SYSTEM OF EXPERIMENTAL DESIGN

GENICHI TAGUCHI

VOLUME ONE

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Engineering Methods to Optimize Quality and Minimize Costs

GENICHI TAGUCHI

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Technical Editor for the English Edition

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Introduction to the English Edition

As this is written, it has been six years since Dr. Taguchi's concepts and methods were introduced into the United States. In those six years these concepts and methods have attracted much attention. Product and production-process engineers who have long striven to improve quality while reducing costs have been greatly impressed by the breadth of Dr. Taguchi's concepts and the appropriateness of his methods. Almost always the engineer's appreciation for these methods has blossomed as familiarity with them has increased. Yet a thorough understanding of Dr. Taguchi's methods has been hampered by the lack of a complete English text. This translation fills that large void, and provides complete access to the grand sweep of Dr. Taguchi's thinking.

Dr. Taguchi's methods to optimize the design of products and production processes in a cost-effective manner represent one of the major advances in the history of manufacturing industries. Because of new inventions, Great Britain reigned supreme from the inception of the Industrial Revolution in 1750 until 1850. From 1850 until 1970 economies of scale were the dominant factor, and the United States gained supremacy. Rapid and economical reduction of variance emerged as a key factor in manufacturing industries in 1950, and became the dominant success factor in 1970, although this was not perceived in the United States until 1980.

Japan is superior in rapid and economic reduction of variance, with the application of Dr. Taguchi's methods as a major factor. In addition to the rapid improvement of product and process design, Dr. Taguchi's methods provide a common language and approach that improves integration of product design and manufacturing processes. Educating both product engineers and production personnel in his methods provides common perspective and objective — a major step in breaking down the traditional barriers between these two groups.

Dr. Taguchi's major contribution has involved the combining of engineering and statistical methods to achieve rapid improvements in costs and quality by optimizing product design and production processes. The greatest problem in quality development is to determine where one is soon enough to facilitate deciding how to proceed further. The traditional approach of problem identification is too slow and too uncertain of success. Dr. Taguchi has given us the quality loss function and the Signal-to-Noise (SN) ratio, which tells us where we are early in product development when we still have time to make improvements at the lowest cost. His use of orthogonal arrays enables a rapid search through millions of design options to find the design with the best SN ratio; i.e., the design that is furthest away from all potential problems.

Dr. Taguchi defines the inverse of quality as the cost or loss to society after a product has been shipped to the customer. His quality loss function allows us to evaluate at the design stage the cost of quality loss in order to strike the optimum balance between manufacturing costs and quality loss.

Continuous and rapid improvement in quality and costs is imperative for success in the increasingly intense international competition in manufacturing industries. It has been my privilege to work closely with Dr. Taguchi during the past four years, and to be a leader in the implementation of his methods in the United States. For those who wish to be technical leaders in this new industrial revolution, this book is essential.

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November 24, 1986

Preface to Volume One

A scientific or technical study always consists of the following three steps:

1. One decides on the objectives.
2. One considers the method.
3. One evaluates the method in relation to the objective.

In this book, the design of experiments method is defined as *a universal-use technique among evaluations*, that is, evaluations as mentioned in point 3 above. Put another way, the design of experiments is the system by which one can efficiently and reliably evaluate (as in point 3) all possible methods being considered for use (point 2) in reaching a particular objective (point 1); this system consists of *the method of laying out calculations and experiments, data analysis method, and rationalization of the characteristic values.*

In 1957, not long after my return home from India, I published the first edition of the Design of Experiments Method, which concentrated on the process of laying out calculations through orthogonal arrays, based on my experiences with a few businesses, through my work at the Japanese Electrical Communication Laboratory, and from my knowledge of several businesses in India. Perhaps because, at that time, related books in the field did not contain examples using orthogonal arrays or using data analysis examples that are not variable data, the first edition was greeted with enthusiasm over and above the expected from various areas. However, the content was no more than an amplification of the theory of R. A. Fisher of Great Britain (the originator of the design of experiments method) and the application of this theory to technical areas. As I wrote in the preface of the first edition, ". . . For researchers and technicians who do not have the leisure to learn *statistical mathematics* from the fundamentals, this volume provides interpretations that will most efficiently impart the grounding necessary to freely perform the design of experiments by orthogonal arrays, which is the central part thereof. . . ."

Fortunately, the first edition was published during the era of industrial recovery after the Second World War. The book saw an unexpected number of printings, and it was used for experiments in a variety of industrial fields. Yet when the book was used in these rapidly changing areas, it became clear that the content of the first edition was inadequate. It became necessary to develop the range of the method and the publication of a revised edition which would be able—at least tentatively—to meet objectives in practical use. In 1962, while I was in the United States, the second edition ("the new edition") was published, after extensive revision. I stated in the preface of that new edition: ". . . It is five years since the old edition was brought out; fortunately, in that time, orthogonal arrays have come into use for the design of experiments and their usefulness, shortcomings, problem points, etc., have gradually come to be clarified by many people, although the old edition was difficult to read. How I groped to find the problem points of experimental studies with how many hundreds, how many thousands, of people either individually or through various research societies, and how many times did I have discussions regarding countermeasures toward these problems. Discussions with sincere, earnest people of research were, for the author, the most valuable and fruitful experiences. . . ."

Since I had left Japan in the midst of proofreading for Volume One of the second edition, great hardships were inadvertently imposed upon the staff of the publication department at Maruzen Company. In addition, these difficult circumstances required that the prefaces to both volumes be written in America. Yet, while working concurrently at university and a laboratory during my stay in America, I was able to observe first-hand the work done by research members of Bell Telephone Laboratories, who used large computers and conducted design calculations freely; as I wrote in the preface to the second edition, I soon regretted my lack of wisdom in only having touched on the application of orthogonal arrays toward design calculations in three pages in that edition. Thus was born my strong desire that, if I were fortunate to have the opportunity of revising the text once more, I would truly prepare adequately and achieve a final edition that would yield no such regrets.

After returning to Japan, I left the Electrical Communication Laboratory and began to lecture at university on the design of experiments. After lecturing to students who lacked actual experience in research, I discovered that it was rather difficult for them to understand the second edition. It became clear that if lectures on data analysis of four units were held in advance of lectures on the design of experiments, a large number of students, even those with no practical experience, would understand the design of experiments method. Also, even though it was clearly pointed out in the second edition that *evaluation toward the reliability of experimental results* is the role of layout by orthogonal array, I had touched only briefly on the introduction to the method of obtaining reliable experiment results, or, in other words, on *rationalization of characteristic values*. While I was at Bell Telephone Laboratories and unencumbered by other tasks, I was extremely fortunate to be able to advance my studies in this area by the example of information transmission by the digital system. The fruits reaped at that time, i.e., expression of dynamic characteristics by SN ratio and applications to instrumentation errors, are the aspects on which the greatest effort was spent in the third edition, and I anticipate that in the future these methods will be used widely in every industrial field.

Based on the background and intentions described above, the following precepts have been adhered to in this third edition.

1. I have stayed away as much as possible from methods with little practical value, such as statistical testing and confidence limits, and I have interpreted the objective of analysis of variance as being quantitative evaluation on the magnitude of the influences of a variety of factors on the target characteristic. The use of F testing, which is only able to evaluate *qualitatively* whether factorial effect exists or does not exist, is discussed as a reference only; the core of the explanations deal with the contribution ratios of factorial effects as *quantitative* evaluation. This is because it is believed that quantitative judgment is more important than qualitative judgment. In this book, therefore, there is nearly no explanation of testing; it is believed that the usefulness of F testing lies only in its role as a substitute for beta coefficients, as shown in Chapter 19. I take the stand that it does not matter if one uses F testing as a substitute for the beta coefficient method, which is somewhat troublesome. Would it not be acceptable to use the judgment method, whereby upon obtaining the variance ratio, one does not use the F table but incorporates the ratio as being effective, by affixing a * symbol if the variance ratio F is at least 2 and by affixing a ** symbol if it is at least 5?

2. For those wishing to use this as a textbook for students who do not have actual work experience, or for those wishing to learn the design of

·xperiments on their own, the method of data analysis in the case of one actor is explained fairly fully in the note at the end of Chapter 1. Also, as o the two-way layout method, which constitutes the basis of data analy-is, the two examples given in the second edition have been increased to ive examples, to better teach the reader how to freely perform analysis n a variety of cases. Furthermore, data analysis other than of variable values is shown in Chapters 2 and 3, and the plan was followed to orga-ize the material from Chapters 1 through 3 to meet the needs of a university course in statistical analysis amounting to about 4 units. It has een my intention to provide the substance for a preparatory course on he design of experiments method.

3. So that Volume One alone would become a standard course on the lesign of experiments, an explanation is given on the central methods hat are important for the fundamentals of orthogonal arrays and layout y orthogonal arrays; methods with a low frequency of use and high-evel methods have been left to Volume Two.

4. An introduction to *response analysis,* which is important in design alculations, and *experimental regression analysis,* which is useful for he fitting of formulas, is provided in Chapter 16 and Chapter 15, respec-ively. These two chapters should be the first chapters to be read by eople engaged in design calculations and those in physical science areas n which observation is central.

5. The remarkable popularization of computers has made possible the ise of analysis methods that are efficient but which contain calculations hat had previously been troublesome, such as minute accumulating analysis. DANEX, of DEMOS, of the Nippon Telephone and Telegraph Public Corporation, is a universal-use program solely for the design of experiments method, and it is capable of calculating nearly all the analy-ses given in this book in a time frame ranging from 1 second to several minutes. Therefore, in this edition, I decided to show methods of data analysis centered about efficiency, rather than being concerned over whether calculations are troublesome or not.

6. Volume Two deals with high-level techniques, with special matters of various individual fields, and with explanations of mathematics and the like. For example, regarding rationalization of characteristic values, mentioned above, much explanation is given on the SN ratio for *evaluation of instrumentation error* and *evaluation of dynamic characteristics,* and about 20 percent of Volume Two is applied to them. I await appraisals and comments from readers in these areas.

7. Data analysis of surveys, observations, and time series, such as in areas related with medical drugs, market survey, and physical sciences, is explained in detail in Chapters 26, 27, and 28, respectively. Experiments and data analysis related to production techniques are discussed in Chapters 20 and 25. In all instances it has been the intention to cover the range

from elementary principles to practical aspects, and I would feel fortunate if this edition were to be useful in a role as a connecting link until specialized volumes for each of these areas appear. Textbooks classed by areas are, indeed, a major challenge that remains in the field of the design of experiments.

Somehow, it seems that the design of experiments method and its applications have become my life's work. Since I believe that this revision will be the final edition, I am deeply appreciative of those individuals who gave me the opportunity of advancing in this area: Dr. Genzaburo Masuyama, who guided me toward the design of experiments method immediately after the end of the war and who gave me the opportunity of plant supervision; Mr. Ken Kayano, who gave me the occasion for application to research and development relations; the late Dr. P. C. Mahalanobois, director of the Statistical Research Laboratory of India, who gave me the opportunity to try applications of the design of experiments method at a plant where the conditions differed rather considerably from Japan; the late Professor S. S. Wilks of Princeton University, who gave me the opportunity to perform research related to the SN ratio in America; and Professor J. Tukey, who is even at present active with his unique insight.

I firmly believe that the state of the results applied to actual problems is the greatest teacher of the effectiveness of a new process. I express my heartfelt gratitude to the large number of businesses that accorded me the opportunity to apply various new aspects of the design of experiments method toward actual problems, and to experiment-related people of the businesses who accorded me aid, directly as well as indirectly. Since the number of individuals to whom I am indebted is so great, I wish to be allowed to omit their names, with regret for the discourtesy.

Lastly, I express my appreciation to Miss Yukiko Yokoyama of Aoyama Gakuin University, who assisted me in regard to numerous calculations and corrections of the great many calculation examples that have been introduced in this book, and to members of the publication department of Maruzen Company, who aided me in publication and proofreading.

GENICHI TAGUCHI

November 3, 1976

How to Use This Book

The contents of this publication are divided into 19 blocs, as follows.

BLOC	TITLE	CONTENT
A	Introduction to Data Analysis (1)	Note 1.1, Note 1.2, the following exercise problem: (*1) Concerning the magnitude of vibrations in a certain machine, we wish to examine whether the magnitude of the deflections of the bearings which constitute the vibrations has any influence. In regard to the deflections of the bearings A, assuming, A_1 = Those of small deflection, A_2 = Those of large deflection, when 10 were taken from among A_1 and 6 were taken from among A_2 and when this machine was constructed and its vibrations were measured, it became as follows:

BLOC	TITLE	CONTENT
		(Unit db) A_1 0.9, 0.3, 0.4, 0.2, 0.1, 0.8, 0.9, 0.4, 0.0, 0.6 A_2 0.6, 1.0, 1.1, 0.9, 1.0, 1.2 Conduct variance analysis and indicate the conclusions.
B	Introduction to Data Analysis (2)	Note 1.3, exercise problem (2) of (2), Note 1.4, the following exercise problem: (*2) For a certain plastic material, we took the temperature A as $A_1 = -20, A_2 = 0, A_3 = 20, A_4 = 40$ [°C], and measured the tensile strength of 3 each. The results are shown below (units are kg/cm² and the working mean of 50 has been subtracted). A_1 A_2 A_3 A_4 13 5 −3 −12 12 3 −5 −16 15 3 −4 −13 Perform an analysis of variance resolved into an orthogonal polynomial, and carry out polynomial expansion using the significant terms.
C	Data Analysis (1)	Sections 1.1.1 to 1.1.2, exercise problems (a), (b), (c) of (1) of (1) Sections 1.1.3 to 1.1.4 of (1) Sections 1.1.5 to 1.1.6 of (1)
D	Data Analysis (2)	Section 1.2, exercise problem (3) of (1), sections 1.3 to 1.5
E	Classification of Characteristic Values	Chapter 2
F	Accumulating Analysis and Frequency Method	Section 3.1.1, exercise problem (1) of (3) Section 3.1.2, exercise problem (2) of (3) Section 3.2.1, exercise problem (3) of (3) Sections 3.2.2 to 3.2.3 Section 3.3

BLOC	TITLE	CONTENT
G	Role of Design of Experiments	Chapter 4
H	Factors and Levels	Chapter 5, exercise problem (1) of (5)
I	Introduction to Orthogonal Arrays	Sections 6.1 to 6.3, exercise problem (a) of (1) of (6) Sections 6.4 to 6.5, exercise problems (b), (c), (d) of (1) Section 6.6, exercise problem (2) of (6)
J	Linear Graphs and Their Applications	Chapter 7, choose one among exercise problems (1), and (2) to (4), of (7)
K	Dummy-Level Technique and Combination Method	Chapter 8, choose one among exercise problems (1), and (2) and (3), of (8)
L	Split-Unit Design	Chapter 9, exercise problems (1) to (3) of (9)
M	Pseudo-Factor Design	Chapter 10, exercise problems (1) to (4) of (10)
N	Partial Supplementing Design	Chapter 11, exercise problem (11), comprehensive exercises (16), (17)
O	Interaction Partially Omitted Method	Chapter 12, exercise problem (12), comprehensive exercises (21), (24), (26)
P	Direct Sum Design	Chapter 13, exercise problem (13)
Q	Partially Expanded Design	Chapter 14
R	Experimental Regression Analysis	Chapter 15
S	Response Analysis	Chapter 16

The topics covered in Volume Two, as listed in the Table of Contents, need no further explanation here.

Instructions for lectures and self-study are shown below; the letters in the "Instructions" column refer to the blocs itemized above.

COURSE NAME	TARGETED PERSONS	INSTRUCTIONS
(1) Fundamentals of Data Analysis	Students, general public who wish to learn the fundamentals	A,B,C,D (30 hours); E,F (30 hours)
(2) Data Analysis	Researchers, technicians	C, Chapter 19, Chapter 21, D,E,F (48 hours); only important parts of Chapter 19 and Chapter 20 could suffice
(3) Introduction to Design of Experiments Method	Researchers, technicians	C,E,F,G,H,I,J,K (48 hours)
(4) Fundamentals of Design of Experiments Method	Self-learners, students	Following Data Analysis of (2), G,H,I,J,K,L,M,R,S, Chapter 35 (total, 96 hours)
(5) Design of Experiments Method	Full-fledged course for researchers and technicians	Besides the Fundaments of Design of Experiments Method of (4), P,Q, Chapter 22, Chapter 23, Chapter 24, Chapter 28, Chapter 32; other chapters suffice as necessary (total, 132 hours)
(6) Design of Experiments Method for Production Personnel	Production personnel	Besides (4), Chapter 19, Chapter 20, Chapter 22, Chapter 24, Chapter 25 (total, 120 hours)
(7) Design of Experiments Method for Instrumentation and Measurement	Individuals involved with measurement and instrumentation	A,B,C,D, Chapter 20, Chapter 21, Chapter 22, Chapter 24

COURSE NAME	TARGETED PERSONS	INSTRUCTIONS
(8) Outline of Design of Experiments Method	Research supervisers, administrators	G,H,I,S,R,M (12 hours)
(9) Design of Experiments Method for Research Supervisers	Research supervisers, designers	A,B,C,D, Chapter 21, S,R,G,H,I,J,K,L,M (48 hours)
(10) Response Analysis	Persons in charge of design	S,R (12 hours)

When classed by industry, different refinements will be needed; see, for example, the different cases presented in Chapter 17. Also, Chapter 26 has examples that relate to medicine and pharmaceuticals and Chapters 27 and 28 give information relating to market survey. Course (4) may also be helpful in specialized areas.

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