Section 1

Theory

Part I

Genichi Taguchi's Latest Thinking

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

1 The Second Industrial Revolution and Information Technology

1.1. Elements of Productivity

In this chapter we discuss the second Industrial Revolution, led by information technology and management's role regarding quality.

Economy and Productivity

To lead a better life we need various kinds of products and services, which are produced by human work and shared by all people. Although products are produced by manufacturers in most cases, one that is difficult to produce is land. Services include quite a few things (e.g., raising babies, nursing bedridden people) that we cannot produce efficiently because they cannot be automated by current technology and need direct human work. On the other hand, productivity of telecommunication, transportation, or banking services can be improved through equipment innovation or automation.

To produce more products and services with the same number of or fewer workers or to improve their quality results in *productivity improvement*. Two hundred years ago, 90% of the U.S. population were farmers. At present, fewer than 2% of Americans are farmers; however, they can produce crops for twice as many people as the entire population of the United States. This implies that their productivity has improved about 110-fold. Yet even if agricultural productivity increased, if 88% among the remaining 90% of U.S. citizens do not produce anything, overall national productivity would not improve. U.S. managers have offered other jobs, such as building railways, making automobiles, and producing telephones or television sets, to many people no longer employed in the agricultural field. In other words, overall productivity has been improved by the production of new products and services. The total amount of products manufactured and services performed is called the *gross national product* (GNP). However, the GNP does not include household services such as raising children, preparing meals, doing laundry, or cleaning. In addition, land and environment are not included in the GNP. This means that the GNP does not reflect real productivity, so the discussion that follows deals only with limited products and services.

Now imagine a case in which a certain company produces the same amount with half the workforce by improving work productivity. If the company keeps half of its employees idle, paying them the same amount in wages, its overall productivity does not increase. When all employees produce twice as much as before, and society needs the products, the company is said to have doubled its productivity. Otherwise, it causes other companies' productivity to deteriorate. In sum, society's overall productivity does not improve. This holds true when one country exports products to another country, causing the loss of many jobs in that country. If there is no need for quantity, increased productivity because of quantity leads to unemployment. Therefore, to improve productivity in the true sense, we should provide jobs to people unemployed as a result of productivity improvement. As companies develop new products, new jobs are created. While productivity improvement such as producing double the products with the same workforce results in partial realization, new jobs, producing new products and services, must also be available to workers newly unemployed. An entity focusing mainly on creating new products and services is a research and development (R&D) department.

We could also have another type of productivity improvement: the creation of twice as valuable a product using the same number of workers. In this case, if our costs are doubled and we sell the products at double the former price, the company's productivity increases twofold. If every company could achieve this goal, all people's incomes would double, they would buy doubly priced products, and as a consequence, the overall standard of living would double. On the other hand, if the company produced products of double value at the same labor cost and sold the products at the same prices, consumers would enjoy twice as high a standard of living in terms of these products. In other words, if all companies offered products of double value at the same price by improving their productivity with the same number of employees, our living standard would double, even if our wages and salaries remained the same. Although, in this case, we did not need to develop a totally new product, we needed to develop production technology that would allow us to produce products of twice the value using the same workforce.

Therefore, wages and living standards are not important from a national point of view. What is important is that we increase the number of products by improving productivity; that once we achieve it, we develop new products, create new industries, and offer jobs to unemployed people; and that once we enhance the quality of products and services, we sell them at the same prices as before. In fact, the price of a color television set is decreasing more than the price of a black-and-white TV set, so although the former is superior in quality, the cost of large-scale integrated circuits remains the same in the end, despite the high degree of integration. These are typical examples of developed technologies that have enabled us to produce higher-quality products at the same cost.

Although Japan's standard of living is lower than that of the United States, Japan's income is higher. An exchange rate is determined by competitive products that can be exported. On the one hand, Japan is highly productive because of several high-level technologies. On the other hand, Japan's productivity in terms of other products and services is low. On balance, Japan's overall living standard remains low. This is because a standard of living depends totally on productivity and allocation of products and services. To raise Japan's overall standard of living, quantitative productivity in agriculture, retail trade, and the service industry should be increased. Otherwise, qualitative productivity should be improved. As a result, Japan should invest in R&D to improve productivity. This is regarded as the most essential role of top management in society. The objective of quality engineering is to enhance the productivity of R&D itself.

Quality and Productivity

As noted earlier, there are two different types of productivity improvement, one a quantitative approach, the other qualitative. As for the latter, the word *qualitative* can be replaced by *grade*, although in this section we focus on quality rather than grade. In the case of an automobile, quality indicates losses that a product imposes on society, such as fuel inefficiency, noise, vibration, defects, or environmental pollution. An auto engine at present has only 25% fuel efficiency; that is, to gain the horsepower claimed, four times as much gasoline is consumed as would seem to be required. Now, if we double fuel efficiency, we can expect to halve noise, vibration, and environmental pollution as well as fuel consumed. It is obvious that the excess fuel consumption is converted into vibration, noise, and exhaust, thereby fueling environmental pollution. Also, it can be theorized that if the fuel efficiency of an engine doubles, Japan's trade deficit with the United States would disappear and global environmental pollution would be reduced by 50%. In contrast, sales in oil-producing nations and petroleum companies would be decreased by half. Even if these companies doubled the price of gasoline to maintain the same number of workers, the global standard of living would be improved, owing to decreased pollution because fuel efficiency would not have changed. Therefore, instead of reducing economically unimportant defects by 0.1% in the production process, engineers should focus on more substantial quality improvement, such as in engine efficiency. That is, since more than 75% of gasoline fuel is wasted, thus incurring an enormous economic loss, to improve fuel efficiency is desirable.

Indeed, petroleum companies might cause joblessness because they cannot maintain their doubled prices; in actuality, however, there are quite a few people who wish to purchase a car. In the United States, many families need a car for each adult. Therefore, if the price of a car and that of fuel decline by half, the demand for cars would increase, and eventually, fuel consumption would decrease less than expected. In quality engineering, improvements in functionality that set up fuel input as a signal and output as mechanical energy are important because we believe that such functionality would mitigate any type of environmental pollution. Thus, quality engineering does not deal basically with improvements using data such as quality characteristics expressed in consumer interests such as fuel efficiency, vibration, pollution, or defects. In short, we in quality engineering define an essential function as a *generic function*. Thus, quality engineering facilitates quality improvement for consumers using a generic function.

Take the function of an electric lamp, whose input for lighting is electric power and whose output is light. Because its efficiency is less than 1%, there is much that might be improved. Suppose that we can prolong the lamp's life threefold, keeping its power consumption the same: Sales of lamp manufacturers would possibly decrease to one-third. Some people would be reluctant to do research that would lead to such a longer-lived lamp. Yet this would not hold true for companies with a smaller market share because they could expand their market share and increase their sales, whereas companies with a larger market share would lose sales. That is, quality improvement could lead to unemployment. Although both qualitative and quantitative improvement could lead to jobless people, qualitative improvement often mitigates environmental pollution or consumption of resources. If a lamp lasts three times as long as before, only-one third of material resources are consumed. In that case, quality improvement is regarded as playing a more important role in living standards than does quantitative improvement. Nevertheless, both bring about unemployment.

Other examples: If car breakdowns decrease, we will need fewer repair shops, and if a tire's life is extended, we will need fewer resources. Accordingly, tire manufacturers' sales will also decline, and as a result, manufacturers will need to offer different jobs to the unemployed or to reduce wages by cutting working hours. Since many people do not usually accept reduced wages, employers should provide new jobs aimed at improving productivity. Then not only would top management have a more positive attitude toward investing in new product development, but developing the capability of R&D engineers would become crucial. As discussed above, a number of people are in need of products and services to subsist. Some of them wish to have higher-quality housing, and some are not satisfied with the current environment. Handicapped or bedridden persons seek services such as nursing whose demand is regarded as unlimited. Technological development to offer such products and services at lower prices is anticipated. Of course, medical treatment to rehabilitate such patients is also crucial, together with preventive measures. From a technical point of view, these fields are so difficult that many more resources should be invested in their research and development. If we do not see any prospect of progress in these fields, additional public investment and national research organizations will be required.

Quality and Taxation

In nations that have a wider variety of products than that in developing countries, qualitative improvement is preferable to quantitative from a social perspective. This is because the qualitative approach tends to reduce pollution and resource consumption. I believe that taxation is more desirable than pollution regulation to facilitate quality improvement. This would include a consumption tax for natural resources (including water) and a pollution tax. The resource consumption tax would stimulate recycling.

For lands not leading to higher productivity (as with housing), proprietors should be forced to pay taxes for their occupancy. In contrast, for public lands or places where many people can visit (e.g., department stores, amusement parks, ski areas), no or only a small amount of tax is needed. This will help to make lands public and supply housing. Occupancy should be allowed; however, equivalent prices should be paid.

Next, except for special cases such as exhaust or noise pollution, environmental pollution should not be regulated but be taxed. Some examples of currently taxed items are cigarettes and alcohol. Despite their harm to human health, they can be dealt with not by prohibition but by taxation.

In sum, even if certain issues are detrimental to society, we should not regulate them but impose taxes on their use. The underlying idea is that to whatever degree we can broaden individual freedom and take action by our free will, a higher level of culture is represented. That is, a real level of production, or real productivity, represents a large sum of individual freedoms. Freedom contains not only products and services or an affluent lifestyle where we can obtain goods freely, but also health and a free life not restrained by others. Indeed, freedom from authority is important; however, that each person not interfere with others is more essential. If we have no other choice but to restrain others' freedom, we need to pay a sufficient price as well as to obtain their consent. For example, the reason that we can receive meals or services from those with whom we are unfamiliar is that we pay a price equivalent to their worth.

So the sum of individual freedoms is regarded as important, even though it is quite difficult to measure. In this regard, the social value of a person should be evaluated by how much freedom he or she can offer. To support this, the government, as an authoritative organization, should not restrain but should protect individual freedom. We might safely say that the government is obligated to regulate those who transgress others' freedom. But here we discuss only productivity improvement that can be calculated economically.

The first Industrial Revolution relieved us from physical labor by mechanizing machining operations within manufacturing processes. After this mechanization, the major jobs of operators were production control, such as preparation of raw material, transportation of in-process products, or machine setup; and quality control, such as machining diagnosis and control and inspection. Because automation requires proper equipment, investment in automation must be augmented.

To reduce the investment in manufacturing processes, process stability needs to be improved in R&D functions. More specifically, speeding-up the production or development of products that have high value, large-scale accumulation, or complicated functions should be studied. All of them require technological development in laboratories to enhance machining performance. In particular, production speedup is effective for reducing the total cost of indirect labor, except in a manufacturing department. As we discuss later, a manufacturing department is responsible for only a small percentage of total complaints in the market because its principal activity is cost reduction. By improving manufacturing cycle time, it contributes considerably to company-wide cost reduction. To achieve this, we need to measure process stability. Primarily, we detail the variability of product quality.

1.2. Developing Productivity

Corporate Organization and Two Types of Quality

To allocate managers and leaders in an organization is one of the primary jobs of top management. To assess the business performance of each department and each person is also one of top management's roles. The performance of top management is judged by a balance sheet. In turn, top managements needs to assess the productivity of managers of each department. Among all departments, an R&D department may be the most difficult but most important to evaluate, as an R&D department should always improve organizational productivity.

Top management is charged with planning business strategies, determining the types of products to be produced, and allocating managers and budgets of engineering departments that design products (R&D and design departments). They must also take responsibility for the results of these departments in business competition in accordance with the balance sheet or profit and loss statement.

In corporate management, product development is considered a major tactic for profitability. It consists of the following two aspects:

1. *Product quality:* what consumers desire (e.g., functions or appearance)
2. *Engineering quality:* what consumers do not want (e.g., functional variability, running cost, pollution)

Engineers, especially those in product design, are required to design in such a way as to improve engineering quality as much as possible in parallel with product quality. If we compete with other companies, our level of quality is expected to exceed those of the other companies. This type of evaluation by management, dubbed *benchmarking*, consists of comparing one's own company with competitors on the two types of quality noted above. That is, an engineering department (in charge of tactics) assesses both product quality and engineering quality as well as production cost against others' results. In addition, the evaluation of production cost is one of the most essential tasks of a production engineering department.

In corporate management, a battle often occurs between manufacturing and sales, both of which are front-line departments. For evaluation of a manufacturing department, see Section 1.4.

Product Quality Design for a Financial System

An engineer is charged with responsibility to design a product with an objective function. For example, a bank's objective function consists of supplying a vast amount of money collected from both capitalists and the public. In the twenty-first century, when electronic money is supposed to prevail, the design of such a financial system does not require gigantic buildings and a large number of bank clerks. In designing a system to gather money, what is most important is whether a moneylender trusts a borrower. When a bank lends money to a company, whether the company continues to pay the interest on the loan is of significance. Such considerations are tied closely to credit.

Checks and credit cards have long been used in Europe and the United States. During my days at Princeton University as a visiting professor, shortly after I opened a bank account, four checkbooks were sent to me. They seemed to say, "You can use freely." However, I did not have any money in the account. Even when a payment due date arrived, I did not need to deposit any money. This was equivalent to a nonmortgage loan. While the bank paid for me, I would be charged interest on the money without a mortgage.

Credit means that money can be lent without security and that credit limits such as $50,000 or $10,000 are determined based on each person's data. How we judge individual credibility is a technological issue. In designing a system, how we predict and prevent functional risk is the most critical design concern. This is about how we offer credit to each person in a society. How to collect credit information and how much credit to set for a given person constitute the most important details in the era of information. In the field of quality engineering, an approach to minimizing risk of deviation, not from function design per se, but from functionality or an ideal state is called *functionality design*. In the twenty-first century, this quality engineering method is being applied to both hardware and software design.

An organization collecting money from a number of people and corporations and lending to those in need of money is a bank. Its business is conducted in the world of information or credit. Such a world of reliance on information (from plastic money to electronic money) has already begun. The question for the customer is whether a bank pays higher interest than others do, or runs a rational business that makes a sufficient profit. What is important is whether a bank will be able to survive in the future because its information system is sufficiently rationalized and its borrowers are properly assessed, even if it keeps loan interest low to borrowers, and conversely, pays somewhat higher interest to money providers. After all, depositors evaluate a bank. A credible bank that can offer higher interest is regarded as a good and highly productive bank. Therefore, we consider that a main task of a bank's R&D department is to rationalize the banking business and lead to a system design method through rationalization of functional evaluation in quality engineering.

Unfortunately, in Japan, we still lack research on automated systems to make a proper decision instantaneously. Because a computer itself cannot take any responsibility, functional evaluation of a system based on software plays a key role in establishing a company. After a company is established, daily routine management of software (update and improvement of the database) becomes more important. Globalization of information transactions is progressing. A single information center will soon cover all the world and reduce costs drastically. Soon, huge bank buildings with many clerks will not be required.

What Is Productivity?

We define productivity as follows: *Total social productivity* (GDP) is the sum of individual freedoms. Freedom includes situations where we can obtain what we want freely, that is, without restraint of individual freedom by others. As discussed earlier, when electronic money systems are designed, numerous people become unemployed because many bank clerks are no longer needed. Once only 100 bank clerks can complete a job that has required 10,000 people, the bank's productivity is regarded as improved 100-fold. Nevertheless, unless the 9900 redundant people produce something new, total social productivity does not increase.

To increase productivity (including selling a higher-quality product at the same price) requires technological research, and engineers designing a productive system constitute an R&D laboratory. An increase in productivity is irreversible. Of course, a bank does not itself need to offer new jobs to people unemployed due to improved productivity. It is widely said that one of the new key industries will be the leisure industry, including travel, which has no limit and could include space travel.

The government is responsible for incrementing GDP at a certain rate. In fact, a nominal increase in GDP, for example 3%, is quite an easy goal to reach because we can attain it by hiking a nominal amount of wages by 3% on a yearly basis. The question is: How much is equivalent to 3% of GDP? This does not indicate a 3% improvement in the standard of living (real GDP), because this is a nominal figure. In elementary schools, where productivity is difficult to improve, we could decrease the number of students in a class, thus employing more teachers and reducing the number of jobless teachers. Raising salaries by 3%, reducing the number of students in a class, or preparing a larger number of academic courses causes more than a 3% increase in cost in the form of additional employment. This is an improvement in the overall social standard of living. Rather than keeping unemployed people doing nothing and paying an unemployment allowance, we should pay unemployed people a certain amount of money to let them work, such as reducing the number of students in a class or preparing a larger number of academic courses. This is an important action to take when attempting to solve the unemployment issue. We will not discuss here whether the necessary expenses would be borne by government or a part of them shared by families of students. Instead, we should determine the improved living standard over a 20-year school life. The best chance to test this is, when a number of classrooms are empty because the number of students is declining.

The debate over whether an enormous expenditure is needed to improve the standard of living of the elderly has heated up. A key point at issue is whether older people can continue to lead healthy lives without a loss of mental acuity. Developing a medicine to prevent such disability is one of the most significant technologies today. On the other hand, organizing a group of people to talk with the elderly before they show signs of senility is more essential than inventing a robot to assist and talk with them.

What is important is to develop practical means of achieving the goal and evaluating it. We should create a specialized laboratory. In fact, there are quite a few people who age without becoming senile who could be studied. Using the Mahalanobis–Taguchi system (MTS), regarded as a key method in quality engineering, we should study how they maintain their health. This also holds true for "medical checkups" for corporate management. We discuss later how a company comes to be considered healthy.

Some corporations run an active and sound business at all times. How we evaluate and predict sound and unsound management is a major issue in business strategy, which is a totally different evaluation system from that of financial accounting, which assesses only results.

Product Planning and Production Engineering

Assuming that each consumer's taste and standard of living (disposable income) is different for both hardware and software that he or she wishes to buy, we plan a new product. Toyota is said to be able to deliver a car to a customer within 20 days of receiving an order. A certain watch manufacturer is said to respond to 30 billion variations of dial plate type, color, and size and to offer one at the price of $75 to $125 within a short period of time. An engineer required to design a short-cycle-time production process for only one variation or one product is involved in a *flexible manufacturing system* (FMS), used to produce high-mix, low-volume products. This field belongs to production engineering, whose main interest is production speed in FMS.

Production engineering thus focuses on improving production speed to reduce the cost of indirect departments, including sales, administration, and development. To achieve the goal by taking advantage of quality engineering, we should stabilize the production process and drastically increase production speed. Because a manufacturing department can improve market quality by a few percent only, it does not need to take that responsibility. Its most important task is to manufacture efficiently products planned and designed by other departments.

1.3. Risks to Quality

Risk Management

In Japan, we have recently had some unexpected events, such as a missile launched over our archipelago, a large-scale earthquake, and a prime minister's sudden resignation due to illness. The media splashed articles about our inappropriate preparation for these risks all over the front pages. In quality engineering we call such risks either *signals* or *noises*. To make preparations in anticipation of extraordinary events is called *strategic planning* in the field of management. One example is an air force that prepares sufficient weapons against enemy attack. The best possible result is that the enemy hesitates to attack for fear of such weapons.

An order to an army to "Get the mountain," meaning to occupy the mountain efficiently, is not strategy but *tactics*. What officers and soldiers on the front line use in battle is not strategy but tactics. What investments in various fields require, especially those in R&D, is *strategy*. Strategy should include generic techniques and advanced technologies that are useful in many fields. Quality engineering in R&D aims at designing robustness (sturdiness, functionality).

On the other hand, quality engineering recommends that we evaluate uncountable noises in the market with only two noise factors. Because market noises are generated by users and are due to their conditions of use, the effects evaluated in their study would be minimal or nonexisting. Take as an example an earthquake-proof building. Being "earthquake-proof" does not mean that the building will not break down at all; it means that the effects of an earthquake will be minimized. Therefore, we do not assess a building using the point on the seismic intensity scale at which it will collapse. Using the signal-to-noise (SN) ratio, we evaluate its robustness to noises at a seismic intensity scale of about 4, for example. In addition, as a countermeasure for human life, earthquake prediction is important as well as earthquake-proof and safety studies. This is because our current houses may not be sufficiently earthquake-proof. Further, a robust house is not economical in the face of an enormous earthquake.

Countermeasures against Risks

We usually have the following noises:

1. Noises due to erroneous or careless use
2. Noises due to the environment
3. Intentional noises such as jamming radio waves

HUMAN ERRORS

Now let's look at noises from number 1 in the list above from the standpoint of quality engineering. Among common countermeasures against such noises are the training of users to head off misuse and the prevention of subsequent loss and damage by, for example, the design of easy-to-use products. In Europe and the United States, the term, *user friendly* is often used for designs whose goal is to prevent misuse of software or medical errors.

Of course, all error cannot be designed out of a product. For example, there are a vast number of automobile accidents every year because of mistakes in driving. Since human errors are inevitable, it is essential to design sensors and alarms to let us know our mistakes or to design a system to avoid a car accident automatically. In developing an integrated sensing system that can judge as human beings do, the MTS process in quality engineering may be instrumental. In other examples, such as handling radioactive substances, human errors cannot be prevented completely. And whereas the incidence of fire per person in Japan is one-third that in the United States, the loss incurred by fire is said to 100 times as much. The reason is that there are no effective measures against fire for such household structures as shoji screens, fusuma sliding doors, and curtains, whereas we are strict with regard to the safety of automobile carpets.

If certain human errors do not lead to such important results as sustaining human life or extremely valuable property, we do not need to take technical countermeasures. For example, if we were to drop a piece of porcelain on the floor and break it, we tend to discipline ourselves so as not to repeat the mistake. On the other hand, risk management handles noises that jeopardize human life, important property, or national treasures. In terms of hardware failures, there are some measures that can be used, such as redundant systems, daily routine check-ups, or preventive maintenance. Such rational design is called *on-line quality engineering* [1, Chaps. 11 and 12].

ENVIRONMENTAL NOISES

There are two types of environment: natural and artificial. The natural environment includes earthquakes and typhoons. From an economic point of view, we should not design buildings that can withstand any type of natural disaster. For an earthquake, for which point on the seismic intensity scale we design a building is determined by a standard in tolerance design. If we design the robustness of a building using the quality engineering technique, we select a certain seismic intensity, such as 4, and study it to minimize the deformation of the building. However, this does not mean that we design a building that is unbreakable even in a large-scale earthquake.

To mitigate the effects of an earthquake or typhoon on human life, we need to forecast such events. Instead of relying on cause-and-effect or regression relationships, we should focus on prediction by pattern recognition. This technique, integrating multidimensional information obtained to date, creates Mahalanobis space (see Section 4.7) using only time-based data with a seismic intensity scale below 0.5, at which no earthquake happens. The Mahalanobis distance becomes 1, on average, in the space. Therefore, distance D generated in the Mahalanobis space remains within the approximate range 1 ± 1. We assume that the Mahalanobis space exists as unit space only if there is no earthquake. We wish to see how the Mahalanobis distance changes in accordance with the SN ratio (forecasting accuracy) proportional to the seismic intensity after we calculate a formal equation of the distance after an earthquake. If the Mahalanobis distance becomes large enough and is sufficiently proportional to its seismic intensity, it is possible to predict an earthquake using seismic data obtained before the earthquake occurs.

The same technique holds for problems of the elderly. In actuality, there are quite a few 80-year-olds who are still healthy and alert. We would collect information from their youth, such as how many cigarettes they smoked. What sorts of information should be gathered is a matter of the design of the information system. For n different-aged persons belonging to a unit space, we create the Mahalanobis space for their information by collecting either quantitative or qualitative data, such as professions. This Mahalanobis space is a unit space. For this information we calculate a distance for a single person who is senile or cannot lead a normal life. If the distance becomes great and at the same time matches the degree of how senile or bedridden a person is, we may be able to forecast and change the futures of some elderly people.

For the most part, some items in the list are not helpful. MTS can also play a significant role in improving prediction accuracy using an orthogonal array, and the SN ratio may be useful in earthquake forecasting and senility in the elderly. To learn more about MTS, see Chapter 21 of this book and other books specializing in MTS.

CRIMINAL NOISES

Many social systems focus on crimes committed by human beings. Recently, in the world of software engineering, a number of problems have been brought about by hackers. Toll collection systems for public telephones, for example, involve numerous problems. Especially for postpaid phones, only 30% of total revenue was collected by the Nippon Telegraph and Telephone Public Corporation. Eventually, the company modified its system to a prepaid basis. Before you call, you insert a coin. If your call is not connected, the coin is returned after the phone is hung up. Dishonest people put tissue paper in coin returns to block returning coins because many users tend to leave a phone without receiving their change. Because phone designers had made the coin return so small that a coin could barely drop through, change collectors could fill the slot with tissue paper using a steel wire and then burn the paper away with a hot wire and take the coins. To tackle this crime, designers added an alarm that buzzes when coins are removed from a phone; but change collectors decoy people in charge by intentionally setting off alarms at some places, in the meantime stealing coins from other phones.

A good design would predict crimes and develop ways to know what criminals are doing. Although the prepaid card system at first kept people from not paying, bogus cards soon began to proliferate. Then it became necessary to deal with counterfeiting of coins, bills, and cards. Another problem is that of hackers, who have begun to cause severe problems on the Internet. These crimes can be seen as intentional noises made by malicious people. Education and laws are prepared to prevent them and the police are activated to punish them. Improvement in people's living standard leads to the prevention of many crimes but cannot eliminate them.

No noises are larger than the war that derives from the fact that a national policy is free. To prevent this disturbance, we need international laws with the backing of the United Nations, and to eradicate the noise, we need United Nations' forces. At the same time, the mass media should keep check on UN activities to control the highest-ranked authority. Although the prevention of wars around the world is not an objective of quality engineering, noises that accompany businesses should be handled by quality engineering, and MTS can be helpful by designing ways to detect counterfeit coins, for example, and to check the credibility of borrowers. Quality engineering can and should be applied to these fields and many others, some examples of which are given below.

1.4. Management in Manufacturing

Ford's Strategy

The first process to which Ford applied the quality engineering method was not product design but the daily routine activity of quality control (i.e., on-line quality engineering). We reproduce below a part of a research paper by Willie Moore.

> **Quality Engineering at Ford**
> Over the last five years, Ford's awareness of quality has become one of the newest and most advanced examples. To date, they have come to recognize that continuous improvement of products and services in response to customers' expectation is the only way to prosper their business and allocate proper dividends to stockholders. In the declaration about their corporate mission and guiding principle, they are aware that human resources, products, and profits are fundamentals for success and quality of their products and services is closely related to customer satisfaction. However, these ideas are not brand-new. If so, why is it considered that Ford's awareness of quality is one of the newest and advanced? The reason is that Ford has arrived at the new understanding after reconsidering the background of these ideas. In addition, they comprehend the following four simple assertions by Dr. Taguchi:
>
> 1. Cost is the most important element for any product.
> 2. Cost cannot be reduced without any influences on quality.
> 3. Quality can be improved without cost increase. This can be achieved by the utilization of the interactions with noise.
> 4. Cost can be reduced through quality improvement.

Historically, the United States has developed many quality targets, for example, zero-defect movement, conformity with use, and quality standards. Although these targets include a specific definition of quality or philosophy, practical ways of training to attain defined quality targets have not been formulated and developed. Currently, Ford has a philosophy, methods, and technical means to satisfy customers. Among technical means are methods to determine tolerances and economic evaluation of quality levels. Assertion 4 above is a way of reducing cost after improving the SN ratio in production processes. Since some Japanese companies cling too much to the idea that quality is the first priority, they are losing their competitive edge, due to higher prices. Quality and cost should be well balanced. The word *quality* as discussed here means market losses related to defects, pollution, and lives in the market. A procedure for determining tolerance and on- and off-line quality engineering are explained later.

Determining Tolerance

Quality and cost are balanced by the design of tolerance in the product design process. The procedure is prescribed in JIS Z-8403 [2] as a part of national standards. JIS Z-8404 is applied not only to Ford but also to other European companies. Balancing the cost of quality involves how to determine targets and tolerances at shipping.

Tolerance is determined after we classify three quality characteristics:

1. *Nominal-the-best characteristic:* a characteristic that incurs poorer quality when it falls below or exceeds its target value m (e.g., dimension, electric current). Its tolerance Δ, where a standard is $m \pm \Delta$, is calculated as follows:

$$\Delta = \sqrt{\frac{A}{A_0}}\,\Delta_0 \tag{1.1}$$

   where A_0 is the economic loss when a product or service does not function in the marketplace, A the manufacturing loss when a product or service does not meet the shipping standard, and Δ_0 the functional limit. Above $m + \Delta_0$ or below $m - \Delta_0$, problems occur.

2. *Smaller-the-better characteristic:* a characteristic that should be smaller (e.g., detrimental ingredient, audible noise). Its tolerance Δ is calculated as follows:

$$\Delta = \sqrt{\frac{A}{A_0}}\,\Delta_0 \tag{1.2}$$

3. *Larger-the-better characteristic:* a characteristic that should be larger (e.g., strength). Its tolerance Δ is calculated as follows:

$$\Delta = \sqrt{\frac{A_0}{A}}\,\Delta_0 \tag{1.3}$$

Since a tolerance value is set by the designers of a product, quite often production engineers are not informed of how tolerance has been determined. In this chapter we discuss the quality level after a tolerance value has been established.

Evaluation of Quality Level and Consumer Loss

A manufacturing department is responsible for producing specified products routinely in given processes. Production engineers are in charge of the design of production processes. On the other hand, hardware, such as machines or devices, targets, and control limits of quality characteristics to be controlled in each process, and process conditions, are given to operators in a manufacturing department as technical or operation standards. Indeed, the operators accept these standards; however, actual process control in accordance with a change in process conditions tends to be left to the operators, because this control task is regarded as a calibration or adjustment. Production cost is divided up as follows:

$$\begin{aligned}\text{production cost} = {} & \text{material cost} + \text{process cost} \\ & + \text{control cost} + \text{pollution cost}\end{aligned} \tag{1.4}$$

Moreover, control cost is split up into two costs: production control costs and quality control costs. A product design department deals with all cost items on the right side of equation (1.4). A production engineering department is charged with the design of production processes (selection of machines and devices and setup of running conditions) to produce initially designed specifications (specifications at shipping) as equitably and quickly as possible. This department's responsibility covers a sum of the second to fourth terms on the right-hand side of (1.4). Its particularly important task is to speed up production and attempt to reduce total cost, including labor cost of indirect employees after improving the stability of production processes. Cost should be regarded not only as production cost but as companywide cost, which is several times that of production cost as expressed in (1.4).

Since product designers are involved in all cost items, they are responsible not for considering process capability but for designing product reliability in such a way that a product functions sufficiently over its life span (how many years a product endures) under various environmental conditions. In designing a product, the *parameter design method*, which is a way of stabilizing product function, helps to broaden a product's tolerances so that it can be manufactured easily. For example, to improve stability twofold means that a target characteristic of a product never changes, even if all possible factors of its variability double. A production engineering department needs to design production processes to reduce total corporate cost as much as possible as well as to satisfy the initial specifications given by a design department. This means that the design and production processes are to be studied until the variability of characteristics of the product produced actually match the allowable total cost, including the labor cost of indirect employees.

No matter how stabilized production processes are, if we do not control them, many defective products are produced in the end. Moreover, we should design stable processes, speed up production speed, and reduce production cost. Speedup of production usually leads to increased variability. In this case, management should play the role of building up a system so that production cost and loss due to quality variability are balanced automatically.

In production processes, the variability of objective characteristics should be restrained at an appropriate level by process control (feedback control of quality and process conditions). This is equivalent to balancing cost in equation (1.4) and loss due to quality or inventory. If cost is several times as important as loss due to quality or increased inventory, cost should be calculated as being several times as great as actual cost. According to Professor Tribus, former director of the Center for Advanced Engineering Studies at MIT, Xerox previously counted the price of a product as four times that of its unit manufacturing cost (UMC). Since the UMC does not include the cost of development, sales, and administration, if the company did not sell a product for four times the UMC, it would not make a profit.

Top management needs to determine a standard for how many times as much as actual cost the quality level should be balanced. Offering such a standard and an economic evaluation of quality level is regarded as a manufacturing strategy and is management's responsibility.

Balance of Cost and Quality Level

Since price basically gives a customer the first loss, production cost can be considered more important than quality. In this sense, balance of cost and quality is regarded as a balance of price and quality. Market quality as discussed here includes the following items mentioned earlier:

1. Operating cost
2. Loss due to functional variability
3. Loss due to evil effects

The sum of 1, 2, and 3 is the focus of this chapter. Items 1 and 3 are almost always determined by design. Item 1 is normally evaluated under conditions of standard use. For items 2 and 3, we evaluate their loss functions using an average sum of squared deviations from ideal values. However, for only an initial specification (at the point of shipping) in daily manufacturing, we assess economic loss due to items 2 and 3, or the quality level as defined in this book, using the average sum of squared deviations from the target. In this case, by setting loss when an initial characteristic of a product falls below a standard to A dollars, its squared deviation from the target value to σ^2, and the characteristic's tolerance to Δ, we evaluate its quality level by the following equation:

$$L = \frac{A}{\Delta^2}\sigma^2 \qquad \text{(for the nominal-the-best or smaller-the-better characteristic)} \tag{1.5}$$

Then, σ^2 is calculated as follows, where n data are $y_1, y_2, \ldots, y_n$:

$$\sigma^2 = \frac{1}{n}[(y_1 - m)^2 + (y_2 - m)^2 + \cdots + (y_n - m)^2] \tag{1.6}$$

$$\sigma^2 = \frac{1}{n}(y_1^2 + y_2^2 + \cdots + y_n^2) \tag{1.7}$$

Equation (1.6) is used to calculate σ^2 for the nominal-the-best characteristic, and equation (1.7) for the smaller-the-better characteristic.

$$L = A\Delta^2\sigma^2 \qquad \text{(for the larger-the-better characteristic)} \tag{1.8}$$

Now

$$\sigma^2 = \frac{1}{n}\left(\frac{1}{y_1^2} + \frac{1}{y_2^2} + \cdots + \frac{1}{y_n^2}\right) \tag{1.9}$$

We evaluate daily activity in manufacturing as well as cost by clarifying the evaluation method of quality level used by management to balance quality and cost.

QUALITY LEVEL: NOMINAL-THE-BEST CHARACTERISTIC

A manufacturing department evaluates quality level based on tolerances as clarified in specifications or drawings. Instead of a defect rate or approval rate, we should assess quality using loss functions. For the nominal-the-best characteristic, equations (1.5) and (1.6) are used.

❐ Example

A certain plate glass maker whose shipping price is \$3 has a dimensional tolerance of 2.0 mm. Data for differences between measurements and target values (m's) regarding a product shipped from a certain factory are as follows:

0.3	0.6	−0.5	−0.2	0.0	1.0	1.2	0.8	−0.6	0.9
0.0	0.2	0.8	1.1	−0.5	−0.2	0.0	0.3	0.8	1.3

Next we calculate the quality level of this product. To compute loss due to variability, after calculating an average sum of squared deviations from the target, mean-squared error σ^2, we substitute it into the loss function. From now on, we call mean-squared error σ^2 *variance*.

$$\sigma^2 = \tfrac{1}{20}(0.3^2 + 0.6^2 + \cdots + 1.3^2) = 0.4795 < \text{mm}^2 \tag{1.10}$$

Plugging this into equation (1.5) for the loss function gives us,

$$L = \frac{A}{\Delta^2}\sigma^2 = \frac{300}{2^2}(0.4795) = 36 \text{ cents} \qquad (1.11)$$

As an average value of plate glass, 0.365 mm is regarded as somewhat large. To check this, we can create an analysis of variance (ANOVA) table.

$$S_T = 0.3^2 + 0.6^2 + \cdots + 1.3^2 = 9.59 \qquad (f = 20) \qquad (1.12)$$

$$S_m = \frac{(0.3 + 0.6 + \cdots + 1.3)^2}{20} = \frac{7.3^2}{20} = 2.66 \qquad (f = 1) \qquad (1.13)$$

$$S_e = S_T - S_m = 9.59 - 2.66 = 6.93 \qquad (1.14)$$

Variance V is equal to the value of variation S divided by degrees of freedom f. Pure variation S' is subtraction of error variance multiplied by its degrees of freedom from variation S. By dividing pure variation S' by total variation S_T, we can obtain degrees of contribution ρ, which represents the quality level. As a result, we have Table 1.1, which, reveals that since the average is much greater than the standard, mean-squared error increases accordingly and thereby leads to enlarging loss due to variability. In a plant, adjusting an average to a target is normally regarded to be easy.

Once the average gets close to the target, variance σ^2 can be changed to approximately match the error variance V_e (Table 1.1). As a result, the following value of the loss function is obtained:

$$L = \frac{300}{2^2}(0.365) = (75)(0.365) = 27 \text{ cents} \qquad (1.15)$$

As compared to equation (1.11), for one sheet of plate glass, this brings us a quality improvement of

$$36.0 - 27.4 = 8.6 \text{ cents} \qquad (1.16)$$

If 500,000 sheets are produced monthly, we can obtain $43,000 through quality improvement.

No special tool is required to adjust an average to a target. We can cut plate glass off with a ruler after comparing an actual value with a target value. If the

Table 1.1
ANOVA table

Factor	f	S	V	S'	ρ(%)
m	1	2.66	2.66	2.295	23.9
e	19	6.93	0.365	7.295	76.1
Total	20	9.59	0.4795	9.590	100.0

time interval of comparison and adjustment is varied, a variance will be changed as well as an average. This is regarded as an issue of calibration cycle in quality engineering. At a factory, we can determine an optimal calibration cycle using the procedure detailed in Chapter 2.

QUALITY LEVEL: SMALLER-THE-BETTER CHARACTERISTIC

Smaller-the-better characteristics should be nonnegative, and the most desirable value is zero. The quality level of smaller-the-better characteristics is given as the loss function L.

❒ Example

Now suppose that a tolerance standard of roundness is less than 12 μm, and if a product is disqualified, loss A costs 80 cents. We produce the product with machines A_1 and A_2. Roundness data for this product taken twice a day over a two-week period are as follows:

Morning:	0	5	4	2	3	1	7	6	8	4
Afternoon:	6	0	3	10	4	5	3	2	0	7

The unit used here is micrometers. $\Delta = 12$ μm and $A = 80$ cents. The quality level using the smaller-the-better characteristic is calculated as

$$\begin{aligned}\sigma^2 &= \tfrac{1}{20}(y_1^2 + y_2^2 + \cdots + y_{20}^2)\\ &= \tfrac{1}{20}(0^2 + 5^2 + 4^2 + \cdots + 7^2)\\ &= 23.4\ \mu\text{m}^2 \qquad (1.17)\end{aligned}$$

$$L = \frac{A}{\Delta^2}\sigma^2 = \frac{80}{12^2}(23.4) = 13 \text{ cents} \qquad (1.18)$$

QUALITY LEVEL: LARGER-THE-BETTER CHARACTERISTIC

The larger-the-better characteristic should be nonnegative, and its most desirable value is infinity. Even if the larger the better, a maximum of nonnegative heat efficiency, yield, or nondefective product rate is merely 1 (100%); therefore, they are not larger-the-better characteristics. On the other hand, amplification rate, power, strength, and yield amount are larger-the-better characteristics because they do not have target values and their larger values are desirable.

❒ Example

Now we define y as a larger-the-better characteristic and calculate a loss function. Suppose that the strength of a three-layer reinforced rubber hose is important:

K_1: adhesion between tube rubber and reinforcement fiber

K_2: adhesion between reinforcement fiber and surface rubber

Both are crucial factors for rubber hose. For both K_1 and K_2, a lower limit for Δ is specified as $\Delta = 5.0$ kgf. When hoses that do not meet this standard are discarded, the loss is $5 per hose. In addition, its annual production volume is 120,000. After prototyping eight hoses for each of two different-priced adhesives, A_1 (50 cents) and A_2 (60 cents), we measured the adhesion strengths of K_1 and K_2, as shown in Table 1.2.

Compare quality levels A_1 and A_2. We wish to increase their averages and reduce their variability. The scale for both criteria is equation (1.9), an average of the sum of squared reciprocals. By calculating A_1 and A_2, respectively, we compute loss functions expressed by (1.8). For A_1,

$$\sigma_1^2 = \frac{1}{16}\left(\frac{1}{10.2^2} + \frac{1}{5.8^2} + \cdots + \frac{1}{16.5^2}\right) = 0.02284 \qquad (1.19)$$

$$L_1 = A_0\Delta_0\sigma^2 = (500)(5^2)(0.02284) = \$2.86 \qquad (1.20)$$

For A_2,

$$\sigma_2^2 = \frac{1}{16}\left(\frac{1}{7.6^2} + \frac{1}{13.7^2} + \cdots + \frac{1}{10.6^2}\right) = 0.01139 \qquad (1.21)$$

$$L_2 = (500)(5^2)(0.01139) = \$1.42 \qquad (1.22)$$

Therefore, even if A_2 is 10 cents more costly than A_1 in terms of adhesive cost (sum of adhesive price and adhesion operation cost), A_2 is more cost-effective than A_1 by

$$(50 + 285.5) - (60 + 142.4) = \$1.33 \qquad (1.23)$$

In a year, we can save $159,700.

Table 1.2
Adhesion strength data

A_1	K_1	10.2	5.8	4.9	16.1	15.0	9.4	4.8	10.1
	K_2	14.6	19.7	5.0	4.7	16.8	4.5	4.0	16.5
A_2	K_1	7.6	13.7	7.0	12.8	11.8	13.7	14.8	10.4
	K_2	7.0	10.1	6.8	10.0	8.6	11.2	8.3	10.6

1.5. Quality Assurance Department

Responsibility of Each Department for Quality

A *strategy* is a system that stimulates employees to rationalize a corporate business process or to endeavor voluntarily to improve productivity. To encourage employees voluntarily to enhance a management system, in particular, it is essential to make them strategically predict and assess the quality level (i.e., part of the quality level: only loss due to manufacturing variability, or A/A_0 in the total loss) of a product at the point of shipping. An individual management system (e.g., preventive quality management system, preventive maintenance) is not strategy but *tactics*, whose design is detailed in Section 2.4. In this section we demonstrate the management of unknown items. The countermeasure to unknown items is a strategy.

The main objective of quality engineering is to offer a common effective procedure for use by an R&D, design, or manufacturing department to improve productivity. That is, quality engineering takes no responsibility for quality, quality improvement, or productivity. Similarly, a computer is in charge of information processing but it cannot solve problems directly and is merely a tool for the person attempting to solve a problem. A computer cannot itself solve a problem.

Quality engineering is also merely an instrument for people to use to solve problems such as improvement of technological development, product design, process design, process control, or product control. If selection of control factors or calculation of SN ratios is inappropriate, eventual improvement of quality or productivity obviously results in failure. On the contrary, to shed light on how to determine improper control factors and SN ratios is one of the roles of quality engineering. In this regard, quality engineering has a feature regarded as evaluation of technological research, or self-management.

Some companies have a quality assurance department. What responsibilities are its members supposed to take? Quality assurance is not just a department that takes responsibility for complaints in the marketplace and tries to compensate customers and solve problems. Quality assurance is not simply a department that apologizes to customers. That is, it does not have the sole responsibility for quality assurance.

A general role of management is to encourage employees to do a good job. To do this, management needs to have authority over personnel affairs and allocation of monetary resources. Managers of the quality assurance department do not have this kind of authority. In the next section we discuss how one deals with the quality assurance personnel's responsibilities and clarifies their duties.

Responsibilities of the Quality Assurance Department

The quality assurance department should be responsible for unknown items and complaints in the marketplace. Two of the largest-scale incidents of pollution after World War II were the arsenic poisoning of milk by company M and the PCB poisoning of cooking oil by company K. (We do not here discuss Minamata disease because it was caused during production.) The arsenic poisoning incident led to many infants being killed after the intake of milk mixed with arsenic. If company M had been afraid that arsenic would be mixed with milk and then had produced the milk and inspected for arsenic, no one would have bought its products. This is because a company worrying about mixtures of arsenic and milk cannot be trusted.

The case of PCB poisoning is similar. In general, a very large pollution event is not predicable, and furthermore, prediction is not necessary. Shortly after World

War II, Fuji Film decimated the ayu (sweetfish) population in the Sakawa River by polluting through industrial drainage. Afterward, it decided to keep fish in the drainage ponds rather than inspecting and analyzing the drainage. By examining the ponds several times a day, company personnel could determine whether the fish were swimming actively. Instead of checking up on what kinds of harmful substances were drained, they made sure that the fish were alive. Since then the company has never caused any pollution as a result of industrial drainage.

Checking on whether something is harmful by using organisms rather than inspecting harmful substances themselves is a practice used widely in Europe and the United States. Since we do not need to specify and measure detrimental substances, specific technologies for measuring them are also not necessary. Thus, we believe that a quality assurance department should be responsible for unknown items. *Their mission is not to inspect to assure that harmful substances are not released, but to inspect whether they have been released and to block them from reaching society when detected.*

For unknown items, specialized technologies do not function at all. Therefore, it is not unreasonable that a quality assurance department take responsibility. We hope that plants all over Japan will adopt such a quality assurance system. In sum, a test for unknown items should be conducted by feeding organisms with substances in question or by using products under actual conditions. More detailed procedures are described in Section 2.5.

References

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