An Innovative Model for Quality Optimization

V.I.N. LEOPOULOS
Asst. Professor
Mechanical Eng. Dept., Industrial Management & O.R. Section
National Technical University of Athens
15780 Zografos, GREECE
Tel: +301 7723585, Fax: +301 772357

CATHERINE A. POUSTOURLI
Dip. Production & Management Engineer, Assistant Instructor
Faculty of Administration & Economics, Business Administration Dept., Technological Institution of Serres
62124 Serres - GREECE
Tel: +303210 49228, Fax: +303210 37748

Abstract: This paper presents a theoretical analysis and a case study based on Taguchi's model in quality engineering. The model promotes a holistic view of quality. Quality related cost and money losses, are not considered just for the manufacturer at the time of production, but for the consumer and to society as a whole. The model determines the response characteristics (measurable and quality characteristics), separates factors which affect the product/process response and classify these factors. The loss function is measured by the deviation from the ideal value. Techniques like Orthogonal Arrays have been developed to reduce the elements of (product) variation around the (product) mean in Total Loss Function. The model gives an efficient way of designing experiments for industrial problems and provides a tool for optimizing manufacturing processes. Case studies are included from a furniture industry and a wood-particleboard manufacturing.

Keywords: Taguchi's Total Loss Function, Signal/Ratios, Orthogonal arrays, robust design, QFD, TRIZ

1. Introduction

1.1 General

The proposed model for implementing robust design is based on Dr. Taguchi's innovative approach to quality. This approach integrated with traditional methods for the design of experiments, resulted in a series of interrelated techniques that help minimize unwanted variability, reduce production waste, and provide greater customer satisfaction [1]. The cost-driven quality engineering, emphasizes the effective application of engineering strategies rather than advanced statistical techniques.

Through the proper design of a system, the process can be made insensitive to variations, thus avoiding the costly eventualities of rejection and/or rework. In order to determine and subsequently minimize the effect of factors that cause variation, the design cycle is divided into three phases of System Design (design of the first degree), Parameter Design (design of the second rank) and Tolerance Design (tertiary design).

1.2 Objectives and methodology

The model based on Taguchi's methodology is essentially a four step procedure which can best be illustrated as follows [2] [3]:

1. Formulate the problem (the quality characteristics, the controllable parameters or design variables)
2. Plan the experiment (orthogonal arrays with Lx symbol, additive model, signal-to-ratios)
3. Analyze the results (Analysis of Mean-ANOM, Analysis of Variance-ANOVA)
4. Confirm the experiment (finding better quality characteristics or signal-to-ratios and different control factors and levels, considering interactions among the control factors).

Taguchi's modeling considers that quality should be designed into product from the start, not by inspection and screening. Quality is best achieved by minimizing the deviation from a target set, not failure to confirm to specifications. Is not based only by rejections or on the performance, features or characteristics of the product. The cost of quality is measured as a function of product performance variation and the losses measured system wide (Total Loss Function). This loss function takes the following basic quadratic form:

$$L(x) = k(x-m)^2$$

Where L is the loss in money, m is the point at the which the characteristic should be set, x is where the characteristic actually is set, and k is a constant that depends on the magnitude of the characteristic and the monetary unit involved.

The uncontrolled sources of variation are called noise factors.

1.3 Comparison between conventional design techniques and Taguchi's model

Conventional techniques	**Taguchi's model**
transformations	signal-to- ratios
location and dispersion effects	signal-to- ratios
fractional factorials	orthogonal arrays
aliasing procedures	linear graphs
nested designs	inner & outer arrays
sequential designs	one-shot designs
response surface methods	pick the winner
effect analysis	complex anova
residual plots	outliers not considered

1.4 Typical criticisms to Taguchi's model

- too recipe-driven
- sequential investigations not considered
- limited choice of designs
- recommended design may be of suboptimal resolution
- better optimization techniques available
- Signal Noise Ratios may be ineffective
- data transformations ignored
- interactions (typically) ignored

1.5 Goals of the model

The central idea in the model is that variations in a product's performance can inevitably result in poor quality and monetary losses during the product's life span. The sources of these variations can be classified into the two categories of factors namely control and noise.

The proposed model of robust design is based on the identification of optimal settings for product and process parameters which:
- maximize performance
- minimize variation of the factors.

General examples about quality characteristics that approach an ideal value will be consider the efficiency (all efficiencies approach the ideal value of 100%) or the strength (approaches the ideal strength of the material).

Taguchi's Signal-to-Ratio for smaller-the-better quality characteristics is usually an undesired output e.g.
- Defects in cutting/dyeing/smoothing of a metal accessory
- Unwanted by-product or side effect

Taguchi's Signal-to-Ratio for larger-the-better quality characteristics is usually a desired output e.g.
- Fixture strength
- Critical Current

Taguchi's Signal-to-Ratio for nominal-the-best quality characteristics is usually a nominal output e.g.
- Nominal dimensions of mechanical components
- Ratios of chemicals or mixtures
- Thickness uniformity /growth /plating /etching.

The four steps procedure (1.2) leads to the following stages for the application of the model:

Step 1

a. Identify controllable (control) factors and uncontrollable (noise) factors.

Step 2

b. Construct design matrix (inner array) and noise matrix (outer array), inserting in appropriate way the data.

c. For each experimental point in the inner array, the absolute value of the factors difference is calculated, via the correspondence between the data of the outer array.

Step 3

d. Conduct and analyze experiment.

Step 4

e. Optimize performance.

f. Confirm results.

For the application of the model the following remarks should be taken into consideration:

1. The decisions, which concern the factors (design and noise), are made by the experimentation team, and should take into account similar environment of use as well as the cost of control.
2. Signal-to-Ratio can be used for stage d. An alternative is to separate analysis of mean performance (location) from robustness (dispersion).
3. Control factors are grouped into 3 categories: controls dispersion (robustness), controls location, and neither. We first set dispersion effect factors at optimal settings, then adjust location via other factors and then set 3rd category factors at most economical setting.

2. Development of the model

2.1 Signal to ratios

Goal of the model is to minimize one of 3 typical signal-to-ratios (SNRs) [4],[5].

For (non-negative) **smaller-the-better**

$$\eta = -10\ \mathrm{Log}_{10}\ (\ 1/n\ \ \Sigma\ Y_i^2\ )$$

The Y variable denotes the raw performance of a system of n repeated measurements per experiment. Maximization of the smaller-the-better Signal-to-Ratio is equivalent to minimization of the loss function.

For **larger-the-better**

$$\eta = -10\ \mathrm{Log}_{10}\ (\ 1/n\ \ \Sigma\ 1/Y_i^2\ )$$

For target-the better (**nominal the best**)

$$\eta = 10\ \mathrm{Log}_{10}\ (\ \mu^2 / \sigma^2\ )$$

where ì is the mean and ó^2 is the variance.

2.2 Orthogonal Arrays

Constructing matrix experiments using special matrices, called Orthogonal Arrays (OA) allows the effects of several parameters to be determined efficiently and is an important technique in Taguchi's model. To actually construct an OA, control parameters or design variables must be assigned to the columns of an array, and the integers in the array columns are translated into actual settings of the assigned parameters. The unassigned columns are deleted from the array [2].

The purposes of conducting matrix experiments [5] (using Orthogonal Arrays) are:

- to achieve insensitivity to noise by determining the best settings of control factors (minimize variations in its output Y_i)
- to identify the 'adjustment factor' (to adjust the level of Y_i)

This is achieved by Taguchi's 2-Steps
First step → minimize variance
Second step → adjust the mean-on-target

2.3 Interactions between Factors

The model considers interaction between noise factors and control factors. Interaction between control factors is not taken into consideration [5].

Use of Orthogonal Array implies that we can not or ought not consider interactions between control factors. We include only control factors that do not interact with each other, say A, B, C and D. This is shown in the following table:

Expt.No.	Control Factor A	Control Factor B	Control Factor C	Control Factor D
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

The method can include interaction between control factors, let it be 'R' and (A, B, C or D) with repeated use of Orthogonal Arrays (OA) [5]. If there is a single control factor 'R' that may have strong interactions with several control factors, then we can simply repeat the entire OA experiments at two different levels of 'R'. All interactions, between 'R' and any one of A, B, C and D, can be studied taken into consideration.

This type of interaction is shown in the following table

SPINDLE SPEED	Expt.No.	Control Factor A	Control Factor B	Control Factor C	Control Factor D
600 rpm	1	1	1	1	1
600 rpm	2	1	2	2	2
600 rpm	3	1	3	3	3
600 rpm	4	2	1	2	3
600 rpm	5	2	2	3	1
600 rpm	6	2	3	1	2
600 rpm	7	3	1	3	2
600 rpm	8	3	2	1	3
600 rpm	9	3	3	2	1
900 rpm	10	1	1	1	1
900 rpm	11	1	2	2	2
900 rpm	12	1	3	3	3
900 rpm	13	2	1	2	3
900 rpm	14	2	2	3	1
900 rpm	15	2	3	1	2
900 rpm	16	3	1	3	2
900 rpm	17	3	2	1	3
900 rpm	18	3	3	2	1

The method can include interaction between a noise factor 'X' and (A, B, C or D) with repeated use of OA [5]. If there is a single noise factor 'X' that may have strong correlation with several control factors, then we can simply repeat the entire OA experiments at two different levels of 'X'. All correlations between 'X' and any one of A, B, C and D can be studied.

This type of interaction is shown in the following table (use two sets of L9 array)

MATERIAL HARDNESS	Expt.No.	Control Factor A	Control Factor B	Control Factor C	Control Factor D
SOFT	1	1	1	1	1
SOFT	2	1	2	2	2
SOFT	3	1	3	3	3
SOFT	4	2	1	2	3
SOFT	5	2	2	3	1
SOFT	6	2	3	1	2
SOFT	7	3	1	3	2
SOFT	8	3	2	1	3
SOFT	9	3	3	2	1
HARD	10	1	1	1	1
HARD	11	1	2	2	2
HARD	12	1	3	3	3
HARD	13	2	1	2	3
HARD	14	2	2	3	1
HARD	15	2	3	1	2
HARD	16	3	1	3	2
HARD	17	3	2	1	3
HARD	18	3	3	2	1

- The OA based experiments, say L9 as in this example, require that two samples are made for each row (each row indicates one combination of control factors A, B, C and D)
- The measured values of quality characteristics are noted for that row
- Analysis then gives 'best' settings for control factors A, B, C and D that would give least sensitivity to the noise factor, say hardness as in the above example.

This is equivalent to the repeated use of OA shown earlier

					NOISE FACTOR Material Hardness	
Expt.No.	**Control Factor A**	**Control Factor B**	**Control Factor C**	**Control Factor D**	**LEVEL 1**	**LEVEL 2**
1 /10	1	1	1	1	SOFT	HARD
2 /11	1	2	2	2	SOFT	HARD
3 /12	1	3	3	3	SOFT	HARD
4 /13	2	1	2	3	SOFT	HARD
5 /14	2	2	3	1	SOFT	HARD
6 /15	2	3	1	2	SOFT	HARD
7 /16	3	1	3	2	SOFT	HARD
8 /17	3	2	1	3	SOFT	HARD
9 /18	3	3	2	1	SOFT	HARD

2.4 Causes of variations-noise factors

Every product's life goes through four stages:
Design, manufacturing, customer usage and aging.
Every stage has a "product quality" associated with it. Conventional design methods improve "quality" at each stage only after the product passes through that stage. Robust design improves "quality" at all the life stages at the design stage itself.

The main causes of variations-noise factors are presented in the following table:

MANUFACTURING VARIATIONS	OPERATING CONDITIONS	DETERIORATION (AGING)
Raw materials Manufacturing Equipment Workmanship	Environment Temperature, humidity, supply voltage, dust, vibrations Human error Loading Heavy duty Light duty	Components Consumables

To minimize right at the design stage the effects of,
Manufacturing variations: we must include these factors as noise while conducting matrix experiment
Operating variations: we must include these factors as 'additional' testing conditions for measurements. Normal testing conditions are for capturing the effect of noise included during the matrix experiments.
Variations due to aging: we must include these 'deteriorations' as noise while conducting matrix experiment. Include the "consumables" factors as additional testing conditions for measurements.

3. Case study

In the following case studies the design of the matrix experiment and the factors is presented. We focus in the appropriate information from the experiments, for the improvement of the deviation from the target (minimization of the defects with the type of function: smaller the better). It should be mentioned that with these case studies presented the model till the phase of Parameter Design (§1.1).

3.1 The choice of the most important factor

In this case study, we present the choice of the most important factors in the adhesive procedure between a particleboard and a melamine sheet, in a wood-particleboard manufacturing.
The typical steps that we follow, in accordance to §1.2 and §1.5 are:

- ❖ We choose the variables that we wish to examine (in the following case 6 variables and one interaction)
- ❖ We choose two levels for each main variable
- ❖ We assign variables to the columns of a Taguchi matrix. Appropriate columns are left blank for particular interactions, in this case column C for interaction AB.
- ❖ We carry out the work according to the levels 1 and 2 of each row.
- ❖ We put the results of our measuring in the results column (number of products)
- ❖ We work out the effects according to the levels 1 and 2 of each row and we put the results in the effect row.

From the study of the factors that affect the quality, we have the following values:

No.	Factors	Level 1	Level 2
A	Temperature of mix	70 °C	60 °C
B	Coating temperature	50 °C	45 °C
C	Interaction AB		
D	Coating speed	15 mm/sec	11 mm/sec
E	Adhesive thickness	0.7 mm	0.4 mm
F	Adhesive temperature	110 °C	95 °C
G	Cure time	1.5 min	1.0 min

The Taguchi L_8 matrix for 6 variables and 1 interaction is:

Exp. No	A	B	C	D	E	F	G	RESULTS
1	1	1	1	1	1	1	1	30
2	1	1	1	2	2	2	2	34
3	1	2	2	1	1	2	2	33
4	1	2	2	2	2	1	1	37
5	2	1	2	1	2	1	2	38
6	2	1	2	2	1	2	1	42
7	2	2	1	1	2	2	1	34
8	2	2	1	2	1	1	2	39

The total mean of results of each factor is:
(30+34+33+37+38+42+34+39)/8 =35.78

A1 = (30+34+33+37)/4 = 33.50
A2 = (38+42+34+39)/4 = 38.25

The result of increasing A (temperature of mix) from 60 to 70 is: [A2-A1] = 4.75 (absolute value)

The result of increasing B (coating temperature) from 45 to 50 is:
B1 = (30+34+38+42)/4=36.00
B2 = (33+37+34+39)/4=35.75
[B2-B1] = 0.25

The other effects are worked out in a similar manner according to the levels 1and 2 of the table. The overall results are:

Exp. No	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**No of products**
1	1	1	1	1	1	1	1	30
2	1	1	1	2	2	2	2	34
3	1	2	2	1	1	2	2	33
4	1	2	2	2	2	1	1	37
5	2	1	2	1	2	1	2	38
6	2	1	2	2	1	2	1	42
7	2	2	1	1	2	2	1	34
8	2	2	1	2	1	1	2	39
effect	**4.75**	0.25	3.25	**4.25**	0.25	0.25	0.25	
importance	**1**	4	3	**2**	4	4	4	

From the above table we conclude:

- The most important factors are A and D
- For best results A and D should be set high (effect of both is positive)
- There is a significant interaction between A and B (shown in column C)
- Careful examination of the results shows that is best to have one of these variables set high and the other low. Since we have already decided to set A high, it is best to have B set low.
- Since the effects of the other variables are less important, their levels can be decided according to other criteria, such as cost or absence of control
- We must always remember that these matrices can sometimes give misleading results. So we must always check the results in separate experiments.

3.2 Minimization of defects in a chair assembly production

The manufacturing system concerns the production of a metal accessory as a chair assembly in a furniture industry. The quality characteristics of these assemblies (parts) depend on 7 factors. For each of them we choose two values (levels). So we need to work with the $L_8(2^7)$ Orthogonal Array, that is an array with 8 rows of experiments, 7 columns of factors and 2 levels .

From the factors study we conclude that the 7 factors, which influence the quality of this particular type of parts (assemblies) are:

No.	Factors	Level 1	Level 2
A	Roughness of surface	rough	smooth
B	Hardness of material	hard	soft
C	Surface's dyeing	One layer of dye	Two layers of dye
D	Temperature	25°C	30°C
E	Cutting's conditions	Without grease	With grease
F	Speed of cutting	15 mm/min	20 mm/min
G	Smoothing	YES	N0

The Taguchi matrix for 7 variables (factors) is :

Exp. No	A	B	C	D	E	F	G	% defects
1	1	1	1	1	1	1	1	15
2	1	1	1	2	2	2	2	6
3	1	2	2	1	1	2	2	10
4	1	2	2	2	2	1	1	40
5	2	1	2	1	2	1	2	60
6	2	1	2	2	1	2	1	12
7	2	2	1	1	2	2	1	8
8	2	2	1	2	1	1	2	10

One sample of 10 parts is selected in each experiment. In the last column of the above table appears the number of defects found.

The total mean of results of each factor are:
(15+6+10+40+60+12+8+10)/80=2.01

Correspondingly the means of each factor are:

A1= (15+6+10+40)/40=1.77
A2= (60+12+8+10)/40=2.25

The result of the subtraction of the two levels for the factor A is:
[A2-A1] = 2.25-1.77 = 0.48

The other results are worked out in a similar manner according to the above calculations. The overall results are:

	A	B	C	D	E	F	G
level 1	1.77	2.33	0.98	2.33	1.17	3.13	1.88
level 2	2.25	1.70	3.05	1.70	2.85	0.90	2.15
subtraction	0.48	0.63	2.08	0.63	1.68	2.23	0.28
importance	5	4	2	4	3	1	6

We conclude that the most important factors are F, C and E. The importance of each factor is the absolute value of the subtraction between the results of the two levels.

In addition the best combination who gives the less percentage of defects are: A1, B2, C1, D2, E1, F2 and G1.

In many cases the improvement of quality is not achieved with the factors design only (phases of System Design and Parameter Design). In these cases we need to control all the causes of deviation from the ideal value (Tolerance design), e.g. monitoring of environmental conditions, accuracy of the equipment etc.

4. Conclusions and further research

Dynamic applications of Taguchi's model are useful for future models of a product. The ideal function of a design represents the theoretically-perfect relationship between performance and a signal input to a device. These applications are particularly important for e.g. measurement devices and control of manufacturing processes.

An interesting subject of research is to further extend the model of Taguchi by integrating a model which will be a combination of QFD (Quality Function Deployment), TRIZ (Theory of Inventive Problem Solving) and Taguchi's model of the design process [6], [7].

Missing from QFD is a hindrance factor for the engineering and optimization. This hindrance factor in engineering can be overcome with the solution concepts generated via TRIZ. TRIZ is weak, however, in the areas of customer-driven requirements and optimization. QFD provides the customer input and Taguchi provides the process for determining the best parameter values for a robust design. Taguchi's model lack the customer driven priorities and the tools required for system definition. These are provided by QFD and TRIÆ respectively.

References

[1] AMERICAN SUPPLIER INSTITUTION, www.amsup.com/taguchi _methods, 2001

[2] CENTER FOR NONDESTRUCTIVE EVALUATION, IOWA STATE UNIVERSITY, www.cnde.iastate.edu/staff/bforoura/HTML/taguchi.html, 2001

[3] THE FUNDAMENTAL TAGUCHI CONCEPTS, http://kernow.curtin.edu.au/www/taguchi/ , 2001.

[4] TAGUCHI METHODS, www.colorado.edu/EngMgmtProg/usrey/5550/taguchi.html , 2001

[5] TAGUCHI METHODS, Dr. P. R. Apte, 2001

[6] THE QFD, TRIZ AND TAGUCHI CONNECTION: CUSTOMER-DRIVEN ROBUST INNOVATION, www.mv.com/ipusers/rm/qfdtriz4.htm, 2001.

[7] THE QFD, TRIZ AND TAGUCHI CONNECTION : CUSTOMER-DRIVEN ROBUST INNOVATION, John Terninko, Ph.D., The Ninth Symposium on QFD, June 10, 1997.