Quality Engineering and Taguchi Methods: A Perspective

Robust product design and parameter design — methods to develop products that will perform well regardless of changes in uncontrollable environmental conditions or that are insensitive to component variation — are key concepts in the work of Dr. Taguchi. We should encourage design and manufacturing engineers to apply these useful ideas. But in designing experiments and analyzing data — key aspects of the practical implementation — better and simpler methods are available and should be preferred over Taguchi's less intuitive and more cumbersome approaches.

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During the last few years we have witnessed a surge in interest in quality improvement. Quality improvement, or as it used to be called, quality control, is a field with a long history that continues to grow. New contributions are made every year. In the 1960s and 70s there was a slump in the Western development partly because of misunderstanding of the enormous economic benefits of quality control. During that period, quality control was mostly perceived as a set of techniques for sorting and final inspection of products. Thus, quality control was seen as an added expense.

This view is rapidly changing. Many companies are now developing a much more visionary company-wide quality improvement strategy. Perhaps the most important development is that in some companies, management is coming to the fundamental conceptual understanding that quality does not necessarily come at a higher cost. By using quality improvement concepts, quality engineering methods, and quality management principles, it is possible to develop products and processes of higher quality at lower overall cost. In fact, quality management is an integrating concept for cost-effective, rational, cooperative manufacturing of high-quality products and for delivering high-quality services.

In conjunction with the broader vision of quality management we are also seeing a rapid development of new quality engineering concepts. In particular, we are hearing a lot about Taguchi methods. The history of quality control, engineering statistics, and quality engineering is little known and few people can put Taguchi methods in perspective. But without a proper perspective, managers and engineers might commit

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themselves and their companies to long-term strategies and expensive educational programs that later might turn out to be imprudent. Although the review of Taguchi's methods provided in this article is somewhat critical, the purpose is not to be negative and in particular not to criticize Dr. Taguchi personally. The intent is instead to alert engineers and managers to the fact that although many of Taguchi's *engineering ideas* are very useful, his *statistical* inventions are inefficient, and also more cumbersome and less intuitive than need be. We can do better.

This really is good news. If we can improve on the methods used by our competitors, we have the foundation for a better strategy. In an effort to become more competitive, it is important to use the best and simplest tools available.

Quality Improvement and Quality Engineering

Concern about quality of manufactured goods goes back as far as ancient Egypt.[1] In more modern times, pioneering industrialists such as Joshua Wedgwood and Henry Ford emphasized the importance of delivering high-quality products at a low price and made that philosophy the basis for their business success.

The earliest applications of statistical methods for quality control date back to the 1920s and are due to Dr. Walter A. Shewhart and his associates working for Bell Laboratories and Western Electric. Through Shewhart's efforts, Quality Control became an engineering discipline in its own right. His two books[2,3] are as important today as when they were first published. Blanton Godfrey has written an interesting article on the early history of statistical quality control at Bell Laboratories.[4]

Shewhart inspired many people both in the United States and abroad. Perhaps he found in Great Britain the most receptive foreign audience. At the time, quality control was seen as a way of fending off the depression, then at its worst.

Despite the fact that most of the fundamental ideas of quality control

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have been around since World War II, quality improvement today seems to be the most promising avenue for American industry to follow in its current struggle to regain competitive strength. This can be said with confidence, for it is widely acknowledged that a major reason for the success of many Japanese companies is the use of the quality improvement philosophy they originally learned from Shewhart's friend and long time associate, Dr. W. Edwards Deming.[5]

Always a Better Way of Doing Things

What is quality improvement? Without trying to come up with a stringent definition, quality improvement is operating on the philosophy that there is always a better way of doing things. To find out how to do things better, we use simple scientific methods of data collection, data analysis, and experimentation as a catalyst for our engineering and other knowledge. An excellent introduction to the fundamental and perhaps most powerful tools for quality improvement in manufacturing is Ishikawa's *Guide to Quality Control*, originally written for factory foremen.[6] The late Professor Ishikawa describes what has become known as the Seven Tools: check sheets, Pareto diagrams, cause and effect diagrams, histograms, stratification, scatter plots, and graphs. The seven tools and the spirit in which they are used by Ishikawa are simple applications of a scientific approach to problem solving.

Every process generates information that can be used to improve the process.[7] For example, when a product fails it also produces information (that it failed and under what circumstances) that can be used to find the cause for failure. In turn, that information can be used to gain understanding of "why" the problem occurs and to permanently fix it or change the system. We therefore need to "listen" to the process. But to listen, we need "hearing aids" such as control charts and the other seven tools.

The widespread and creative use of the seven tools for solving all kinds of problems, manufacturing as well as service-related, at all organizational levels of Japanese companies has profoundly increased the quality and reduced the cost of their products. It is widely believed that these tools, despite their simplicity (or perhaps because of it), have significantly contributed to Japan's success.

Lately "Taguchi methods" and Quality Function Deployment (QFD) have received attention. Eureka writes that "The use of QFD and Taguchi Methods has been instrumental in helping Japanese companies to improve quality, reduce cost, cut product development time in *half*, and achieve major competitive market advantages."[8]

Taguchi methods undoubtedly are applied extensively in selected industries, but data from Japan provided by Professor Kusaba, Musashi Institute of Technology, and the Japanese Union of Scientists and Engineers (JUSE) seem to indicate that Taguchi's personal contributions to quality engineering have been applied only on a rather limited basis in that country. In evaluating the role of statistical methods in Japanese quality control, Kusaba writes:

As regards the so-called Taguchi method, the basic usage of the orthogonal array has been widely adopted since the 1950s as a type of the design-of-experiment method. By contrast, its complicated usages represented by the pseudo-factor method, and the concepts of SN-ratio and on-line QC are the choice of only a small number of people. The reasons are: 1) In spite of their originality, these methods have not been provided with sufficient logical explanation; 2) The usage of the methods requires special skills; 3) SN-ratio is effective in solving a limited range of problems, but the use of logarithms makes it difficult to get the physical meaning of the errors calculated, ordinary analytic techniques are far simpler, have high testing power, and are effective enough as well as convenient.[9]

Orthogonal arrays were invented in Great Britain by researchers from that country and India in the 1940s. They have been applied by quality professionals in the United States and Great Britain since that time.

In the same article, Professor Kusaba supplies an interesting table reproduced here as Fig. 1. It is a statistical tabulation of methods used in case studies presented at the Quality Control Annual Conferences held each year in Japan. From this table it is clear that the seven tools are in fact the most utilized methods and more likely are key ingredients in Japan's success. Note also the use of the generic term "design of experiments."

I think Japan's secret weapon is the company-wide, cooperative use of a scientific approach to problem solving. In particular, the scientific attitude as characterized by the Plan-Do-Check-Action (PDCA) circle, also known as the Deming Cycle or Deming Wheel. Used throughout all organizational levels and across all functions, in a spirit of genuine cooperation, this approach is extremely powerful. When an overall scientific attitude characterized by the PDCA circle is adopted, the seven tools and more advanced statistical methods, such as design of experiments, naturally present themselves as the tools for particular jobs.

History of Industrial Applications of Design of Experiments

Although the seven tools have played an important role in improving quality in Japan, they are most applicable to ongoing processes. To be more effective we need to start the quality improvement effort upstream at product design and process design.

This need was recognized by the pioneers in quality control. One of these was L. H. C. Tippett, who worked for the British cotton industry on practical problems associated with the manufacture of cotton products from the mid 1920s and onwards. He had been exposed early in his career to the ideas of the British statistician, Sir R. A. Fisher, about design of experiments. Fish-

er's methods for effective experimentation, developed for agriculture, were a fundamental break with the tradition of only varying one factor at a time. On the contrary, he recommended varying all factors simultaneously in what is known as a factorial experiment. This method, and the later developments of fractional factorials and orthogonal arrays by British, Indian, and American scientists, provided great savings in experimental effort. Fisher's method also provides more information about the system studied than traditional, one-at-a-time experiments.

Tippett immediately saw the great potential for using Fisher's experimental design methods for improving the very difficult process of transforming raw cotton of great variability to a final product (such as dress shirts) where almost no variation is allowed. Tippett wrote extensively about the use of statistical methods in industry and his applications include, in addition to cotton industry examples, electrical, mechanical, and foundry industry examples. He also taught short courses to people from a variety of industries. A visionary paper written in 1936 outlines in clear terms Tippett's broad view on the use of statistics for quality improvement. In particular, he pointed out that "The need for the application of statistical methods to control of quality in industry lies in the fact that all industrial products are subject to some degree of uncontrolled variation."[10]

Tippett was in close contact with the work of Shewhart and refers often to Shewhart's books and papers. He must certainly have attended Shewhart's 1932 lectures in Great Britain organized by the statistician Egon S. Pearson, another British pioneer in the area of quality control. These lectures had great impact on the British audience and led to the formation of the Industrial and Agricultural Research Section of the Royal Statistical Society. They also led to the publication of the *Supplement of the Journal of the Royal Statistical Society*, which in the following decades published

year	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87
(Fundamental)																		
graph	29	16	19	18	19	15	26	36	26	20	40	40	44	59	70	88	55	78
cause & effect diagram	28	16	15	18	19	16	23	36	30	35	30	35	42	56	57	40	52	39
Pareto chart	6	7	10	9	12	2	10	22	17	21	18	20	23	33	36	34	34	40
histogram	5	-	2	5	4	5	16	12	14	15	11	17	22	28	25	37	33	36
control chart	7	4	1	8	5	5	8	12	8	15	11	20	23	26	21	23	20	13
scatter diagram	3	-	-	7	-	3	4	12	15	13	6	6	2	13	13	15	24	22
process capability	-	-	-	-	-	1	-	-	2	-	1,	1	4	1	2	7	-	3
nomograms	-	-	-	-	1	2	4	-	-	-	-	-	-	-	1	-	-	-
(General)																		
design of experiment	18	8	14	13	15	14	14	27	12	14	27	29	44	36	59	49	45	43
correlation & regression	10	5	-	9	4	3	13	6	9	9	10	11	16	17	10	20	18	18
analysis of variance	2	3	-	3	1	1	-	2	9	4	4	6	2	5	4	7	5	10
statistical test & estimation	1	1	-	-	3	3	6	3	6	2	1	5	1	1	1	3	3	9
optimization & EVOP	1	-	1	-	-	-	1	-	-	-	1	-	1	1	1	-	1	-
time series	-	-	-	-	1	2	-	-	-	-	1	-	2	1	1	2	-	1
cumulative method	-	-	-	1	-	1	1	-	-	-	-	-	2	-	1	1	-	-
sampling inspection	-	-	-	-	-	-	-	-	-	2	2	1	1	1	-	-	-	
(Multivariate Analysis)																		
multiple regression	3	2	3	3	5	2	4	3	5	12	4	5	17	12	14	23	13	8
principal component analysis	-	-	-	1	1	-	1	6	1	6	6	3	4	7	8	7	4	2
discriminant and cluster analysis	-	-	-	-	1	2	-	1	-	2	2	1	1	4	11	3	4	2
quantification theory	-	-	-	-	-	-	-	-	-	-	-	-	4	5	2	7	8	
others	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	-	-	
(Miscellaneous)																		
tree analysis & QFD*	-	-	1	-	-	1	3	-	6	6	30	29	42	18	14	43	32	40
FTA	-	-	-	-	-	-	-	-	-	-	-	-	11	8	14	10	18	
FMEA	-	-	-	-	-	2	1	-	6	5	3	10	-	11	12	9	4	4
Weibull distribution	3	-	1	-	1	3	-	2	4	3	2	1	1	4	3	7	2	3
distribution theory	3	5	1	4	5	3	5	7	1	4	-	2	5	3	5	3	1	-
sensory test	-	-	4	2	1	4	2	4	-	2	-	2	3	1	5	3	-	
relation chart	-	-	-	-	-	-	-	-	4	4	5	7	6	5	4	15	7	6
PERT	-	-	-	-	-	-	-	-	2	2	4	2	1	1	1	3	2	-
simulation	1	1	1	3	-	-	-	-	2	1	3	-	1	3	1	2	-	3
computer technic & EDPS	-	-	-	-	-	-	-	-	-	-	-	-	2	6	6	1	10	
others	5	1	1	4	2	1	1	-	2	4	2	1	2	4	-	12	6	9
No. of presentations	126	60	65	94	110	97	95	114	107	130	138	148	178	172	202	210	183	175

* QFD: quality function deployment chart

Fig. 1. *Statistical Methods used in Presentations of Quality Control Annual Conference held in Japan, sponsored by Union of Japanese Scientists and Engineers (JUSE). Reproduced from Professor Kusaba's article ,"Statistical Methods in Japanese Quality Control,"* Societas Qualitatis, Vol.2, No. 2, May/June 1988. *Note that several methods sometimes were used in the same case study.*

many outstanding papers on the application of statistical methods to industrial problems and in particular on the use of experimental design.

During those early years, quality experts and statisticians in the United States and Great Britain cooperated closely. For example, the Massachusetts Institute of Technology (MIT) sponsored an Industrial Statistics Conference in 1938. Among the speakers were Dr. Walter A. Shewhart[11] from Bell Labs, and Leslie E. Simon,[12] then captain of the U.S. Army Ordinance Department, and later general and author of the book *An Engineer's Manual of Statistical Methods.*[13] From academia came the statistician S. S. Wilks,[14] Princeton University, who was very active in the area of engineering applications of statistics and later co-author with J. S. Hunter and I. Guttman of the book *Introductory Engineering Statistics,*[15] and H. A.

Freeman,[16] Professor of Statistics at MIT, who later wrote the book *Industrial Statistics*[17] which includes several applications of design of experiments to industrial quality problems.

At this 1938 conference Tippett presented two very extensive lectures[18,19] on the use of statistical methods: 1) "The Statistical Principles of Experimentation, With Particular Reference to Experimentation in Textile Factories," and 2) "Statistical Aspects of the Control of Quality in Textile Manufacture." These lectures, which were subsequently published, show that design of experiments was then considered an integral part of statistical methods for quality control and improvement.

Ten years later, after World War II, Tippett was again invited back to MIT to give a series of lectures. His

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lecture notes are preserved in an interesting book entitled *Technological Application of Statistics,* published in 1950.[20] About half of this book is devoted to control charts and other process control-oriented methods, but the other half is on design of experiments for quality improvement.

During the following decades, Tippett and many other pioneers successfully applied design of experiment techniques and statistics in industry for reducing variation in production processes and for developing better quality products. However, their efforts never received widespread industrial recognition in the United States and other Western countries. The chemical and pharmaceutical industries are exceptions and design of experiments continued to be practiced in agricultural research, which was the area that originally inspired Sir Ronald A. Fisher to develop the fundamental concepts of experimental design in the 1920s. Incidentally, Fisher was urged to do this by his friend Gosset, also known under the pen name *Student,*[21] who worked for Guinness's brewery where he developed the first modern statistical methods out of industrial necessity. It is curious that Western industry did not see the potency of design of experiments because many interesting examples were published in the forties, fifties, and sixties in American journals such as *Industrial Quality Control.* Perhaps it was too easy to make a profit otherwise, and competition was not as tough as today.

Taguchi Methods

On the contrary, the Japanese saw very early the benefits of using design of experiments in the development of new products and processes. One of the best-known people in this area is the engineer Genichi Taguchi who for a long time worked for the Electrical Communication Laboratories in Japan.[22,23] He successfully applied design of experiments and other statistical methods he had learned from the United States and Great Britain in the early

1950s to more effective industrial product development.

Design of experiments is vital in new product development because time spent experimenting with prototypes and debugging products and processes often is prohibitive. Western industries, unfortunately, too often rush products into the marketplace without sufficient development and testing, even relying on the customers to discover defects or malfunctions. This approach is signified by frequent recalls of defective products — the cost of which the consumer, of course, eventually has to pay.

Efficient experimental methods are the basis for economically feasible and thorough product development and testing as well as experimentation aimed at improving production processes. Fisher's method and later developments such as fractional factorials, orthogonal arrays, and response surface methods constituted a major, but largely ignored, advance in modern manufacturing technology. The difference between trial and error and one-at-a-time methods so common among Western engineers today, and even the most rudimentary application of Fisher's experimental design methods is truly dramatic. Fisher's methods are key ingredients in what have lately been described in the United States as "Taguchi methods."

Taguchi has invented methods such as signal to noise ratios, accumulation analysis, and linear graphs, but it is experimental design that does the trick. Taguchi's own inventions are not only inefficient in extracting the available information from often expensive and hard won data, but are also more complicated than methods which have become standard among Western statisticians. Had his statistical methods been shortcuts used as alternatives to more cumbersome but perhaps more correct methods, there would be no problem in recommending his techniques. But the fact is that many of Taguchi's statistical inventions are both more complicated *and* less efficient than mainstream statistical methods. Thus, his statistical inventions can hardly be said to constitute

improvements or enhancements over other methods well-known to statisticians.

Robust Product Design

Taguchi's important and useful contribution is rather his engineering idea of *robust product design* and *parameter design.* A robust car, for example, is a car that not only starts and runs well under ideal environmental conditions, but performs well even when the temperature is 110°F and the humidity is 90 percent, or when the temperature is −30°F and the humidity is 0 percent. Thus robust products are insensitive to changes in uncontrollable conditions or other kinds of variability.

We also use the term "robust" about products that are insensitive to production variation from nominal values of the parts from which they are assembled. This is important because when products are produced under mass production conditions, the components invariably differ from their specified nominal values. If assembled products can be made robust (insensitive) to component variation, production tolerances can be opened up, and that often means great savings in production costs.

Taguchi's method for making products more robust is called *Parameter Design.* This method is based on the idea that the design parameters of a product can be manipulated by experimental methods with the objective of finding product design configurations that are less sensitive to variation. Taguchi's best-known example concerns the manufacture of tiles. Rather than buy a new expensive kiln that would have less temperature variation, the Ina Tile Company of Japan experimentally found that by adding an inexpensive lime additive to the clay, fewer tiles would break due to temperature variation in the old kiln. Thus a simple cheap solution was found whereby the tiles were made robust to temperature variation.

Robust products and parameter design are important and very useful ideas. They should be included as standard concepts used by all

design engineers. Many expensive efforts to improve process capabilities may be unnecessary. Taguchi's concept is in sharp contrast to the conventional and expensive approach of reducing product variability by controlling and eliminating causes of variability. Although the objective of this experiment was Taguchi's useful notion of robust product design, the solution to the problem in the Ina Tile example, as many other examples of "Taguchi methods," is a straightforward application of Fisher's method of fractional factorial experiments.

Beyond Taguchi's Methods

To carry out parameter design Taguchi often recommends experimental design plans, known as inner and outer array designs. They are often wasteful in terms of the number of tests needed and hence are relatively expensive to conduct. For parameter design, he insists that signal-to-noise ratios be used for analysis of the data. The more natural statistics, the average and the standard deviation, as well as a good homegrown "product," called Exploratory Data Analysis, pioneered by the American statisticians John W. Tukey and Cuthbert Daniel, would be much better and also simpler to understand. Exploratory data analysis is a collection of ideas about plotting and graphing data in ways that are informative and stimulating for the engineer's intuition. Nothing fancy—just a common sense application of the idea that a picture is worth a thousand words. Using Taguchi's cumbersome and inefficient statistical methods is better than doing nothing at all, but if we have accepted the competitive challenge, why not use better and simpler mainstream statistical tools? For more details, see Box, Bisgaard and Fung.[24]

Industrial statisticians in the United States and Great Britain have since the 1950s developed many useful and practical methods for experimental design and data analysis. These methods are not in-

cluded in Taguchi's teaching. Most prominent among these omissions are response surface methods. This is a set of techniques whereby the experimenter, in a step-by-step learning process, seeks optimal conditions. This approach often means great savings in experimental effort, more surely leads to optimal conditions, and most importantly, leads to better engineering understanding of the system under study. In addition, response surface methods are no more complicated than "Taguchi methods."

Part of the problem with the promotion of Taguchi methods is that they are supposed to constitute "a separate technology."[25] That implies that the user is asked to make a choice between Taguchi methods and mainstream statistical methods. That implication is unfortunate because the statistical toolbox is very large and contains many useful and practical tools. What tool to use in a specific situation should preferably be determined by the problem at hand. Setting things up as mutually exclusive alternatives, and advising the user to choose Taguchi Methods, leads to the dismissal of good practical tools invented in the West such as Cuthbert Daniel's Normal Plot technique.[26]

Daniel's Normal Plot is a graphical method for analyzing data from unreplicated factorial experiments—the kind of experiments used by Taguchi. In addition to being more appropriate for unreplicated factorial experiments than the more complicated technique of Analysis of Variance (ANOVA) favored by Taguchi, it is also extremely simple to apply and speaks directly to the right (intuitive) side of the brain.

The impression of exclusiveness is further promoted by misleading statements. For example, Sullivan[25] claims that:

Traditional statistical theory has created very little change in 30 years. U. S. statistical specialists have been successful in maintaining the status quo for U. S. industries. In recent years there has been a modest change in company operations through the application of statistical process control (SPC). However, traditional Design of Experiments

(DOE) has had no impact at all unless modified for the Taguchi way of thinking.

One of the tenets for quality professionals is, "Let us talk with data."[27] In fact, the "27th Quality Control Conference for Foremen" held recently in Japan had as its motto "Make judgment according to facts and act on the facts." Taguchi definitely has been able to create an unprecedented interest in the United States in design of experiments for quality improvement. For this interest, we should be very grateful. But to claim that traditional design of experiments has had no impact is at best uninformed.

An overwhelming collection of published examples of successful applications of designed experiments for quality improvement can be found in the journals *Industrial Quality Control, Applied Statistics, Supplement to the Journal of the Royal Statistical Society, Proceedings of the American Society for Quality Control, Electrical Manufacturing, Technometrics, Journal of the American Statistical Association, Food Technology, Tooling and Production, Biometrics, Journal of the American Society of Naval Engineers, Journal of the Institute of Petroleum, The Industrial Chemist, American Statistician, Chemical Engineering, Journal of the Society of Plastic Engineering, Journal of American Leather Chemists Association, American Society for Testing Materials Bulletin, Electrical Engineering, Analytic Chemistry, Rubber Age, Tappi, Bell Systems Technical Journal, Blast Furnace and Steel Plant, Industrial and Engineering Chemistry, American Society of Mechanical Engineers Transactions, Journal of Quality Technology,* and many others. The published examples are, of course, just the tip of the iceberg. It seems hard to believe that people over a period of more than 40 years would continue to publish examples that had "no impact at all."

So why did Western statisticians in the past not succeed in get-

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ting a large number of engineers to use design of experiments? And why was Taguchi more successful? "Quite simply, the Japanese have a secret ingredient: they do it and we don't."[7] That is the difference rather than any difference in technique. And when they did it, they *saw* the benefits. The manufacturing environment is hectic (often because equipment and employee time are tied up with the production of defects and rework). People are under great pressure to get products out of the door. Like other applications of "work smarter—not harder," experimentation for quality improvement means spending time up front but saving time and money later. Western management is unfortunately forced to keep their eyes on next quarter's revenue and therefore is not receptive to ideas that might have a longer-term payback. Moreover, the economic benefits of quality improvement can be hard to quantify, or even be *unknown and unknowable* as Deming says.[5] Thus I believe the reason why experimental design methods were not used so much in the West in the past is unrelated to methodology, but instead because of the perceived business and the lack of understanding of the economic benefits of improving quality. Just as Deming was not "discovered" in the West until the Japanese showed us the benefit of quality management, so did experimental design have to be re-imported. Unfortunately it often takes a crisis before the need for change is perceived.

One of the advantages of experiments based on Fisher's factorials, fractional factorials, and orthogonal arrays is that the conclusion often is so obvious that any method of analysis would lead to the right conclusion. This is the primary reason for the success of "Taguchi methods." In fact, most of the case studies of Taguchi methods published over the past years can be analyzed with simpler mainstream statistical methods providing a more informative analysis with more insight into the engineering problems involved. For an example, see the analysis provided by Box[28] of Quinlan's[29] prize-winning experiment. This is because the design of experiment principles used basically are the same as mainstream practice. Both schools of thoughts are based on Fisher's method of factorial experiments. The primary differences lie in the subsequent data analysis. But why make that more complicated? In a time of serious competitive problems for American industry it seems unfortunate to follow Taguchi's dogmas and discard better and simpler alternatives.

Science and Technology

There is also another more philosophical difference between mainstream quality control thinking and that of Taguchi. Reading Dr. Deming's books and articles, for example, one is struck by the scientific heritage of his management theory. Taguchi, on the other hand, seems to claim that quality engineering is different from science. In a recent article, Taguchi writes:

There is a great difference between science and technology. Many people have heard the story that "proves" that a horsefly can't fly, which hangs in the office of a well-known American corporate president. Engineers have the responsibility of designing things that function, whether or not it is possible to prove why.[30]

This argument might have some initial appeal because there clearly are cases in industry, where a detailed scientific explanation is lacking or only partially possible with the current state of knowledge. Trying to find a complete scientific cause and effect explanation would sometimes even be a waste of time and money. But equally often, engineers will find themselves stuck, unable to make further progress if they don't know "why." Upon further reflection, I think most people will see that separating science and technology is an unproductive approach.

(For clarification it should be pointed out that by a scientific approach, I do not mean engineering based solely on deductive reasoning from predetermined theories, but rather an inductive—deductive approach based on iteration between theories, conjectures, and hypothesis on the one hand and experimentation, observation, and data analysis on the other.)

Most of the industries that the United States is proud of are heavily based on the interplay between science and technology. Science-based industries significantly contribute to this country's economy and to its foreign export. Moreover, the most significant aspect of the modern quality improvement approach is the scientific attitude to problem solving. This scientific approach applies even (in particular, one might say) to the most mundane problems, not only to "high tech" problems. By combining scientific knowledge, scientific and experimental methods, and developing new knowledge in the course of developing new technology, manufacturers have developed many commercially successful products. The scientific approach was the driving force behind the industrial revolution. The struggle to understand "why" paid off handsomely. Cooperation between scientists and engineers will bring us further prosperity and new technology in the future. Ironically it is even the work of one of this century's most eminent *scientists*, Sir R. A. Fisher, that is the foundation for what has been labeled Taguchi Methods.

Taguchi's distinction between science and technology attempts to set things up as alternatives, from which we have to choose the one or the other, when in fact we can have both. Science and technology are not alternatives; they are two intimately connected and inseparable parts that by their interplay fuel progress.

Conclusion: We Have Only Seen the Beginning

Taguchi has had a tremendous impact on industry over the past few years. He has mobilized an unprec-

edented interest among engineers for design of experiments and quality improvement. He has helped us focus attention on quality improvement and shown the economic benefits of designing quality into products upstream rather than inspecting out bad products downstream. His concept of robust product design, parameter design, and the concept of loss functions to emphasize that increasing costs are associated with deviations from target values are valuable *contributions* to the science of quality engineering.

But as in any other science, many people make contributions. Ideas that pass the test of time are *added* to the existing body of knowledge. This way the quality of the science and engineering disciplines continues to improve, and ideas that are not so useful are quickly forgotten. Rather than *replacing* traditional design of experiments and mainstream data analysis methods developed over the past 50–60 years with Professor Taguchi's set of techniques, it would be better to *add* his useful ideas to current practice, to use simpler mainstream statistical methods when available, to create appropriate new techniques where they are needed, and to retain the many useful mainstream statistical techniques that go far beyond the limited scope of "Taguchi methods."

We should take up the challenge from Japan and develop our own strategy for quality improvement. The Japanese did not just copy the early American methods and ideas for quality control. They took what they found useful and developed their own ideas too. We have only seen the beginning of what can be done by combining statistical thinking, quality engineering, and quality management. Just as the Japanese benefitted from listening to Deming, Juran, and Ishikawa, so can we. Clearly we should also listen to the useful engineering ideas contributed by Taguchi. But we should apply the principle that "there is always a better way of doing things," rather than locking ourselves to a fixed set of methods.

With this approach we can develop our own strategy for creating better quality products and services at lower cost, become more competitive, create more and better jobs, and ultimately serve society better. Quality improvement also applies to the techniques we use, to their exposition, and to the principles for quality management.[31]

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