CASE 90

Feedback Control by Quality Characteristics

Abstract: This study demonstrates the use of on-line quality engineering at an early stage. It is an interesting case study for many reasons. On-line quality engineering has not been fully utilized.

1. Introduction

In off-line quality engineering, since we consider a generic function, signal factor, control factor, or noise factor and optimize design parameters with an orthogonal array, we can easily and intuitively follow the PDCA (plan–do–check–action) cycle. But in on-line quality engineering, to derive a loss function we need to scrutinize and clarify measurement or adjustment cost through on-site research at production lines. Figuratively speaking, on-line quality engineering requires untiring and low-key activities as groundwork, but only a company that wrestles actively with both off-line and on-line quality engineering can survive fierce competition.

Many companies, including ours, are striving consistently to reduce waste in direct and indirect workforce departments on a daily basis. However, we have been urged to innovate not only with new products and processes but also with existing ones by making the most of quality engineering techniques. So to promote on-line quality management in our company, we hold training seminars directed to managers and supervisors in the production division. The objective of the seminars is to understand the basic concepts and use of the loss function as a first step to improving quality and reducing cost.

For building a case study as a typical example for members in our in-house training seminar, we picked the following case: "Feedback Control by Quality Characteristics in Machining Component *K*" under the slogan "Do it first."

2. Current Feedback Control of Component *K*

Component *K* is machined in an integrated production line consisting of eight processes and nine quality characteristics. Among them we selected dimension *H* as associated with more than 40 subsequent processes for each component, required to be within a predetermined tolerance in all the processes. Since we had been told to attempt feedback control under a stable process condition rather than a warm-up process condition, we began to improve process stability and take measurements (including periodical fluctuations) as a grass-roots activity.

Through this research, analysis, and improvement, with the cooperation of the manufacturing and production engineering departments, many problems, such as treatment of removed material, dimensional adjustment procedures, and or measuring methods have come up. To make dimensions range within adjustable limits, we selected the idea of "fast, low-cost, and safe" as our basic policy.

Parameters

As a result of investigating the processes relevant to component *K*, we obtained the following parameters, which are currently controlled (some of them are denoted by a sign because of their confidentiality).

- *Design standard:* $m \pm 30$ μm; tolerance: $\Delta = 30$ μm
- *Loss by defect:* $A = 60$ yen (disposal cost per component at the point of completing component *K*)

- *Measurement cost:* B_0 = 1572 yen (estimated by the measurement time for component *K*)
- *Current checking interval:* n_0 = 300 components (one component per box is measured)
- *Current adjustable limit:* D_0 = 25 μm
- *Time lag:* l_0 = 50 components
- *Current average adjustment interval:* U_0 = 19,560 components (harmonic mean of all adjustment intervals regarding dimension *H*)
- *Current average adjustment cost:* C_0 = 5370 yen (weighted mean of all adjustment intervals regarding dimension *H*)
- *Measurement error variance:* $\sigma^2_{m0} = 10^2$ μm^2 (large error due to poor precision of the special measurement instrument)

Current Loss Function

Based on our investigation into the current processes, we computed the current loss function as

$$L_0 = \frac{B_0}{n_0} + \frac{C_0}{U_0} + \frac{A}{\Delta^3} + \left[\frac{D_0^2}{3} + \left(\frac{n_0+1}{2} + l_0\right)\frac{D_0^2}{U_0} + \sigma^2_{m0}\right]$$

$$= 5.24 + 0.27 + 13.89 + 0.43 + 6.67$$

$$= 26.50 \text{ yen} \tag{1}$$

We see that the current loss amounts to 26.5 yen, and Figure 1 is a bar chart representing its content. This chart reveals that the loss inside the adjustable limit accounts for 52%.

3. Optimal System

To minimize the current loss, L_0, we designed an optimal control system. Since each process is controlled by quantitative characteristics and the adjustment method of quality characteristic *H* is clearly defined, using a quality management system based on feedback control, we attempted to optimize the processes.

Calculation of Loss L_1 by Feedback Control

While maintaining our current process conditions, we studied the optimization of processes using only the on-line approach. We computed the optimal measurement interval, n_1, and optimal adjustable limit, D_1:

$$n_1 = \sqrt{\frac{2U_0B_0}{A}\frac{\Delta}{D_0}} \tag{2}$$

$$= 1215 \text{ components}$$

$$\rightarrow 1250 \text{ components every 5 hours}$$

$$D_1 = \left(\frac{3C_0D_0^2\Delta_0^2}{Au_0}\right)^{1/4} = 9.4\ \mu\text{m}$$

$$\rightarrow 10\ \mu\text{m} \tag{3}$$

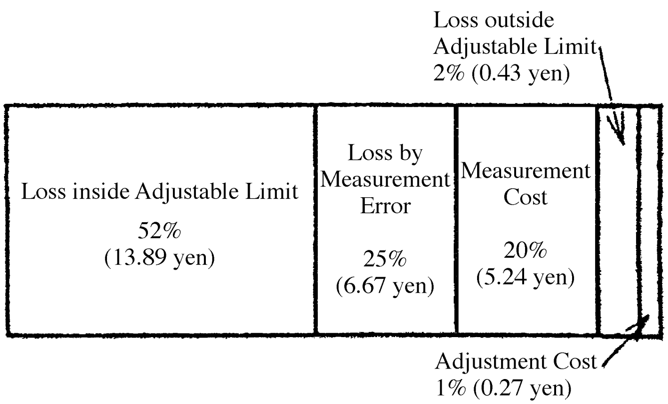

Figure 1
Current loss, L_0

Once the optimal measurement interval and adjustable limit were determined, we could predict the average adjustment interval (U_1) under the condition

$$U_1 = U_0 \frac{D_1^2}{D_0^2} = 19{,}560 \left(\frac{10^2}{25^2}\right)$$

$$= 3130 \text{ components} \qquad (4)$$

The loss by feedback control under the optimal configuration can be calculated by substituting the newly computed optimal measurement interval, n_1, adjustable limit, D_1, and average adjustment interval, U_1, into equation (1) as follows:

$$L_1 = \frac{B_0}{n_1} + \frac{C_0}{U_1} + \frac{A}{\Delta^2} \left[\frac{D_1^2}{3} + \left(\frac{n+1}{2} + l_0\right)\frac{D_1^2}{U_1} + \sigma_{m_0}^2\right]$$

$$= 1.26 + 1.72 + 2.22 + 1.44 + 6.67$$

$$= 13.31 \text{ components} \qquad (5)$$

Comparison between L_0 and L_1 by Analysis Chart

Using a bar chart, we compared the current loss, L_0, and optimal loss, L_1 (Figure 2).

Problems in an Optimal System

By adopting the optimal condition, we obtained a reduction in total loss from 26.50 yen to 13.31 yen, an almost 50% improvement. However, the optimal configuration still involves the following three problems: (1) the measurement loss still accounts for the majority, 50%; (2) both the measurement cost (9%) and adjustment cost (13%) need to be reduced; (3) the technical feasibility of the optimal adjustable limit of $D_1 = 10$ μm to reduce the loss is still unknown.

4. Further Improvement from the Optimal Configuration

Next, we took measures for further improvement. We studied technical problems lurking in the optimal system from the standpoint of some specific technologies.

Loss by Measurement Error

The loss due to the measurement error causes 50% of the total loss after optimization. Therefore, we took the following improvement measures.

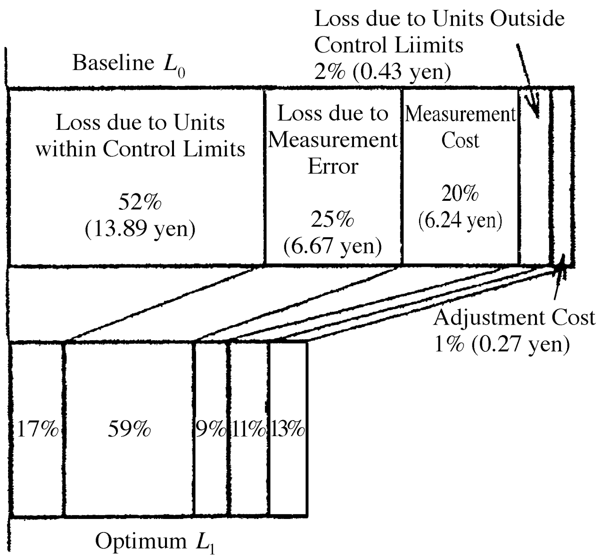

Figure 2
Comparison of loss between current and optimal conditions

Detailed Measures

- ❑ Renewal of the current measuring instrument, jigs, and tools
- ❑ Preparation of measurement standards

After adding two 5-mm peaks on the raw material of component *K*, we used it as our actual standard. In that way we could calibrate environmental errors such as temperature in machining processes.

Estimation of Measurement Error Variance (σ^2_{m1}) after Taking Measures Toward Improvement Throughout the improvement process, we can ameliorate each parameter and obtain the following new values:

- ❑ *Checking interval:* n_m = 1 day (once before starting operation)
- ❑ *Calibration limit:* D_m = 3 μm (checked using the actual standard)
- ❑ *Average calibration interval:* U_m = 264 days (estimated to be calibrated after a year)
- ❑ *Time lag:* l_m = 0 (checked when a machine is stopped before starting operation)
- ❑ *Standard error variance:* $\sigma_s \approx 0$

Then the measurement error variance, σ^2_{m1}, can be estimated with the following equation for the error variance:

$$\sigma^2_{m_1} = \frac{D^2_m}{3} + \left(\frac{n_m}{2} + l_m\right)\frac{D^2_m}{u_m} + \sigma^2_s \qquad (6)$$

Consequently, we can reduce it to 17% as compared with the current 10 μm.

Measurement Cost

The measurement cost accounts for 9% of the entire loss. Since there are 40 places whose dimensions were equal to leading the dimension of *H* to a long measurement time, we studied the following items:

1. Introduction to three-dimensional coordinate measuring or a fast measuring machine. Because of the long measurement time, transportation cost, and machinery cost, we cannot adopt it.
2. Automation of data processing in the current measuring instrument. As a result, we could reduce measurement time by two-thirds.

Expressing these items as measurement cost, we obtained B_1 = 524 yen.

Adjustment Cost

As a result of investigating current adjustment methods, we found that three methods among the current seven involve time-consuming procedures. So we modified these adjustment methods. The modifications can reduce the adjustment time, and we finally came up with the following adjustment cost: C_1 = 4110 yen (estimated by C_0).

Loss within Adjustable Limit

The optimization turned out to improve the loss inside the adjustable limit drastically. However, since the new adjustable limit was decreased to D_1 = 10 μm, we needed to secure 1/2.5 times as much as the current 25 μm. To ensure this adjustable limit, we adopted the following technical measures:

- ❑ Adjustment of standards for peaks 1 to 5 in the data (input) in the machining program
- ❑ Adjustment in the balance of both the right and left sides in the peak cutter

We investigated modification of the optimal adjustable limit D_1. It turns out to be difficult to secure D_1 = 10 μm for all dimension *H*'s, even if we assume the technical measures above. Therefore, we set up D^*_1 = 15 μm on a practical basis.

5. Estimation of Improvement of Feedback Control

After taking the aforementioned improvement measures, we obtained the following parameters. Then we estimated the improvements in loss and process capability index.

Improved Loss

Each Parameter Obtained after Improvement The following are changed parameters after technical improvement measures. Except for them, all parameters are the same as those for the optimal configuration.

- ❑ *Measurement cost:* B_1 = 524 yen
- ❑ *Adjustment cost:* C_1 = 4110 yen

- *Adjustable limit:* $D_1^* = 15$ μm (on a practical basis)
- *Time lag:* $l_1 = 17$ components (through reduction of B_1 by two-thirds)
- *Measurement error variance:* $\sigma_{m1}^2 = 3.0$ μm²

Using these parameters, we estimated the optimal measurement interval, n_1^*, and average adjustment interval, U_1^*.

$$n_1^* = \sqrt{\frac{2U_0B_1}{A}\frac{\Delta}{D_0}}$$

$$= 701 \text{ components} \rightarrow 750 \text{ components every 3 hours} \qquad (7)$$

Under these conditions we predicted the average adjustment interval:

$$U_1^* = U_0 \frac{D_1^{*2}}{D_0^2} = 19{,}560\left(\frac{10^2}{25^2}\right)$$

$$= 7042 \text{ components} \qquad (8)$$

Estimation of Loss

$$L_2 = \frac{B_1}{n_1^*} + \frac{C_1}{U_1^*} + \frac{A}{\Delta^2}\left[\frac{D_1^{*2}}{3} + \left(\frac{n_1^*+1}{2} + l_0\right)\frac{D_1^{*2}}{U_1} + \sigma_{m0}^2\right]$$

$$= 0.70 + 0.58 + 5.00 + 0.84 + 0.20$$

$$= 7.32 \text{ yen} \qquad (9)$$

Comparison of Improved Benefits For the improved benefits discussed above, we compared losses under current conditions, optimal current conditions, and after improvement. Figure 3 is an analytical chart for losses L_0, L_1, and L_2. Comparing the loss function under current conditions and the practical loss function after improvement, we can save 19.18 yen per component, or 10.1 million yen annually. However, even after improvement, the loss inside the adjustable limit accounts for a large portion of the 68%, so further improvement is required.

Process Capability Index

Comparing process capability indexes under both current and optimal conditions, we obtained the following improvement:

$$\text{current } C_p = \frac{2\Delta}{6\sigma_0} = \frac{2\Delta}{6\sqrt{\dfrac{D_0^2}{3} + \left(\dfrac{n_0+1}{2} + l_0\right)\dfrac{D_0^2}{U_0} + \sigma_{m0}^2}} = 0.56$$

$$\text{optimal } C_p = \frac{2\Delta}{6\sigma_2} = \frac{2\Delta}{6\sqrt{\dfrac{D_1^{*2}}{3} + \left(\dfrac{n_1^*+1}{2} + l_1\right)\dfrac{D_1^{*2}}{U_1} + \sigma_{m1}^2}} = 1.06$$

Thus, an almost twofold improvement can be expected.

6. Notes on Feedback Control Activities

In our case, selecting one of the nine quality characteristics, we attempted to reduce cost by using the loss function. For other quality characteristics, by taking full advantage of each specific technology, we can build an optimal system for the entire machine through cost reduction based on a loss function. At this point we need to take notice of the following. For measurement costs, we should consider a feasible and efficient setup for reduction of measurement time and optimal measurement interval for all characteristics, including the use of specialized measurement technicians.

As for adjustment cost and inside- and outside-adjustable limit costs, the key point is to establish component production processes with less variability as well as those that are fast, low-cost, and safe, through use of off-line quality engineering. The resulting benefits through these improvements are unveiled gradually in terms of workforce reduction or enhanced company credibility. From the viewpoint of management, the most vital issue is to estimate how much the reduction in labor cost, users' complaints, or repair cost contributed to cost reduction. That is, instead of stressing workforce reduction after improvement, we should be able to

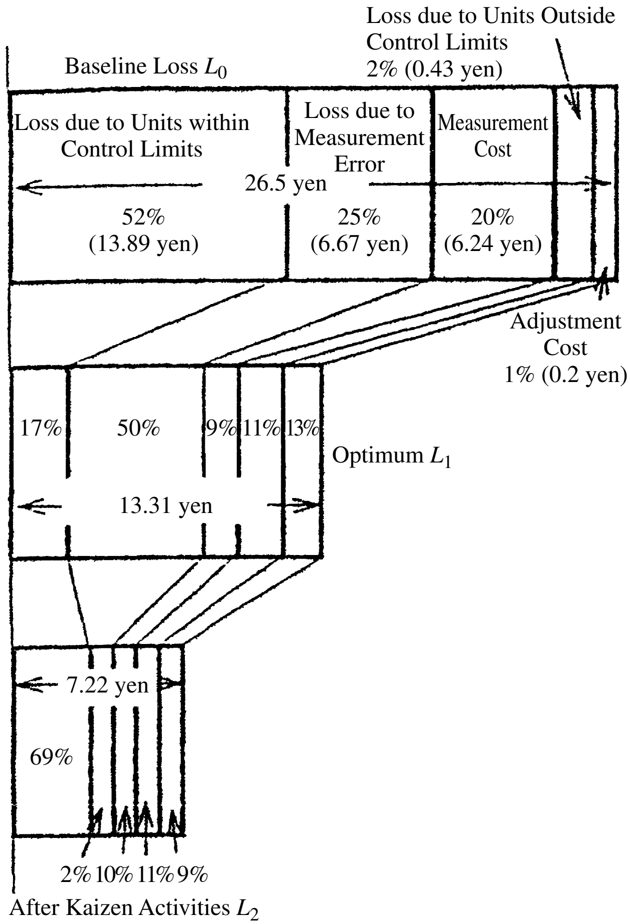

Figure 3
Cost and loss reduction through on-line quality engineering

reflect the financial benefit that accrues through the use of quality engineering.

We strongly hope that a number of case studies focusing on off-line and on-line quality engineering in a reciprocal manner will be reported in the future at conferences held by associations all over the country, including the Quality Engineering Study Group and the Quality Engineering Symposium.

Reference

Toshio Kanetsuki, 1996. An application of on-line quality engineering. *Quality Engineering*, Vol. 4, No. 1, pp. 13–17.

This case study is contributed by Toshio Kanetsuki.