25 Process Diagnosis and Adjustment

25.1. Introduction

Some quality characteristics, such as soldering and electric welding, cannot be measured on a continuous scale; they either pass or fail. Although process conditions can be adjusted to control these characteristics, costs would increase significantly if we attempted to control all conditions. Frequently, we do not know what condition is causing problems. However, one cannot possibly anticipate and check for all potential future problems, such as arsenic contamination of milk or PCB (polychlorinated biphenyl) contamination of food oil, for example. For quality control testing to find unknown items, it would be necessary to design and conduct a performance test or animal test that would incorporate all possibilities. In this chapter we examine the design of a process control system when measurement technology is not available. The only possible test is to check whether or not a product functions or when go/no-go gauges are used. In this situation, the emphasis is on minimizing costs of control and not on potential loss due to the variability of products.

25.2. Quality Control Systems and Their Cost during Production

Let us consider a process control problem where the state of the process—normal or abnormal—is judged by inspecting the noncontinuous quality characteristics of the product. The unit of production will be determined as follows: In the case of parts and/or components, the unit is the number of units produced; in the case of liquid, power, gas, or electric wire, the unit of production is the quantity of output per second or per meter. It will be assumed that the product is checked within an interval of n units, and if the process is judged to be normal, production

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

continues. However, if the process is judged to be abnormal, the process is brought back to its normal condition before continuing production. For example, health checks on human beings are done at certain intervals, and if there is any problem, the person will be treated and brought back to work after recovering to a normal healthy state. Our problem is to discover the most effective method for diagnosis and treatment of production processes.

The parameters are defined as follows:

- ❏ A: loss of producing a product under an abnormal process condition
- ❏ B: diagnostic cost (per diagnosis)
- ❏ C: adjustment cost, the cost of bringing an abnormal process back to its normal state, given as the sum of the loss due to process stoppage and the treatment cost, derived by (the cost of screening out defectives is included in some cases)

$$C = C' \text{ (loss due to process stoppage per unit of time)} \times t \text{ (mean stoppage time due to process failure)} + C'' \text{ (direct adjustment cost such as labor cost for tool replacement and the tool cost)}$$

- ❏ $\bar{u}$: mean failure interval, which is derived as

$$\bar{u} = \frac{\text{quantity of production in the period}}{\text{number of failures in the period}}$$

If the number of failures is zero from the start of production to the present, the following is used:

$$\bar{u} = 2(\text{quantity of production in the period})$$

- ❏ l: time lag, the number of output units produced between the time of sample taking and the time of process stoppage/adjustment if the process is diagnosed as abnormal (expressed in terms of the number of output units)

Therefore, L, the quality control cost per unit of production when process diagnosis and adjustment is performed using inspection interval, n, becomes the following:

L = (diagnostic cost per unit of production) + (loss of producing defectives between diagnoses using interval n) + (process adjustment cost) × (the possibility of process adjustment) + (loss due to time lag)

$$= \frac{B}{n} + \frac{n+1}{2} \times \frac{A}{\bar{u}} + \frac{C}{\bar{u}} + \frac{lA}{\bar{u}} \tag{25.1}$$

❒ Example

An automatic welding machine sometimes fails due to welding-head abrasion and carbon deposition. Currently, the welded spots of a product are inspected at

100-unit intervals. Tensile strength and welding surface are inspected to find non-welded or imperfectly welded product. If the machine fails, the product is scrapped and the loss per unit is 50 cents. Diagnosis cost B is \$1.60. Although it does not take time to sample, inspection takes 4 minutes to perform. Thirty units can be produced during inspection. Therefore, the time lag, l, for this inspection method is 30 units. Furthermore, production in the past two months was 84,000 units and the number of failures during this period was 16.

The adjustment cost, C, when the machine fails is \$31.70. It is derived in the following way: First, when the machine fails, it has to be stopped for about 20 minutes. The loss due to stoppage (which has to be covered by overtime work, etc.) is \$47.10 per hour. The products were found to be acceptable at the previous inspection and remained so until the hundredth unit produced since the last inspection. A binary search procedure is used to screen the 100 units. If the fiftieth is checked and found to be acceptable, the first 50 products are sent to the next process or to the market. If the seventy-fifth, in the middle of the last 50, is found to be defective, the seventy-sixth to hundredth are scrapped. This process is continued to identify acceptable product. The search process is continued until no more than four items remain. They are scrapped, since further selection is uneconomical. This screening method requires inspection of five products; the cost is \$8. Direct costs such as repair and replacement of the welding head, which can be done in 20 minutes, is \$8. Thus, the total adjustment cost is $C = \$31.70$.

The parameters for this problem can be summarized as follows:

A: loss of producing a defective = 50 cents

B: diagnostic cost = \$1.60

C: adjustment cost = \$31.70

$\bar{u}$: mean failure interval = 84,000/16 = 5250 units

l: time lag = 30 units

n: diagnostic interval = 100 units

By substituting the above into equation (25.1), the following is derived:

$$
\begin{aligned}
L &= \frac{B}{n} + \frac{n+1}{2}\frac{A}{\bar{u}} + \frac{C}{\bar{u}} + \frac{lA}{\bar{u}} \\
&= \frac{1.60}{100} + \frac{101}{2}\left(\frac{0.50}{5250}\right) + \frac{31.70}{5250} + \frac{(30)\,(0.50)}{5250} \\
&= 0.016 + 0.0048 + 0.006 + 0.0029 = \$0.0297 \qquad (25.2)
\end{aligned}
$$

The quantity control cost for failure of the automatic welding machine is \$0.0297 per unit of output when diagnosis/adjustment is done at 100-unit intervals. (*Note:* If we had a welding machine never known to fail, no diagnosis cost would be necessary and no welding machine adjustment would be necessary, since no defective products would ever be produced. Therefore, the value of L in equation (25.2) would be zero. In reality, such a machine does not exist, and even if it did, it would be very expensive.) If the interest and depreciation of the machine permit output higher than the current machine by 10 cents, introduction of a new machine would increase the cost by 7 cents per output.

It is surprising that the processing cost difference is only 3 cents between a machine that never fails or a tool whose life is infinite and a welding machine that fails eight times a month and has a limited life. Of course, if the diagnosis/adjustment method is irrational, the difference will be greater. Since the mean failure interval is once every three days, one may think that diagnosis can be done once a day. In such a case, the diagnostic interval n is 1500 units, and the quantity of daily production and quality control cost L becomes

$$\begin{aligned} L &= \frac{1.60}{1500} + \frac{1501}{2}\left(\frac{0.50}{5250}\right) + \frac{31.70}{5250} + \frac{(30)\,(0.50)}{5250} \\ &= 0.0011 + 0.0715 + 0.0060 + 0.0029 \\ &= \$0.0815 \end{aligned} \tag{25.3}$$

This means an increase of loss due to lack of diagnosis by 0.0815 − 0.0297 = \$0.0518 per unit of output over the current control method, which diagnoses the process at 100-unit intervals. This means an increase of cost due to an extended inspection interval by \$2176 per month.

On the other hand, if the inspection interval is reduced to $n = 50$, one-half of the current method, then

$$\begin{aligned} L &= \frac{1.60}{50} + \frac{51}{2}\left(\frac{0.50}{5250}\right) + \frac{31.70}{5250} + \frac{(30)\,(0.50)}{5250} \\ &= 0.032 + 0.0024 + 0.0060 + 0.0029 \\ &= \$0.0433 \end{aligned} \tag{25.4}$$

In this case, the cost increases due to excessive diagnosis by \$0.0136 per product compared to the current diagnosis interval. What is the optimal diagnosis interval? This problem is addressed in the next section.

25.3. Optimal Diagnostic Interval

The three elements that are necessary to design an on-line quality control system for a production process are the process, the diagnostic method, and an adjustment method. The production process is characterized by loss A of producing a defective and mean failure interval $\bar{u}$, which are treated as system elements. The parameters of the diagnostic method are diagnostic cost, B, and time lag, l, and that of the adjustment method is adjustment cost, C. However, individual parameter values simply represent unorganized system elements. Improvement of the elements in a system is an engineering technology (specialized technology) issue and not an issue of quality and/or management engineering (universal technology).

What combines the process, diagnosis method, and adjustment method is diagnostic interval n. The determination of a diagnostic interval n is an issue of system design and not an issue of the technology in specialized fields. The main issue of quality improvement during production is to minimize the L, given by equation (25.1), as close to zero as possible. Improvement of the technology of specialized fields is not the only way to improve quality.

The cost of quality control given by equation (25.1) can be reduced through optimization of the diagnostic interval n. The optimal diagnostic interval is the interval that roughly equalizes the first term, the diagnostic cost per unit of output, and the second term, the loss of producing defectives between diagnoses in equation (25.1).

The optimal diagnostic interval, n, is given as

$$n = \sqrt{\frac{2(\overline{u} + l)B}{A - C/\overline{u}}} \tag{25.5}$$

❐ Example

For the automatic welding machine example in Section 25.2,

$$n = \sqrt{\frac{(2)(5250 + 30)\ (1.60)}{0.50 - 31.70/5250}} = 185 \tag{25.6}$$

The loss per unit product becomes [see equation (25.2)]

$$\begin{aligned} L &= \frac{1.60}{185} + \frac{186}{2}\left(\frac{0.50}{5250}\right) + \frac{31.70}{5250} + \frac{(30)\ (0.50)}{5250} \\ &= 0.0086 + 0.0088 + 0.0060 + 0.0029 \\ &= \$0.0263 \end{aligned} \tag{25.7}$$

Therefore, by altering the diagnostic interval from 100 to 185 units, we obtain a cost reduction of 0.0297 − 0.0263 = \$0.0034 per unit. This translates into a cost reduction of 0.0034 × 42,000 = \$143 per month. Although this number appears to be small, if there are 200 machines of various types and we can improve the cost of each by a similar amount, the total cost improvement will be significant.

It does not matter if there is substantial estimation error in parameters A, B, C, $\overline{u}$, and l. This is because the value of L does not change much even if the value of these parameters changes by up to about 30%. For example, if loss A due to a defect is estimated to be 70 cents, which is nearly a 40% overestimation over 50 cents, then

$$\begin{aligned} n &= \sqrt{\frac{(2)\ (5250 + 30)\ (1.60)}{0.70 - 31.70/5250}} \\ &= 156 \text{ units} \end{aligned} \tag{25.8}$$

that is, a difference of about 15% from the correct answer, 185 units. Furthermore, quality control cost L in the case of $n = 156$ units is

$$L = \frac{1.60}{156} + \frac{157}{2}\left(\frac{0.50}{5250}\right) + \frac{31.70}{5250} + \frac{(30)\,(0.50)}{5250} = \$0.0266 \qquad (25.9)$$

that is, a difference of \$0.0003 per product compared to the optimal solution. Therefore, the optimal diagnostic interval can be anywhere between ±20% of 185 (i.e., between 150 and 220), depending on the circumstances of the diagnostic operation. For example, if there are not enough workers, choose 220 units; however, if there are surplus workers, choose 150 units.

Equations (25.1) and (25.5) are the basic formulas for process adjustment.

25.4. Derivation of Optimal Number of Workers

Various automatic machines do the actual processing in production processes, while humans do jobs such as transportation of material and parts, mounting, process diagnosis/adjustment, partial inspection, and tooling. The elimination of human labor has been achieved at a rapid pace: for example, by automation of transfer and mounting processes using conveyers and transfer machines and automatic mounting using automatic feeders. However, human beings are necessary for control systems, which involve process diagnosis, problem finding, and process adjustment. In other words, most of the work being conducted by humans in today's factories is process diagnosis and adjustment. This means that we cannot rationally determine the optimal number of workers in a factory without a diagnosis/adjustment system theory. The following simplified example illustrates this point.

❒ Example

LP records are produced by press machines (this is an example from the 1960s) in a factory that has 40 machines, and each machine produces one record every minute; weekly operation is 40 hours. Dust on the press machines and adjustment error sometimes create defective records. Process diagnosis/adjustment is currently conducted at 100-record intervals. The defective record, A, is \$1.20; the cost per diagnosis is \$8.00; diagnosis time lag l is 30 records; the mean failure interval of the press machine is 8000 records; adjustment time when a press machine breaks down is two hours on average; and adjustment cost C is \$50. Derive the optimal diagnosis interval and the optimal number of workers necessary for the factory operation.

Since there are 40 press machines, the number of records produced in one week is (1 record)(60 minutes)(40 hours)(40 machines) = 96,000 records. Therefore, the number of diagnoses per week is 960 and total diagnosis time is

$$(960)(30 \text{ minutes}) = 28{,}800 \text{ minutes} = 480 \text{ hours} \tag{25.10}$$

since the time required for diagnosis is equal to time lag l.

By dividing this by the weekly work hours of one worker, 40 hours, we obtain 12; in other words, 12 workers are necessary for diagnosis only. On the other hand, the number of failures per week is 96,000 ÷ 8000 = 12. Thus, the time for repair and adjustment is

$$(2 \text{ hours})(12) = 24 \text{ hours} \tag{25.11}$$

This is fewer than the weekly hours of one worker. Therefore, a total of 13 workers are currently working in this factory for diagnosis and adjustment.

From equation (25.5), the optimal diagnostic interval is

$$n = \sqrt{\frac{(2)(\bar{u} + l)B}{A - C/\bar{u}}} = \sqrt{\frac{(2)(8000 + 30)(8)}{1.20 - 50/8000}} \approx 330 \text{ units} \tag{25.12}$$

This implies that the diagnostic frequency can be increased by 3.3 times the current level. The number of diagnosing workers can be 1/3.3 of the current 12 workers, or 3.6. Thus, one worker should take 10 machines, checking one after another. It is not necessary to be overly concerned about the figure of 330 records. It can be 250 or 400 once in a while. A worker should diagnose one machine about every 30 minutes.

On the other hand, the frequency of failure will not change, even if the diagnostic interval is changed, meaning that one person is required for adjustment. Thus, five workers is more than enough for this factory. If a diagnosing worker also takes the responsibility for adjusting the machine that fails, he or she can take eight machines instead of 10, and the diagnostic interval can still be extended to 10 machines. This is because the diagnostic interval can be changed by 20 to 30%. Therefore, the maximum number of workers for diagnosis and adjustment of this press process is four or five. Using five workers, the number of defectives will increase by 3.3 times, and the total quality control cost, L, will be

$$\begin{aligned} L &= \frac{B}{n} + \frac{n+1}{2}\frac{A}{\bar{u}} + \frac{C}{\bar{u}} + \frac{lA}{\bar{u}} \\ &= \frac{8}{330} + \frac{331}{2}\left(\frac{1.20}{8000}\right) + \frac{50}{8000} + \frac{(30)(1.20)}{8000} \\ &= 0.0242 + 0.0248 + 0.0062 + 0.0045 \\ &= \$0.0597 \end{aligned} \tag{25.13}$$

which is a cost improvement over the current quality control cost, L_0,

$$L_0 = \frac{8}{100} + \frac{101}{2}\left(\frac{1.20}{8000}\right) + \frac{50}{8000} + \frac{(30)(1.20)}{8000}$$

$$= 0.08 + 0.0076 + 0.0062 + 0.0045$$

$$= \$0.0983 \qquad (25.14)$$

by $0.0386 per record. For one week, this will mean a profit from the quality control system by

$$(0.0386)(60 \text{ minutes})(40 \text{ hours})(40 \text{ machines}) \approx \$3700 \qquad (25.15)$$

If one year has 50 operation weeks, this is a rationalization of quality control by $185,000 per year. Furthermore, the optimal defective ratio, p, of this factory is

$$p = \frac{n+1}{2} \times \frac{1}{\bar{u}} + \frac{1}{\bar{u}} = \frac{331}{2}\left(\frac{1}{8000}\right) + \frac{30}{8000}$$

$$= 0.024 = 2.4\% \qquad (25.16)$$

If the actual defective ratio is far greater than 2.4%, there is not enough diagnosis; however, if it is less than 2.4%, this means that there is excessive checking. Even the new diagnostic interval will incur a quality control cost of 6 cents per record; it is necessary to attempt to reduce the cost closer to zero.