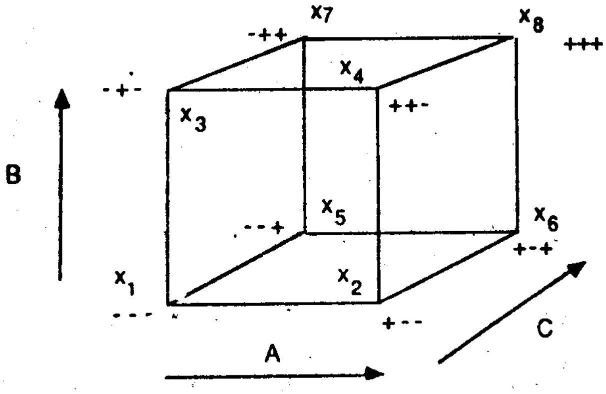


Figure 12: The three-factor design

We see that using the first three columns of the orthogonal array is just a different way of describing the use of the factorial design we discussed in the last section. If we describe the first three columns as A, B,C then a little inspection shows that column 4 is A x B, 5 is A .x C, 6 is B x C and column 7 is A x B x C. Traditionally these columns are used to measure the interactions between the first three factors A, B, C. The interaction effects are .calculated as before by multiplying the relevant column of signs by the X's and divided by 4. The definitions of these interaction effects need not concern us here; we' simply note that they are measures of the extent to which the three factors A, B, C fail to act independently of each other on the response of the system or the extent to which the effect of one depends on the levels of the others. If, as Taguchi and his followers usually do, we ignore the possibility of interactions then the last four columns of the array can be assigned to four other factors D; E, F, G. The effects of changing these factors can now be calculated in exactly the same way as for the first three.

The assumption of no interactions is, of course, a major one; serious doubts have been expressed in the statistical and quality control literature about the advisability of these designs being recommended for use by people who do not know the full implications of the assumptions being made and the consequences of these assumptions being wrong.

This example illustrates the appeal of the designs offered by Taguchi: here we see seven factors being explored in only eight runs, the results of which can be analysed by simple arithmetic Statisticians will recognise this array (called an L_8 array by Taguchi)as a saturated-fractional factorial design Other designs used by Taguchi include full and fractional factorials, Graeco-Latin squares and Plackett-Burman designs:

Interim Summary

Figure 13 summaries the Taguchi approach to Quality Engineering. This comprises a philosophy of robust product design, a specification of how to achieve this (parameter design), and a collection of design tools (orthogonal arrays) for carrying this through.

Design a Robust' Product.
which is insensitive to:

- manufacturing variation
- environmental/user variation
- deterioration of components

Use Parameter Design to do this:

systematically investigate the effects of varying different design factors

Use Orthogonal Arrays

-to design these experiments.

Figure 13: Taguchi Approach to Quality Engineering

I want to look now at some special aspects of the methods Taguchi uses in implementing these recommendations. First, consider an example taken from a paper by Box (8) which illustrates in a very simple way one of the innovations introduced by Taguchi into industrial experimental, design.

Crossed Arrays

Suppose a food company has developed a new cake mix which is essentially a mixture of three ingredients viz: flour, sugar and .egg. When, the cakes are baked under recommended conditions of temperature and baking time the resulting hedonic index is 6.7 i.e. a, number of' cakes are rated, on a 'scale of 1 to 10, by a tasting panel and the average score is 6.7. Figure 14 shows the results of a traditional factorial study of the effects of varying the composition of the .mixture: each of the three components is varied upwards (+) and downwards (-) from the current levels (0) in all cases the recommended oven temperature and baking time are used.

Design variable F	S	E	T t	0 0
0	0	0	6.7	
-	-	-	3.1	
+	-	-	3.2	
-	+	-	5.3	
+	+	-	4.1	
-	-	+	5.9	
+	-	+	6.9	
-	+	+	3.0	
+	+	+	4.5	

F=flour, S= sugar, E =egg, O = current level = reduced level, + = increased, level baking temperature, t = baking time
Figure 14: A traditional experiment: cake – max data

The results suggest that the current composition is about optimal: only one higher score is obtained and this is unlikely to be significantly higher. Some of the mixtures produce very bad cakes.

But what would happen if the instructions regarding oven temperature and baking time are not followed. To investigate this Taguchi would recommend a second array which requires these factors to vary in the experiment. Figure 15 shows the results of an experiment where the mixture composition was varied as before and for each of the nine mixtures investigated five different baking regimes were investigated' also. The baking regimes consist of standard conditions and then the 4 combinations generated by shifting both temperature and baking time upwards and downwards. The value of such an exercise can be seen from this example the scores for the current formulation are highly sensitive to the baking conditions. The third last row of the array shows a more robust product formulation - one which will give a good cake almost irrespective of the baking conditions within the limits investigated.

Taguchi calls the array describing the levels of the variables over which the manufacturer has control an "inner array". The "outer array" .sets up variation in factors which will not normally be under the manufacturer's control. either during manufacture or in the field, as in this example The factors in this array arc often described as "noise factors". The role of the outer array is to simulate the effects of uncontrollable factors (such as environmental conditions, for instance) on the performance of the system under study. The intention is to choose a combination of the factors which are under the designer's control which will result in. a product or process which is insensitive to variations in noise factors which are not under the designer's control, except in an experimental situation

Design variables			Environmental variables					
F	S	E	T t	0 0	- -	+ -	- +	+ +
0	0	0		6.7	3.4	5.4	4.1	3.8
-	-	-		3.1	1.1`	5.7	6.4	1.3
+	-	-		3.2	3.8	4.9	4.3	2.1
-	+	-		5.3	3.7	5.1	6.7	2.9
+	+	-		4.1	4.5	6.4	5.8	5.2
-	-	+		5.9	4.2	6.8	6.5	3.5
+	-	+		6.9	5.0	6.0	5.9	5.7
-	+	+		3.0	3.1	6.3	6.4	3.0
+	+	+		4.5	3.9	5.5	5.0	5.4

Figure 15: Expanded cake-max experiment

In this simplified example the results of the crossed arrays experiment could be analysed by inspection. This would not be Taguchi's normal approach. I will illustrate his mode of analysis for crossed arrays shortly using a real manufacturing example. First, however, I would like to introduce an important distinction Taguchi draws between different types of controllable or design factors.

Control and Adjustment Factors

In his books he discusses a TV power circuit containing many components, but focuses on just two for the purposes of the example. The circuit is required to produce an output voltage of 115V; the two circuit elements affect the output voltage as follows: the transistor affects output in a non-linear way, the resistor affects it linearly. Over a design life of 10 years the h_{FE} parameter of cheap resistors can be expected to vary by ±30%. So if we use the transistor to target the output voltage (h_{FE} = 20. gives V= 115V, Figure 16) we get a range of 23V in the output. If on the other hand we recognise the non-linear effect on output variation of the transistor and set h_{FE} at 40 the output range will be reduced to 5V

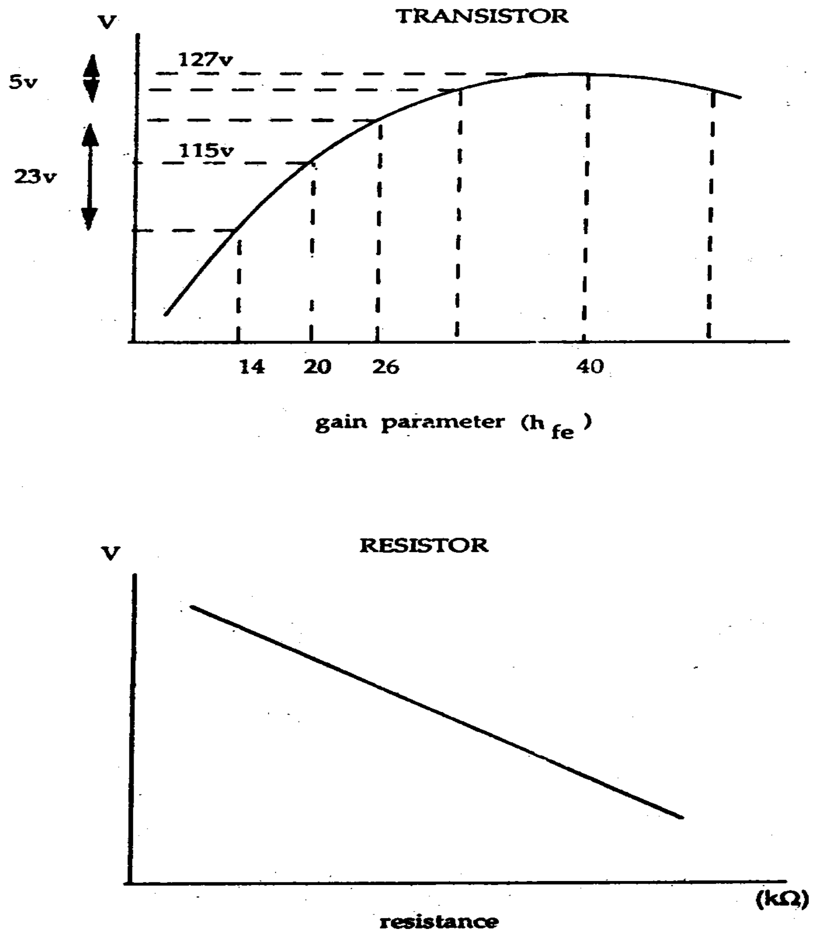


Figure 16: Exploiting non-linearities to achieve low variability

The output is off-target but since the resistor has no differential effect on variability we may now use it to adjust the output voltage until it is back on its target value of 115V. By exploiting the non -linear effect of h_{FE} on output voltage (and hence on output variability) we have succeeded in improving the stability of the output voltage without increasing costs. If the current level of variability is too high we will have to resort to higher quality components i.e. tolerance design is required.

Factors which affect the variability are called control factors while those that can be used to target the performance system without affecting the variability are called signal or adjustment factors. In this illustration the nature of the non-linearity was understood and therefore could be exploited. In general this will not be the case and we will have to use parameter design experiments to discover which factors affect which characteristics of the performance of the system, under study.

Analysis of Experimental Data

Consider now another example of the use of crossed arrays. This example was published by the Baylock Manufacturing Corporation

Engineering Staff (9). The problem was to develop a connector which could be connected to a nylon tube and have sufficiently high pull-off force to be fit for use in car-engines. There were four controllable factors (see Figure 17):

A: Interference;
B: Connector wall thickness;
C: Insertion depth; and
D: Percentage adhesive in connector pre-dip.
Noise factors involved the post-assembly conditioning of the samples prior to testing:
E: Conditioning time;
F: Conditioning temperature; and
G: Conditioning relative humidity.

The controllable factors are set out in what Taguchi calls on L_9 array where each factor is varied over three levels. A full factorial design would require 3 x 3 x 3 x 3 = 81 runs, this is a cut down version designed for situations where no interactions are expected this design is what was traditionally called a Graeco-Lation Square. The three noise factors are each varied over two levels according to the L_8 design we discussed in some detail earlier

For every combination of the controllable factors the design requires eight experimental runs corresponding to the eight combinations of noise factors. Thus the full experiment consists of 72 runs. Once the experiment has been completed the noise array is ignored and the eight response values are combined into a single performance measure which Taguchi calls the signal-to-noise ratio (Figure 18). Taguchi recommends different S/N ratios for different purposes but they are all defined in such away that large values are desirable. Before discussing the performance measures the discussion of the analysis of these designs will be completed.

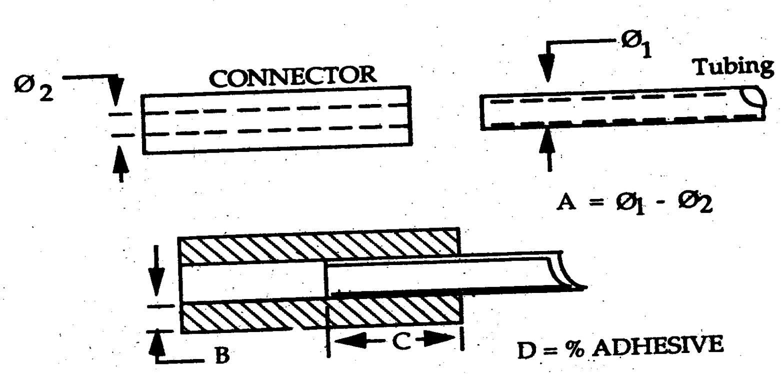


Figure 17: The factors 10 the connector study

Run No	A	B	C	D	2 2 2	2 2 1	2 1 2	2 1 1	1 2 2	1 2 1	E F G	S/N
1	1	1	1	1	19.1	20.0	19.6	19.6	19.9	16.9	9.5	24.025
2	1	2	2	2	21.9	24.2	19.8	19.7	19.6	19.4	16.2	25.522
3	1	3	3	3	20.4	23.3	18.2	22.6	15.6	19.1	16.7	25.335
4	2	1	2	3	24.7	23.2	18.9	21.0	18.6	18.9	17.4	25.904
5	2	2	3	1	25.3	27.5	21.4	25.6	25.1	19.4	18.6	26.908
6	2	3	1	2	24.7	22.5	19.6	14.7	19.8	20.0	16.3	25.325
7	3	1	3	2	21.6	24.3	18.6	16.8	23.6	18.4	19.1	25.711
8	3	2	1	3	24.4	23.2	19.6	17.8	16.8	15.1	15.6	24.832
9	3	3	2	1	28.6	22.6	22.7	23.1	17.1	19.3	19.9	26.152

Figure 18: Crossed arrays designed for connector study

Once the data are reduced to S/N ratios we have nine design points each with an S/N ratio. The analysis may consist of traditional analysis of variance (ANOVA) followed by graphical analysis of the results or the ANOV A step may be omitted.
If the mean value of the S/N ratio calculated for each of the three levels of the four

controllable factors graphs may be drawn (Figure 19) which show the results of the experiment.

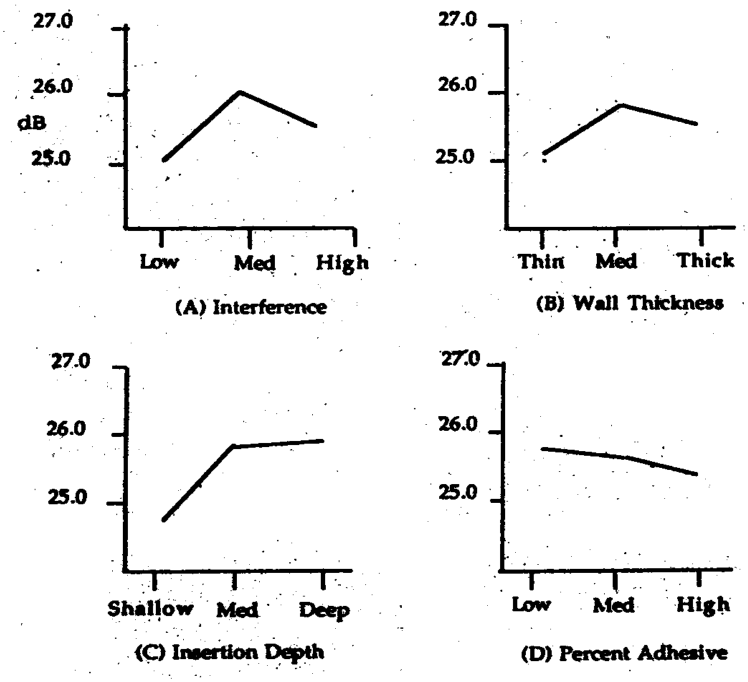


Figure 19: Result of Baylock experiment

Since the S/N ratio is defined in such a way that large values are desirable the analysis can simply mean inspecting those graphs and picking that combination of the levels of the four factors which gives highest S/N results. In this case we might choose A Medium, C medium or deep, B medium and D low (ANOV A was used in the actual analysis. of these data and suggested that Band D had little effect, which means that the most convenient levels of these factors could be chosen).

The simplicity of this analysis is one of the attractive features of the Taguchi package of methods. The orthogonal array provides: a recipe for designing the experiment and the graphical analysis of results can be carried out and understood without requiring formal statistical training. There is, of course, a danger that it will become a purely mechanical exercise which takes no account of the nature of the data. However, properly used, orthogonal arrays represent an extremely powerful approach both to design and analysis of industrial experiments, one which can contribute significantly both to product quality and cost savings.

Signal to Noise Ratios and the Loss Function

Taguchi's performance measures, his signal-to-noise ratios have attracted considerable adverse comment in the statistical and quality control literature (10, 11,12). He has, apparently, defined a very large number of such measures but the three shown in Figure 20 are the ones most commonly used and written about.

Objective: response as small as possible

$$SN = -10\log_{10}\left[\frac{1}{n}\sum {y^2}_i\right]$$

Objective: response as large as possible

$$SN = -10\log_{10}\sum 1/{y^2}_i$$

Objective: closeness to target

$$SN = 10\log_{10}(y^{-2}/s^2)$$

$$where\ \bar{y} = \frac{\sum y_i}{n}\ s^2 = \frac{\sum(y_i-\bar{y})^2}{n-1}$$

Figure 20: signal to noise ratios (SN)

These ratios are, at least partly motivated by Taguchi's concept of a loss function as a fundamental approach to measuring quality.

The Loss Function

If we consider, for example, the TV power circuit which had a target output voltage of 115V. Taguchi would say that any departure from 115V is undesirable and implies a loss. The loss function will be complicated but experience suggests that in most cases it can be approximated by a quadratic function. A family buys a TV and uses it for a number of years. Due to deterioration of components the power circuit output begins to vary from 115V. Let's assume it drops below 9OV.The picture becomes too dim and the contrast too weak to be corrected by the adjustment controls; either the power Circuit must be repaired or the TV set replaced. For simplicity, suppose the set becomes unusable also if the voltage output rises to 140V. If we assume that, averaged over a population of consumers, the average cost of either repairing or replacing the TV is 30,000 yen then figure 21 shows that the loss function can be represented by:

$L = 48(y - 115)^2$.

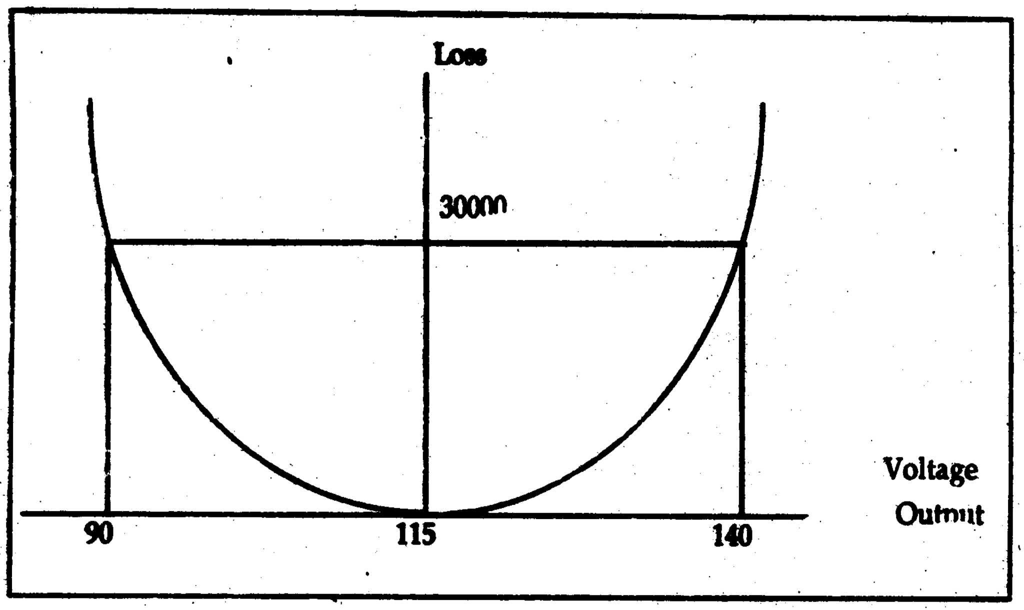
Taguchi would now use this loss function to make decisions about' manufacturing tolerances. Consider for instance the decision as to whether or not a circuit with output voltage 112V should be released to a customer. We suppose that the circuit could be adjusted to 115V simply by replacing a resistor at a cost of ¥l00.The implied loss to the ultimate consumer is:

$L = 48(112 - 115)^2 = ¥432$..

Taguchi comments: "To inflict a loss of ¥ 432 on the customer in order to save yourself ¥100 is worse than criminal", (the criminal reference relates to the possibility of a pick pocket stealing one's wallet - in this case there is no net loss to society) (5).

So at what stage should the' manufacturer be prepared to release a circuit which is not on target? The loss function gives the answer. If ¥100 is the cost of bringing the output voltage (Y) back on target, then:

$$100 = 48(y - 115)^2$$
$$y = 115 \pm 1.4v$$



$$L(y) = k(y - 115)^2$$
$$30000 = k(140 - 115)^2$$
$$k = \frac{30000}{(25)^2} = 48$$
$$L(y) = 48(y - 115)^2$$

Figure 21: Obtaining the loss function

The manufacturing tolerance should therefore be ±1.4V. This is an extremely tight manufacturing specification especially when compared to a customer requirement of something like ± 25V.This example brings home the power of the loss function as a quantitative expression of the Japanese obsession with continuous and never ending quality improvement. Ever if the high moral sentiments are alien to profit oriented Western ears, even if on technical grounds the estimation of such loss function appears fraught with difficulties we have to bear in mind that we find ourselves in competition with people who will use them and seek to achieve tolerances very much tighter than we consider acceptable.

Signal to noise ratio

Consider now an experiment where the desired output (Y) is as small as possible i.e ·zero. In this case the loss is proportional toy^2. If we take n Observations the average loss is$1/n\Sigma y^2$ taking logs simply rescales the loss and as the average tends to zero - log (average loss) tends to infinity. So the first signal-to-noise ratio in figure 20 is designed to become large as the loss becomes small. The second signal-to-noise ratio simply replaces y_i by $1/y_i$, .so it gets large as y_i gets large. The third signal-to-noise ratio is not so obviously connected to the loss function but Box has shown that a relationship can be established if certain assumption about the underlying-distribution of the data can be made (11).

There has been much discussion of these signal-to-noise ratios in the literature and they have stimulated research on appropriate performance measures (11, 12).

Concluding Remarks

The term "Taguchi Methods" covers many things but in this lecture it has been taken to mean a philosophy of robust design, a methodology, viz parameter design, for achieving this and a collection of design, and analysis tools for implementing this methodology. The use of experimental design to optimise product and process performance (defined in robust terms) using cheap materials/components is a new departure, in most Western industries. The use of efficient statistical designs as opposed to the traditional vary-one-factor-at-a-time approach is a very important part of the Taguchi package and one which will almost certainly bring huge economic benefits with it. The emphasis on analysis of variability as well as means. the distinction between control factors (that affect variability) and signal factors (that can be Used to ,adjust output to. a target value) are useful new ideas on a technical level. Overall, the package of methods both for design and analysis, advocated by Taguchi, is attractive for its simplicity and the readiness with which it can be absorbed and implemented even by those with little background in statistical methods,

The reservations which have been expressed about this package are important, but they are important at a technical level: there is little disagreement with, what Taguchi says needs to be done or with the broad thrust of the approach to achieving higher quality levels. The reservations relate to a lack of emphasis on interactions, to inefficient use of statistical techniques such as analysis of variance, to lack of emphasis on data analysis and validation of assumptions required for the statistical methods used and to the performance measures Taguchi advocates. Undoubtedly, the blending of good statistical practice with Taguchi's quality engineering ideas can only benefit both sides of the argument. In this regard the raising of Taguchi to "Guru" status and the development of a cult around these "Taguchi "Methods" is both intellectually unsound and jeopardises the long-term credibility of the methods themselves, leaving them open to being like so many other "flavours of the month"

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