Section 3

Taguchi's Methods versus Other Quality Philosophies

Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

39 Quality Management in Japan

39.1. History of Quality Management in Japan

Dawn of Quality Management

The idea that the quality of a product should be managed was born in Japan a long time ago. We can see some evidence that in making stone tools in the New Stone Age, our ancestors managed quality to obtain the same performance around 10,000 years ago. In the Jomon Period, a few centuries before Christ, earthenware were unified in terms of material and manufacturing method. In the second half of the Yayoi Period, in the second or third century, division of work (specialization) occurred in making earthenware, agricultural implements, weapons, and ritual tools. After the Tumulus Period, in the fourth or fifth century, the governing organization summoned specialized engineers from the Asian continent and had them instruct Japanese engineers. For the geographical reason that Japan is a small country consisting of many archipelagoes, this method of convening leaders from technologically advanced foreign countries has been continued until the twentieth century.

Japan did not document these techniques before the twentieth century. The major reason for this is that numerous technologies were imported from overseas, and superb technologies, such as the manufacture of Japanese swords, were inherited through an apprenticeship system. In Japan, technological inheritance often relies more on "learn, steal, and realize" than on "instruct or communicate." In fields other than manufacturing [e.g., Judo, Kendo (swordsmanship), Kado (flower arrangement), or Sado (tea ceremony)], Japanese leaders give detailed instructions to apprentices and make them learn the reasons for themselves. This is regarded as one of the most typical instructional methods in Japanese culture. Another instructional method relied on masters leaving know-how to descendants in the next generation (called "ogisho"). These were considered not modern commentaries or manuals but difficult-to-comprehend documents that could be understood only through repeated discipline. Therefore, even if a superb technology was born, it was not spread widely and did not boost the total technological level. Even after the Meiji Era arrived in 1868 after the Edo Shogunate was toppled, the major methods of technological innovation were introduced through foreign documents or importation of engineers.

In the area of scientific quality management, quite a few technologies were introduced. In 1931, when Shewhart completed *Economic Control of Quality of Manufactured Product,* the Shewhart control chart began to be used in the manufacturing process for light bulbs. It was in 1935 when the design of experiments, pioneered by Fisher, was first utilized in Japan. Even under the militaristic regime during World War II, which suppressed research activities, translation of bibliographies by Carl Pearson was continued and a Japanese-unique sampling inspection chart was invented by Toshio Kitagawa. By the end of the war, statistical methods were being applied to production processes in some military plants [1,2]. Nevertheless, as a whole, quality management levels in manufacturing products, except for craft products such as pottery or lacquerware, was not so high; therefore, "if it's cheap, it's bad" symbolized prewar Japanese products.

Period Following World War II

Many books have already detailed quality management in Japan after the war. In 1946, the GHQ of the Allied Forces summoned experts in statistical research from the United States to study required resources and telecommunication network systems needed for reviving Japan. The investigation significantly stimulated Japanese statisticians and quality management researchers. In 1950, W. Edwards Deming, a U.S. specialist in sampling theory and statistical quality management, instructed Japanese quality management researchers in statistical quality management. His key advice was: (1) product development and production is an endless cycle (shown in Figure 39.1), and by repeating this cycle, we can advance our products and corporate activity to produce them (this cycle is called the *Deming cycle* in Japan); and (2) statistical procedures can be applied to various stages in corporate management. After his instruction in Japan, various companies put his advice into practice.

Based in part on money, Deming donated from royalties on the textbook used for his lectures, the Deming Prize was founded in 1951 [3]; it is still awarded to companies that accomplish significant results through strenuous quality management. The first companies to win the prize in 1951 were Yahata Steel, Fuji Steel, Showa Denko, and Tanabe Seiyaku. Since the Deming Prize played an essential role in developing Japan's industry worldwide, it was regarded as "the Messiah" in Japan's industries.

Between the end of the war and the 1960s, statistical quality management methods, developed primarily in Europe and the United States, were studied vigorously and subsequently adopted by many companies and formulated as the Japan Industry Standards (JIS). In this period, companies focused mainly on introducing

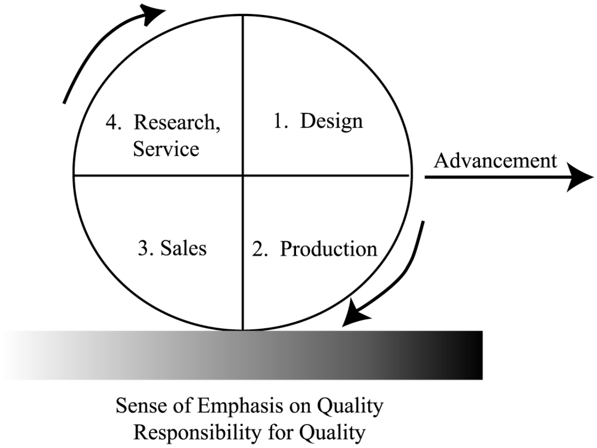

Figure 39.1
Deming cycle

statistical methods such as the Shewhart control chart, statistical testing, sampling inspection, and Fischer's design of experiments. It is often dubbed the *SQC* (statistical quality control) *period.*

While the Shewhart control chart [4] (Figure 39.2) contributed considerably to the production process, it brought about another result. The fundamental managerial concept behind the control chart—that we should recognize that any type

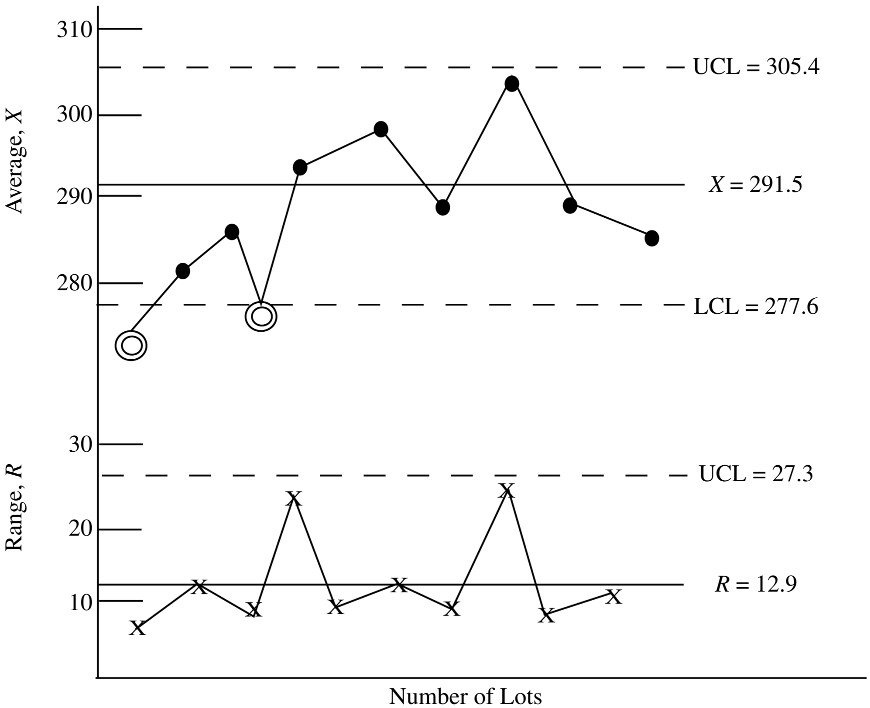

Figure 39.2
X-R control chart

of job always has variability, define a normal result using past data, determine control limits for an abnormal state, monitor the result once an abnormality happens, start an investigation, find the cause, and take corrective measures—contributed much to general management.

Based on the Deming cycle illustrated in Figure 39.1, the management cycle (*PDCA cycle*) was invented and used repeatedly to improve business. The "P" in PDCA represents "plan," to plan how we implement a job and what results we attain before working on the job. The "D" "Do," to fulfill the job as planned. The "C" represents "check," to check whether or not we have accomplished the same result or followed the same process as scheduled. The "A" represents "action," to analyze the cause and take measures if the result has not been achieved. Since this cycle is applicable not only to management and improvement of the production process but also to many other kinds of businesses, job improvement based on quality management has started to spread. The PDCA cycle (Figure 39.3) has been emphasized as a key method in TQC (total quality control), in line with Shewhart's concept of management.

In 1954, J. M. Juran, an advisor in the American Management Association at that time, was invited to Japan by Japanese quality management researchers. In Juran's lectures and instructions, statistical methods as one of the pillars of modern quality management were not mentioned. On the contrary, managerial aspects of quality management were stressed. Although this concept was implemented by Feigenhaum in the United States, it stood out as total quality control (TQC) in the second half of the 1960s in Japan.

Evolution from SQC to TQC

In the 1960s, trade in products such as automobiles, machinery, and electric appliances, all of which had been protected by the Japanese government during Japan's postwar rehabilitation period, was liberalized. Although quality management activity was reinforced to make the products more competitive, it was necessary to enhance products' attractiveness as well as their quality. Therefore, all departments from product planning to sales, or all hierarchical people from top management to manufacturing operators, were encouraged to participate in quality management activity, and at the same time, interdepartmental activity was reinforced. This was TQC (later changed to TQM).

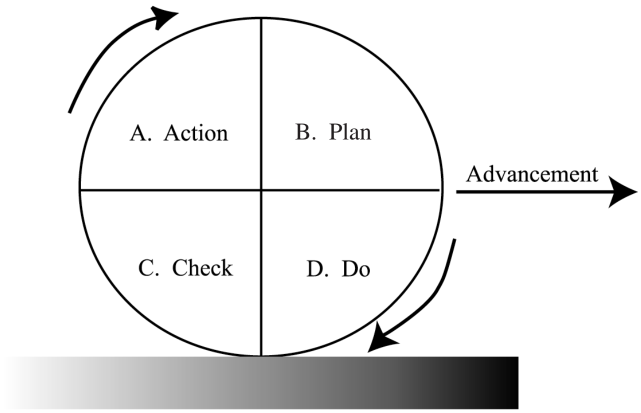

Figure 39.3
PDCA cycle

TQC stresses not only presentation of the PDCA as top management's policy and deployment of the policy to middle management in charge of a core of corporate administration but also companywide promotion of job improvement. To filter the job improvement activity down to bottom-level employees, the *QC circle* was introduced and subsequently spread nationwide. The QC circle, founded by the Japanese Union of Scientists and Engineers in 1962, contributed tremendously to quality improvement.

The other characteristic of TQC was to synthesize quality management procedures by introducing quality assurance and reliability management, which had been pioneered in the United States. The concept of quality assurance, including compensation to customers, was introduced to solve the problems caused by huge complicated public systems or their failures. The mileage assurance for automobiles was a typical example. Since indemnification incurred by system failures diminishes corporate profit, each company was urged to reduce system failures. As a result, quality assurance systems were established and reliability management was introduced in many companies. For example, reliability management was used in the Apollo program developed by NASA at that time. In Japan it was introduced in large-scale public works such as the Shinkansen bullet train program by National Railway (currently, JR) and the satellite program by the National Space Development Agency (NASDA), the automotive industry, or private joint enterprises with U.S. companies. The reliability management program manages what tasks should be completed, when they should be implemented, which departments should take responsibility, and how the problems should be solved from the product planning stage to use by consumers. Reliability management techniques such as FMEA, FTA, and design review were introduced in the 1970s and 1980s.

At the same time, *quality function deployment* (QFD) was developed by Shigeru Mizuno and Yoji Akao and adopted immediately by various companies. The quality table had been tried since 1966 and was proposed in the official book published in 1978 [5]. QFD and quality engineering (to be detailed later) are the two major powerful quality management techniques that were born in Japan and spread worldwide.

Since to improve and assure product quality, improvement and assurance of material and part quality were required, quality management and assurance were expanded to suppliers of materials and parts. This trend diffused from assembly manufacturers to part suppliers, from part suppliers to material suppliers, and then to all industries. As a consequence, many Japanese products are accepted worldwide. To illustrate this, one of every four automobiles being driven in the United States is produced by Japanese manufacturers. Ironically, self-regulation of exportation of automobiles to the United States was continued for a long time because of complaints by the U.S. automotive industry. Sony and Panasonic brand products are sold throughout the world; and the electric scoreboard in Yankee Stadium, known as the U.S. baseball hall of fame, was replaced by a Japanese product.

Diffusion of Quality Management Activity

Since quality management activity evolved into the TQC and contributed greatly to the prosperity of the entire country, led by the manufacturing industry, TQC became known as a crucial means of managing a corporation in Japan. In the 1970s, nonmanufacturing industries such as the building, electric power, sales, and service industries adopted TQC. For the building industry, Takenaka Corp. and Sekisui Chemical in 1979, Kajima Corp. in 1982, Shimizu Corp. in 1983, Hazama in 1986, and Maeda in 1989 challenged and won the Deming Prize. Kansai Electric Power in the electric power industry won the prize in 1984, and Joban Hawaiian Center in the leisure industry was awarded the prize in 1988. Since the 1980s, all types of industries have introduced quality management activities. Bank and distribution industries, book-selling industries (e.g., Yaesu Book Center), the restaurant industry (e.g., Ringer Hut), and even public agencies such as prefectural and municipal offices have attempted to adopt quality management.

As TQM spread over other industries, its original aspect that quality problems should be solved based on data faded somewhat; in contrast, managerial aspects, including policy management, started to be emphasized. As a result, the concept of statistical methods, which had been playing a key role, was lowered in importance. In fact, the percentage of statistical topics released in the research forum of the Japanese Society for Quality Control has declined to a quarter of the total topics presented previously. In the meantime, the seven new QC tools, dealing with language information in the 1980s, and the seven product planning tools, handling planning issues in the 1990s, were newly invented. Both tools reflect the movement of quality management to nonmanufacturing industries.

Stagnation of Quality Management in the Second Half of the 1990s

When the Japanese economy, led by the manufacturing industry, reached a peak in the latter half of the 1980s, a number of companies attained top-rank status in the world. Also at that time, the income of the Japanese people became the highest in the world. As a consequence, a "bubble economy" was born whereby, instead of making a profit through strenuous manufacturing activity (or value added), we invested surplus money in land, stocks, golf courses, leisure facilities, or paintings to make money in the short term. The value of major products and services was determined only by supply and demand. The key players in the bubble economy were the financial industry, such as securities companies and banks, the real estate industry, the construction industry, and the leisure industry, all of which introduced TQM later or not at all. Since the "bubble" broke in 1992 and the prices of stocks and land slumped, these industries have been suffering. Unlike the manufacturing industry, these industries have blocked foreign companies from making inroads into the Japanese market.

The tragedy was that many manufacturers rode the wave of the bubble economy and invested a vast amount of money in stocks and land to make a short-term profit. These manufacturers suffered tremendous losses, and consequently, lost time and money they could have used to maintain quality management activities. Since the mid-1990s, the Japanese quality management activity has lost momentum. In fact, the quality management movement itself has sometimes been regarded as a bubble, just at the time that quality management is desperately needed.

39.2. Quality Management Techniques and Development

Quality engineering, with design of experiments as a main driver in developing it, is covered in this section.

Seven QC Tools and the QC Story

The first step in quality management is to solve quality problems quickly and thus to improve quality. Most quality management techniques were invented and developed for this purpose. While high-level statistical methods such as control charts, statistical tests, multivariate analysis, or design of experiments are utilized in quality management, in most cases, one of the simpler methods, often dubbed the *seven QC tools,* are used. These tools are easy to understand and use. (The number 7 has strong connotations in Japan and was used purposefully.) The seven tools are as follows: (1) control chart, (2) Pareto chart, (3) histogram, (4) graphs, (5) cause-and-effect diagram, (6) scatter diagram, and (7) check sheet.

As the quality management movement spread nationwide, when and how to utilize it to solve quality problems was questioned by many. Therefore, manuals called *QC story* were compiled so that anyone could easily take advantage of the methods. QC story was originally invented by Komatsu, a Japanese manufacturer of bulldozers that had manuals written for quality improvement giving examples of their use of quality circles. In the QC story, the process of quality problem solving or quality improvement consists of the following eight steps, and each step clarifies its objective and the QC tools to be used:

Step 1: Setup of the item to be improved (*reason for selection of the item*)

- *Objective:* Determine the problems or item to be improved.
- *Means:* Compare the objective and current problem and clarify the gap. Define the importance of the problem and the priority.
- *QC tools to be used:* check sheet, control chart, Pareto chart, histogram.

Step 2: Grasp of current problem

- *Objective:* Pick up a key point for improvement.
- *Means:* Convert the problem into a magnitude of variability. Find “good” and “bad” and clarify where variability to be eliminated lies by comparing both. This is a key point for improvement.
- *QC tools to be used:* check sheet, histogram, Pareto chart, graphs.

Step 3: Planning of improvement schedule

- *Objective:* Plan a schedule to make an efficient improvement. At the same time, establish an improvement target.
- *Means:* Draw up a schedule to investigate the cause of variability leading to “good” and “bad,” take measures to turn “bad” into “good,” and confirm the effect. Also, prove whether the objective is attained if “bad” is changed into “good.”
- *QC tools to be used:* None.

Step 4: Analysis of causes

- *Objective:* Identify the cause to generate the variability of “good” and “bad.”
- *Means:* (1) Select candidates generate the variability of “good” and “bad”; (2) specify the differences that cause the variability of “good” and “bad” using data analysis; (3) replace the differences with technical meanings.
- *QC tools to be used:* check sheet, cause-and-effect diagram, graphs, Scatter Diagram.

Step 5: Consideration and implementation of measures

- *Objective:* Consider the conditions to produce only “good.”
- *Means:* Take measures for the cause to generate the variability of “good” and “bad.”
- *QC tools to be used:* None.

Step 6: Confirmation of effects

- *Objective:* Confirm the effects of measures.
- *Means:* Confirm whether to produce only "good" and how to attain the objective using data analysis.
- *QC tools to be used:* Tools used in step 2 (to compare situations before and after improvement).

Step 7: Standardization, systematization, and prevention

- *Objective:* Consider the measures to prevent the same problem from occurring again.
- *Means:* Understand the causes in terms of methodology and system and implement standardization or systematization to prevent them.
- *QC tools to be used:* None.

Step 8: Review of completed process

- *Objective:* Learn from experience to improve the problem-solving process.
- *Means:* Wrap up good and bad points in the completed process and improvements.
- *QC tools to be used:* None.

Quality Function Deployment to Incorporate the Customers' Needs

After several trials and errors in the second half of the 1960s, *quality function deployment* was proposed in the Japanese quality management field in 1978 [5]. Proposed by Shigeru Mizuno and Yoji Akao, quality function deployment is a method of reflecting customers' voices in product design and clarifying production management items to satisfy them. After it was released, this method was adopted in the development process by many corporations.

Quality function deployment is implemented in accordance with Figure 39.4. In the first step, by allocating customers' voices in the rows of a matrix and product quality characteristics in the columns, we determine corresponding product quality

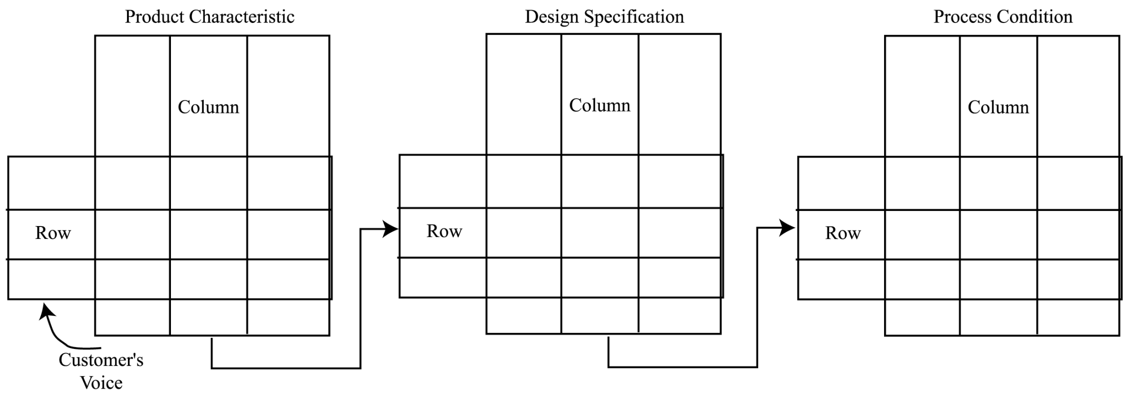

Figure 39.4
Structure of quality function deployment

characteristics to prevent customers' voices from being overlooked. In the second step, by assigning product quality characteristics in the rows of a matrix and characteristics of a subsystem or part in the columns, we determine corresponding characteristics of a subsystem or part to satisfy product quality characteristics completely. This process is launched at the stage of determining process conditions to attain part characteristics and maintenance procedures to product performances.

In short, quality function deployment is a method of putting information in order. Even if we use this method, no new information is generated. However, it still helps us significantly. Human beings tend not to pay attention to the importance of information because they lack knowledge of others' experiences. Even our own experiences tend to fade away as time goes by. Sometimes miscommunications happen. For all these reasons, if we arrange information using quality function deployment and all people in charge of development take advantage of this information, the possibility of higher customer satisfaction will be increased.

As for statistical methods, the principles of component analysis, factor analysis, and cluster analysis were used more widely to put customers' voices and product quality characteristics in order. In addition, the multiregression analysis was adopted by many users to comprehend the relationship between customers' voices and product quality characteristics. All of them are categorized in multivariate analysis [6].

Quality function deployment was introduced vigorously by U.S. quality management specialists between the latter half of the 1980s and the 1990s as a competitive tool. One well-known example in the United States was Ford's development of a new car model, the Taurus.

Design of Experiments

The design of experiments dates back to research on an experimental method of improving barley conducted by R. A. Fisher working for the Agricultural Laboratory in Rosenstadt in the suburbs of London. Used widely for quality improvement in Japan, primarily after World War II, this method contributed greatly to quality improvement in Japanese products.

BEGINNING OF THE APPLICATION OF DESIGN OF EXPERIMENTS IN JAPAN

In 1925, Fisher's *Statistical Methods for Research Workers* was released [7]. Ten years later, the Faculty of Agriculture of the Hokkaido University led the way in applying Fisher's design of experiments (experimentation using a small number of samples) to agricultural production. In 1939, Motosaburo Masuyama applied this technique to medical science.

APPLICATION OF DESIGN OF EXPERIMENTS TO INDUSTRIAL PRODUCTION

The first experiment using an orthogonal array in the scene of industrial production was performed during World War II in the United States to improve the yield in penicillin production. Shortly after the war, Morinaga Pharmaceutical conducted an experiment under the direction of Motosaburo Masuyama. Thereafter, the design of experiments started to be used on a regular basis in postwar Japan. Motosaburo Masuyama, Genichi Taguchi, and other experts in the design of experiments, as well as applied statisticians, helped various industries conduct a great number of experiments. The number of applications of the design of experiments increased in line with a boom in quality management activity in Japan, thereby boosting Japan as one of the top-ranked countries in applying the technique. It was not unusual that operators themselves studied the design of experiments and performed experiments.

After the mid-1950s, the number of universities or colleges introducing the design of experiments in their curriculums rose and contributed to engineers being familiar with the technique. In addition, nonprofit organizations offered lectures on the design of experiments to industrial engineers, which contributed considerably to promoting the technique. In this sense, the Japanese Union of Scientists and Japanese Standards Association were outstanding. To date, several thousands of company engineers have attended high-level lectures about the design of experiments given by both organizations above. As a result, the number of companies applying the technique has increased annually. In Europe and the United States, experts in statistical methods often instruct engineers in-house. Engineers graduating from mechanical, electrical, or chemical engineering departments learn the design of experiments and apply it to their own fields. Because of this, Japan boasts of being number 1 in terms of the number of experimental applications.

With respect to the number of researchers using the design of experiments, Japan reached the top in the 1970s. Among these researchers, Genichi Taguchi is one of the most famous in the world. Although he is known as a researcher and promoter of quality engineering, he is still considered a great expert in the design of experiments. The layout design of experiments, such as the level-labeled orthogonal array (called Taguchi's orthogonal array), assignment of interactions using a linear graph, multilevel assignment, dummy-level method, pseudofactor method, and the data analysis method, such as accumulation analysis and 0/1 data analysis, are Taguchi's major contributions to the design of experiments.

The ability to use the design of experiments to comprehend the causes of quality problems contributed much to quality improvement of Japanese products after World War II. This technique is an essential method of quality improvement for engineers. Yet in most cases, the design of experiments was used not in the stage of design optimization but in the phase of cause analysis after quality problems occurred [9,10].

STUDY OF ORTHOGONAL ARRAYS AND ORTHOGONAL EXPERIMENTS

One of the most typical applications of the design of experiments is experiments using an orthogonal array to assign all experiments systematically. The concept of experimentation using an orthogonal array dates back to Fisher. Due to the technical difficulty he experienced interpreting high-order interactions, he studied experimental layout leaving them out [7]. He based his experiments on the Latin square (also called the Greco Latin square). Thereafter, engineers the world over studied the orthogonal Latin square and orthogonal array Consequently, one research report by a U.S. team was released in 1946 [8]. Although full-scale research on an orthogonal array began in Japan after the war, much research was related to the characteristics of an orthogonal array and application methods based on them, whereas the U.S. study focused on how to create an orthogonal array and its mathematical aspects. A typical example was Taguchi's research in the 1950s and 1960s. Taguchi replaced elements labeled -1 and 1 or -1, 0, and 1 in an orthogonal array by 1, 2, and 3, representing the level of a factor for an experiment, and rearranged the array by reordering its columns in increasing order. At the same time, by taking advantage of the research on columns where interactions emerge, he assigned interactions called *linear graphs* and recommended multilevel assignment to improve ease of use. In his books, he illustrated actual applications to explain how to use the method. His development of easy-to-use orthogonal arrays, linear graphs to allocate interactions and multiple levels, and demonstration of actual applications boosted the popularity of the orthogonal arrays in Japan. Sample arrays are shown in Table 39.1 and Figure 39.5.

While he assigned interactions to linear graphs, Taguchi had a negative opinion about selecting interactions in actual experiments. He insisted that he had devised linear graphs to allocate interactions easily only in response to many engineers' keen interest, but that we should not pursue interactions. He also maintained that since an orthogonal array was used not for the purpose of partial experimentation but for checking the reproducibility of factor effects, main effects should be allocated to an orthogonal array. As a result, other researchers who were using Fisher's design of experiments stood strongly against Taguchi's ideas, and this controversy continued until the 1980s. This dispute derived from the essential difference in objectives between Taguchi's and Fisher's experiments. Whereas Taguchi emphasized design optimization, Fisher looked at "quantification of contribution for each factor." Because this controversy was caused partially by Taguchi's avoidance of the conditional "in case of," after his concept was systematized as quality engineering in the mid-1980s, the dispute gradually calmed down.

In addition to Taguchi's linear graphs, other assignment techniques to deftly allocate factor interactions were studied. For example, to vie with Western research, techniques such as the resolution III, IV, and V were released and applied to actual experiments.

BEGINNINGS OF QUALITY ENGINEERING

In 1953, an advanced experiment was performed at Ina Seito (currently known as INAX) located in Aichi prefecture in the middle of Japan. Masao Ina described this experiment in the book *Quality Control*. In addition, Taguchi's book on the

Table 39.1
Taguchi's orthogonal array (L_8)

	Column						
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

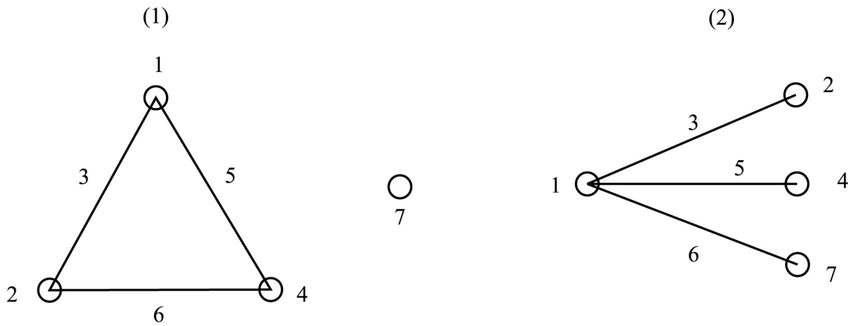

Figure 39.5 Taguchi's linear graphs (L_8)

design of experiments described the experiment, after which much attention was paid by some Japanese engineers.

Seito had baked tiles using an expensive tunnel kiln. Because of the large positional variability in the tunnel's inside temperature, they had faced much variation in dimensions, glosses, and warping after baking. Although a common countermeasure in quality management was to reduce the temperature variability, they modified the mixture of materials (design) instead. As a consequence, once a certain mixture was fixed and a certain "secret medicine" was added at 0.5% by weight, tiles baked evenly and variability in dimensions, glosses, and warps was drastically reduced. Since Seito kept this experiment confidential afterward, even Taguchi, who cooperated in the experiment, did not introduce the details.

This experiment was very significant . At that time, there had been two known methods of improving quality: (1) to find the causes of variability and to manage them, or (2) a feedback (or feedforward) method of making repeated adjustments to eliminate eventual variability. The Seito experiment shed light on a third option: "attenuation of causal effects."

At this time Taguchi began to dedicate much of his research to how to apply the attenuation of causal effects to other engineering fields. His efforts became known as parameter design (robust design) in the latter half of the 1970s.

CLASSIFICATION OF FACTORS

In terms of experimental purpose, Taguchi's design of experiments greatly differed from Fisher's, although the former was founded on the latter. Many of the experiments undertaken by Taguchi focused not on a natural scientific concept of calculating factor-by-factor contributions for variability in product characteristics but on an idea of stabilizing product characteristics for variability, such as electrical power fluctuation or lapse of time. This fundamental difference between their purposes stems from the fact that Fisher worked for the Agricultural Laboratory and thus dealt with nature, whereas Taguchi worked for the Telecommunication Laboratory of the Nippon Telegraph and Telephone Public Corporation (currently NTT), a technological laboratory. Therefore, what derived from this technological purpose was factor classification. Taguchi took into account stability and reliability in actual production and use, such as production variation, consumers' use, and environmental conditions. Although these factors were called *indicative factors* at that time, they are now called *noise factors* (or *error factors*). While noise factors affect values of product characteristics, engineers cannot set up or fix their values at a desired level. Factors that engineers can select and fix at their disposal are dubbed *control* factors. Each is handled differently in layout of experiments and *analysis.*

Quality Engineering

Quality engineering has been developing since the Seito experiment in 1953 and is still under development. Although some engineers became interested in the experiment after release of the report in 1959, a limited number of engineers understood it well. Since many of the leaders of TQM had mastered Fischer's design of experiments, quality engineering was not accepted as being in the mainstream of TQM. Not until the late 1980s did quality management experts began to understand the significance of quality engineering. Thereafter, younger researchers in quality management and applied statistics started to evaluate quality engineering, and consequently, it gained acceptance, especially after presentation of a paper on parameter design offered in *Technometrics* by the American Statistical Association in 1992 [11].

Although quality engineering was seen as a method of incorporating quality in the design stage of a new product in the 1980s, it developed into a method of incorporating quality in the technological development stage. One of the main reasons that it started to be widely accepted in Japan is that the Quality Engineering Society was founded in the spring of 1993.

DEVELOPMENT INTO PARAMETER DESIGN (ROBUST DESIGN)

After the Seito experiment in 1953, Taguchi developed "attenuation of causal effects" into "parameter design" by helping to conduct experiments at several companies. His motivation was to apply the design of experiments to incorporation of quality at the initial design stage instead of quantitatively analyzing causes of quality problems after they occurred. He thought that a method of "attenuation of causal effects" must be used to incorporate quality. Taking into account that the mainstream in quality management at that time was into problem solving, Taguchi's idea can be seen not as quality management but as technological improvement. This was the main reason that some engineers began to pay attention to it. Figure 39.6 shows the debug model.

Initially, after conditions regarding the environment or use were assigned to the outer array of an orthogonal array and control factors (design parameters) were allocated (direct product experiment), whether there existed interactions

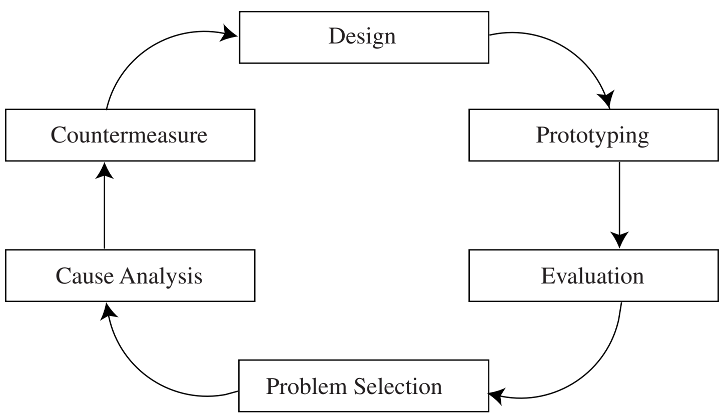

Figure 39.6 Development using debug model

between control and indicative factors was analyzed, and control factor levels then could be stabilized as part of a procedure of determining design parameters to attenuate causal effects.

Questioning the concept of *repetition* (accidental error), which played a key role in Fischer's design of experiments, Taguchi conducted experiments by forcibly changing levels of factors leading to errors (indicative factors). Although this reinforced the parameter design, it generated mathematical difficulty for the SN ratio, as detailed below. An example of a direct product experiment is shown in Table 39.2.

At the same time, Taguchi was aware that the magnitudes of errors varied in accordance with design conditions. Therefore, he proposed that the magnitudes of errors be constant under all design conditions. Also, he doubted the feasibility of a statistical test based on homogeneity of variance. Thus, he questioned the concept of discount coefficient, which is not detailed in this book, and the SN ratio.

BIRTH OF THE SN RATIO

Research was done on the accuracy of measuring instruments in the 1960s and 1970s, where the scale of an SN ratio represented the intensity of signal to noise. Noises such as variability in measuring environment conditions or measurement methods altered output values and degraded measurement accuracy. Ideally, we would expect that output, y, is proportional to objective value, M, and has no errors. Thus, an ideal condition can be expressed as:

$$y = \beta M \tag{39.1}$$

A measurement instrument is an apparatus to estimate input based on output. Since we cannot be aware of what types of errors are added when measuring, we estimate input using equation (39.1), indicating the ideal condition with no error assumed. That is, we can express input M by transforming equation (39.1) as follows:

$$M = \frac{y}{\beta} \tag{39.2}$$

Considering that an actual measurement instrument is affected by various noises $e(M)$, we rewrite equation (39.1) as follows:

$$y = \beta M + e(M) \tag{39.3}$$

Thus, to more precisely estimate input M, we should use the following transformed version of equation (39.3):

$$M = \frac{y - e(M)}{\beta} \tag{39.4}$$

This implies that when we estimate input using equation (39.2), the following estimated input error from equation (39.2) exists:

$$M - M = \frac{-e(M)}{\beta} \tag{39.5}$$

Table 39.2
Example of a direct product experiment

	Column											Distance
No.	*A* 11	*B* 4	*C* 5	*D* 3	*E* 9	$A \times C$ 14	$A \times B$ 15	*R*(Car) 1,6,7	*V*(Position) 2,8,10	*e* 12	*e* 13	K_1 K_2 K_3
1	1	1	1	1	1	1	1	1	1	1	1	
2	2	1	1	1	2	2	2	1	2	2	2	
3	1	2	2	1	1	1	2	2	1	2	2	
4	2	2	2	1	2	2	1	2	2	1	1	
5	2	1	1	2	1	1	2	2	3	1	1	
6	1	1	1	2	2	2	1	2	4	2	2	
7	2	2	2	2	1	1	1	1	3	2	2	
8	1	2	2	2	2	2	2	1	4	1	1	
9	2	1	2	2	2	2	1	3	1	1	2	
10	1	1	2	2	1	1	2	3	2	2	1	
11	2	2	1	2	2	2	2	4	1	2	1	
12	1	2	1	2	1	1	1	4	2	1	2	
13	1	1	2	1	2	2	2	4	3	1	2	
14	2	1	2	1	1	1	1	4	2	1	2	
15	1	2	1	1	2	2	1	3	3	2	1	
16	2	2	1	1	1	1	2	3	4	1	2	

The estimated input error above does not indicate the total value. To estimate this, the following mean sum of squares is often calculated:

$$\frac{\Sigma[-e(M)/\beta]^2}{n-1} \tag{39.6}$$

Substituting the following σ^2 into equation (39.6),

$$\sigma^2 = \frac{\Sigma[-e(M)]^2}{n-1} \tag{39.7}$$

we obtain

$$\frac{\sigma^2}{\beta^2} \tag{39.8}$$

This equation (39.8) becomes better as the error increases. Thus, to convert this into an inverse scale, we take its reciprocal:

$$\frac{\beta^2}{\sigma^2} \tag{39.9}$$

The error computed by equation (39.9) is called the *SN ratio error* in the field of measurement.

When we analyze data using the SN ratio, we often make use of the following scale, called the *decibel value of the SN ratio* by taking a logarithm of both sides of the following equation because the equation has an unwieldy form of ratio:

$$10 \log \frac{\beta^2}{\sigma^2} \tag{39.10}$$

The reason that we multiply the logarithm by 10 is that we wish to unify this form with the SN ratio used to indicate the magnitude of noises of electric appliances and to transform original data into more handy ones when analyzed.

In the initial parameter design introduced earlier, we determined optimal levels using plot graphs of interactions between control and noise factors. However, as the number of control and noise factors increases, the number of graphs also rises. For this reason it is painstaking to find the best level for each control factor in actual analysis. For example, even if the effect of a certain noise diminishes at a certain control factor level, another noise quite often strengthens its effect. In this case we cannot easily judge which control factor levels are best. Since the SN ratio is a scale representing an entire effect of all noises, we can determine the best level if we simply select control factor levels leading to the largest SN ratio, which is regarded as quite a handy scale.

Nevertheless, it took years until this SN ratio was understood completely and applied to practical uses. One of the reasons is that equation (39.10) per se has been difficult for ordinary engineers to comprehend. The other is an issue of its statistical background. That is, since it was not known what type of statistical value the SN ratio in equation (9) was supposed to be, any method of significance test and confidence interval calculation of the SN ratio could be introduced when it was invented. Although the fact that if the error is an accidental error (repeated error), noncentral chi-square distribution is applicable was proved afterward, the issue was not easily solved. Because Taguchi only proposed calculating the SN ratio by adding noises to a denominator in evaluating the accuracy of measurement instruments, he did not show what statistical distribution's value equation (39.9) should become. Therefore, many statisticians believe it to be a difficult-to-use metric, and moreover, some of them are skeptical of it. Although this issue is not settled perfectly, it has been proved through accumulated practical applications that we can successfully make an improvement using the SN ratio. In quality engineering, the SN ratio detailed thus far is applied not only for measurement instruments but also for common systems with input and output, currently called the *dynamic SN ratio.*

SYSTEMATIZATION OF PARAMETER DESIGN

After Taguchi succeeded in reducing variability effects of used parts on output voltage of a electric circuit at Nippon Denso (currently known as Denso) and Nippon Electric (currently known as NEC) in the late 1970s, he took advantage of his successes by using quality engineering methods in other corporations. Since in an electric circuit, theoretical formulas expressing output voltage values by constants of used parts was well established in most cases, not many prototypes were needed to easily show that parts' variability effects for output voltage change according to parameter values. In indicating output voltage variability, a scale called *nominal-the-best* was used. This is expressed by equation (39.9) and equivalent to a reciprocal square of variation coefficient that is often used in quality management:

$$-10 \log \frac{\sigma^2}{m^2} \tag{39.11}$$

Since the examples in the parameter design of an electric circuit were extremely easy to understand, an increasing number of companies introduced Parameter design in their development process in the 1980s. One typical company was Fuji Xerox, a joint corporation founded by Xerox Corp. of the United States and Fuji Film of Japan. In 1985 the company implemented parameter design and prescribed parameter design procedures for new product development. Other companies gradually began to adopt the technique as a method of improving product design [13].

In those days, systematization of parameter design was advanced and templates for procedures were also created so that anyone could use the method. Additionally, by taking advantage of examples of an electric circuit, Taguchi showed not merely a parameter design procedure but also tactics to incorporate quality in product design: *two-step optimization.* This consists of the following two steps: (1) to determine design parameters in order to enhance the SN ratio (i.e., to reduce noise effects), and (2) to make adjustments to a target value using design parameters that can change average output and are unrelated to SN ratio. Since two-step optimization can reduce noise effects at first, we can expect to minimize the incidence of quality troubles caused by noises. Consequently, we can reallocate personnel from following up on quality problems to productive design tasks. This change can be appealing to managers in a development department.

TRANSITION OF PARAMETER DESIGN FROM PRODUCT DEVELOPMENT TO TECHNOLOGICAL DEVELOPMENT

If we call the 1980s a period of parameter design in *product design,* quality engineering can then be dubbed a period of parameter design in *technological* *development*. Thus, if we attempt to use parameter design, we cannot take advantage of nominal-the-best parameters as product characteristics. However, if we can incorporate quality in technologies ahead of product planning, quality problems can be minimized and labor hours can be dramatically reduced in the development phase. In addition, if we can make technologies robust to noises, they can be applied to a variety of products.

Two-step optimization implies that we make technologies robust to noise in the first step, and once each product's target is fixed, we make adjustment to each target in the next step. Then what do we measure for optimization in the phase of technological development? The answer is the dynamic SN ratio. By regarding a technology as an input/output system, such as a measurement instrument, we optimize the technology using the dynamic SN ratio, regardless of an individual product's target. At first, Taguchi explained this idea by using the example of plastic injection molding [12]. After 1990, he devoted much of his time to research on what to select as input and output in each technological field. He announced ideas of input and output in various technologies and called each of them a *generic technological function*.

The Quality Engineering Society founded in Japan in the spring of 1993 is regarded as an academic society to study this generic function. As of March 2001, 1835 people are members of this society, and over 70 researchers attended the Research Report Forum in 2000. In fact, most of the research is focused on technological input and output (generic functions). Moreover, some companies have started to report their quantitative results obtained in actual engineering jobs according to quality engineering.

If two-step optimization is regarded as a *tactical* approach, parameter design in the stage of technological development is considered a *strategic* approach. Since more and more people have become aware that the parameter design can contribute much to streamlining the product development process, an increasing number of corporations such as photocopy machine or printer manufacturers are introducing the method companywide.

MAHALANOBIS DISTANCE

Since the late 1990s, Taguchi has begun to propose applying multiple dimensional distance (commonly known as *Mahalanobis distance*) advocated by Mahalanobis, an Indian statistician. Indeed, this is not a means of quality design; however it is applicable to a wide variety of applications, such as inspection, prediction, or pattern recognition. Due to space limitation, we do not cover it here, but refer the reader to Part VI in Section 2 of this handbook.

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