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IMPROVEMENT OF INITIAL TROUBLE WITH A CERTAIN PRODUCT GROUP OF PRODUCTION PROCESSES

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Abstract. *Electronic components that are on the boundaries of acceptable quality often experience unstable states, which may cause abnormal behavior in equipment. For example, this product seems to be distinctive when parts susceptible to* $1/f$ *noise are used. When multiple noise-sensitive parts are used, an abnormality appears due to the influence of the external environment, which is high temperature and humidity in Japan. Many abnormalities are found when multiple* $1/f$ *noise-sensitive parts are used. However, no abnormality is found when these noise-sensitive parts are removed from the device. The rate of quality defects in the parts examined in this study is about* 3%. *To ensure high manufacturing quality, it is essential that engineers are able to mathematically model and predict this phenomenon. We introduced a potential function with the quality boundary width as a variable and we assumed that the width changes stochastically. We also improved component quality using Ginzburg and Landau (GL) free energy to model the quality boundary region and by evaluating the potential function. As a result, we were able to reduce the probability of quality abnormality from* 3% *to* 0.5%.

Keywords:quality improvement, potential function, Ginzburg Landau free energy, fluctuation, order parameter

1. **Introduction.** Professor G. Taguchi established the Quality Engineering Forum in 1993 (now the Quality Engineering Society) under the premise of advancing quality engineering as an academic pursuit. In the Taguchi method, the magnitude of the difference from the desired state is determined such that the definition of error is “ measured value-true value ”[1]. The proper assessment of errors is essential for cost reduction and for ensuring reliability. A potential for loss exists near the design value limit. Dr. Taguchi said that “ discussion of comprehensive judgment of technology is necessary. ” However, many companies have overlooked the role and responsibility of technicians as a consequence of partial short-term work.

The quality problem at the product development stage is the occurrence of product quality dispersion. Dr.Taguchi says that robust design is necessary to resolve the dispersion. Robust design is to make the design parameter value strong against noise. In other words, the designer makes the design resistant to dispersions in usage and environmental changes, and designs that are less likely to deteriorate[1]. With respect to phase transitions, Dr.Yamamoto, etc. reported that free energy was considered as the initial condition when mathematically treating a phase transition phenomenon. They noted that free energy does not increase in the case of a closed system. In contrast, it was reported that thermal noise must be considered when considering causative factors of phase transition[2]. We have reported that an analysis of the rate of return deviation for a certain equipment manufacturer over the past ten years displays " power-law distribution characteristics. " Because the power-law distribution reveals the existence of a phase transition phenomenon, we expect that the rate-of-return deviation and the production system are correlated in a manner that is mediated by the power-law distribution. By performing a data analysis, the relation between the rate-of-return deviation and production throughput has been clarified to some extent. The " fluctuation model of rate-of-return deviation " is self-similar and shows a fractal nature[5, 6, 3]. Also, this power-law distribution characteristic has a " fluctuating " nature during phase transition. For example, occurrence of fluctuation is found at where the phase transition occurs at the point. Then, we have reported on the self-similarity of these fluctuations and noted the f^{-1} and f^{-2} fluctuations[4]. We have also verified self-similarity in the system through experiments on the supply chain system, and have used the supply chain system to produce control equipment. Then, we analyzed the phase transition mechanism in the manufacturing industry by treating manufacturing processes as a closed process when seen as a single manufacturing process, that is, a process on which external forces do not act. We instead defined order parameters within a manufacturing process and further introduce the Ginzburg-Landau free energy[5]. Moreover, we indicated that stable regions of nonlinearity of the production process correspond to the range of phase transitions. On the basis of manpower data, we proposed an evaluation method for production process that decreases or increases the throughput,using multimode vibration theory. We proved quantitatively that synchronization process is much better than asynchronous that[7].

With respect to fluctuation, we reported the applicability of " edge of chaos ", which is used in complex systems, to the manufacturing industry[8]. In the manufacturing industry, " edge of chaos " is caused by a loss of synchronization between the production line and throughput. This phase transition is observed in the process throughput during the manufacture of control equipment. When a delay occurs in a stage of manufacturing, the delay propagates to the successive stage. We reported that this delayed the entire production process, which is equivalent to fluctuations in physical phenomena. A delay in the entire process was also attributed to the propagation of fluctuations (volatility) in our previous study[8]. In our previous study, we also examined the phase transition in the system by using a production flow system[8]. Then, we presented that the stable regions of nonlinearity of the production process correspond to regions of phase transition[5]. On the basis of actual throughput data, using an electrical circuit theory known as multimode vibration theory, we demonstrated that the factor causing reductions in production was throughput variations of work[9].

In this study, regarding with quality improvement, we reported that the rate of return (RoR) was at least proportional to the production lead time. In other words, if RoR forms a log-normal distribution, it is realistic to assume that the cash flow will also have the same log-normal distribution[11, 12]. We implemented a lead-time function and a loss function to calculate the expected loss value[13]. The final quality of a product with electronic components depends on the fundamental instability of those components, as well as their proximity to the boundary of acceptable product quality. When unstable components are also of barely acceptable quality, abnormalities often arise in their function. In the course of manufacturing products from components, noise-sensitive elements are often incorporated. Some products misbehave when they use parts that are susceptible to $1/f$ noise. Close inspection of these devices often reveals quality defects at a rate of about 3%. However, if these noise-sensitive parts are removed from the equipment, the abnormality may be resolved. Product quality in Japan is greatly affected by temperature and humidity. This study aims to purpose and test an effective solution to quality abnormalities in electronic components. We derived a theoretical circuit correction based on the potential function in the product quality boundary region and free energy theory. Regarding with the potential function, we introduce a potential function with a certain width around the boundary of the quality tolerance of the product to reduce troubles in the initial stage of product shipment. We simulated product performance to test its effectiveness. This theoretical approach could improve the function of electronic components and improve their resiliency against defects. In addition, we report that we can correct stochastic fluctuations caused by noise near the quality boundary as much as possible. As a result, when examining the quality distribution of a product lot, quality was improved. The trouble rate improved from 3% to 0.5%. Therefore, this research is a useful report as a quality improvement method at the early stage of production.

2. **Production systems in the manufacturing equipment industry.** The production methods used in manufacturing equipment are briefly covered in this paper. More information is provided in our report. More information is provided in our report[5]. This system is considered to be a " Make-to-order system with version control, " which enables manufacturing after orders are received from clients, resulting in " volatility " according to its delivery date and lead time. In addition, there is volatility in the lead time, depending on the content of the make-to-order products (production equipment).

In Fig.1(A), the " Customer side " refers to an ordering company and " Supplier (D) " means the target company in this paper. The product manufacturer, which is the source of the ordered manufacturing equipment presents an order that takes into account the market price. In Fig.1(B), the market development department at the customer 's factory receives the order through the sale contract based on the predetermined strategy.

Figure 2 illustrates a company 's decision-making process. The business monitors perceived demand trends. When a customer order is received, the perceived trend is analyzed. Based on the analysis, the company is able to decide how to respond to the analyzed demand.

3. **Error propagation and fluctuation.** The basis of our proposed solution is that the width of the product quality boundary region fluctuates with time. As shown in Figure 3, $\theta(x,t)$ is a function of the boundary width fluctuation (x) and time (t). Boundary width fluctuation refers to the width on the left and right, with θ as the centerline. Time is shown on the vertical axis in Figure 3. Figure 3 shows that the errors propagate along with the product. When noise-sensitive elements, which happen to be along the boundary line of the quality distribution, are activated, pronounced fluctuations can be caused by the noise. In these situations, the probability of an error increases (Figure 4), especially when products in the vicinity of the boundary contain unstable electronic components, and therefore have uncertain quality characteristics. For example, in this product, errors typically appear when parts susceptible to $1/f$ noise are used, and these result in a quality defect rate of about 3% when it is in-line with the apparatus. However, these sensitive parts may be removed from the device, preventing the emergence of errors. While the influence of external environments is a critical consideration for manufacturing, it is still possible and beneficial to mathematically model and predict the appearance of product defects.

We defined the free energy of products that were within the product quality boundary region, and then analyzed these products based on the potential function in the boundary region, which constitutes to free energy operating in a stochastic region. We simulated

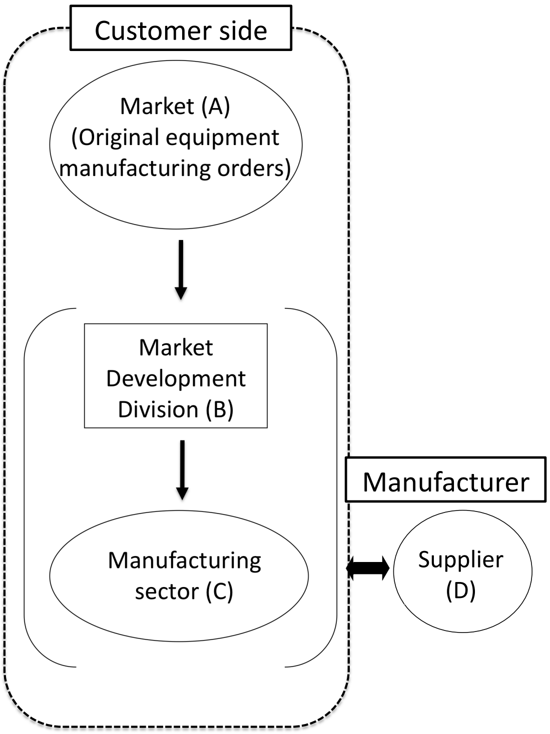

FIGURE 1. Business structure of company of research target

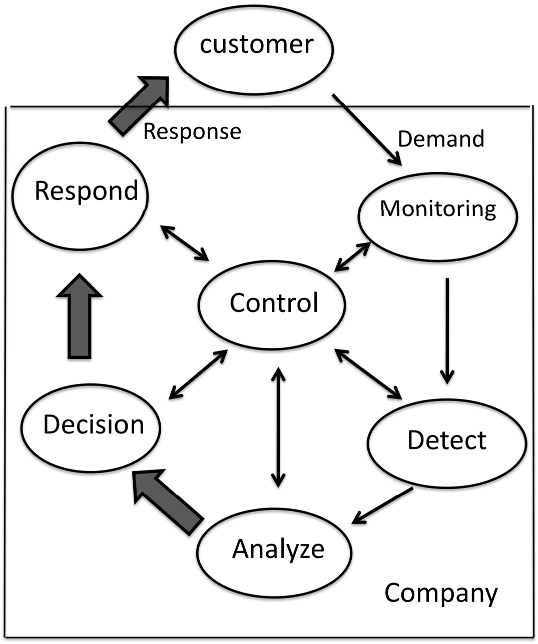

FIGURE 2. Decision-making process within the company

measures that were meant to improve the quality on the premise that there is a quality probability distribution in the boundary area, whose width was assumed to change stochastically. We then introduced Ginzburg and Landau (GL) free energy theory in the quality boundary region and evaluated the resulting potential function. Based on this concept, we proposed a set of corrections for circuits that are sensitive to electrical noise caused by the poor product quality, and then simulated their performance. Our first model of defect potential ignored the stochastic element. The general potential function was defined in terms of a periodic function and noise function.

Definition 3.1. *First model of defect potential ignored the stochastic element*

$$W(\theta) = \int_0^x dx \Big[\Delta\theta(x,t)\Big\{a\nabla\theta - \frac{D}{2}(\Delta\theta(x,t))^2\Big\}\Big] \tag{1}$$

where, a is a constant parameter. $\theta(x,t)$ and $\Delta\theta(x,t)$ are a fluctuation function of boundary width and a variation of fluctuation deviation respectively.

Equation (1) represents that when the boundary value of the tolerance width of the quality distribution is incorporated in the system, it represents “ fluctuation ” due to noise, thereby indicating that product quality increases uncertainty.

Definition 3.2. *Potential function $W(\theta)$ for the boundary width θ*

$$W(\theta) = \int_0^x dx \Big[\Delta\theta(x,t)\Big\{a\nabla\theta - \frac{D}{2}(\Delta\theta(x,t))^2\Big\}\Big] + g(t)\theta(x,t) + r(t) \tag{2}$$

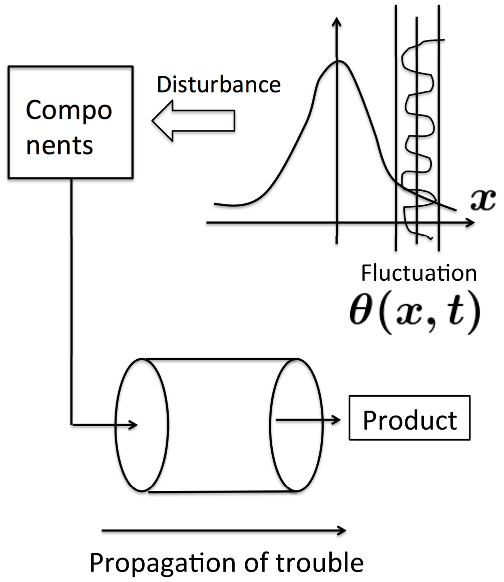

FIGURE 3. Trouble propagation and fluctuation

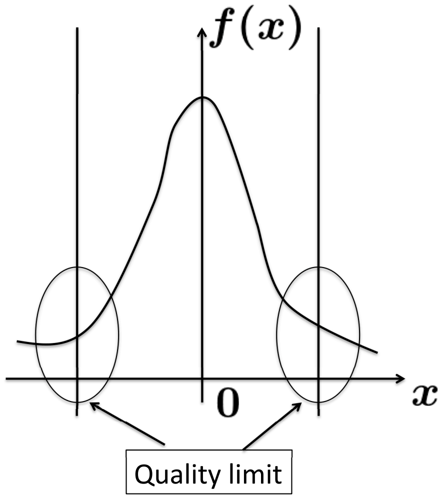

FIGURE 4. Quality probability distribution

where D denotes a constant (> 0). $g(t)$ and $r(t)$ denote a cyclic function and noise function, respectively, and x is a variable belonging to a finite area, S, that has a smooth boundary in one-dimensional Euclidean space. The expression $g(t)\theta(x,t) + r(t)$ denotes an external stress, such as a fluctuation in temperature and humidity, which often causes defects in electronic components in Japan. In other words, this function represents potential with a width x ($0 \leq x \leq X$) for a product near the tolerance boundary. Figure 5 shows the stable phase, boundary phase, and unstable phase. Figure 6 shows a detailed image of the shaded portion of Figure 5. $\varphi^*(\theta,t) = 1$ and $\varphi^*(\theta,t) = 0$ describe stable and unstable conditions, respectively.

Definition 3.3. *Free energies F within boundaries function θ*

$$F = \int_{x\in S} \Big\{\varphi(\theta,t) + \frac{1}{2}r|\nabla\theta|^2\Big\}dx \tag{3}$$

where, r denotes a positive constant, $\nabla(\cdot)$ denotes a $\partial(\cdot)/\partial x$. $\varphi(\theta,t)$ is defined as Equation (4). The production process is according to a thermal diffusion. $\nabla\theta$ represents the gradient energy density of the process in which the product is made. Free energy represents an indicator of stability and instability of products. Generally, the free energy F does not increase with time, so the following equation holds in a closed system[2].

We define the order parameter $\varphi(\theta,t)$ as follows[4, 5]. The order parameter represents the degree of stable phase and unstable phase of the product.

Definition 3.4. *Order parameter $\varphi(\theta,t)$ as product group in the phase*

$$\varphi(\theta,t) = a\cdot h(\theta) + b\cdot\{1-h(\theta)\} + c\cdot g(\theta) \tag{4}$$

where, $h(0) = 0$ and $h(1) = 1$. The function $c\cdot g(\theta)$ has a maximal value as $0 < \theta < 1$ and has zero as $\theta = 0$ and $\theta = 1$. a, b and c denote the normalized parameters for assumed noise intensity in the stable phase and normalized value for assumed noise intensity in the unstable phase respectively.

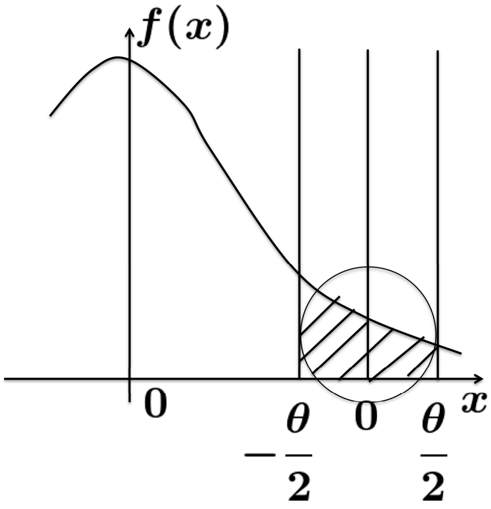

FIGURE 5. Boundary phase, stable phase and unstable phase

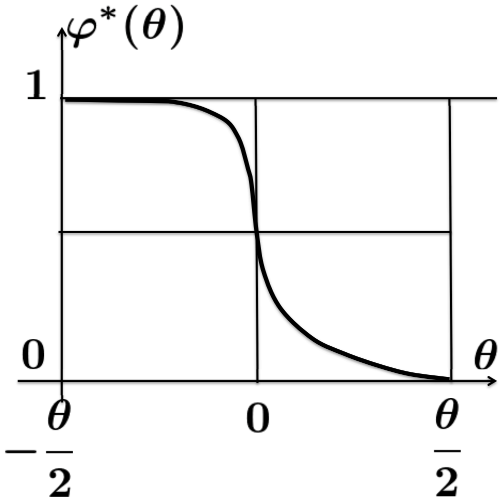

FIGURE 6. Boundary width function

Here, $a(\xi)$ and $b(\xi)$ are constrained as follows.

Assumption 3.1. *ξ and ξ^**

$$0 \leq a(\xi) \leq 1: \quad a(\xi) \cong \frac{1-\xi}{\xi^*} \tag{5}$$

$$0 \leq b(\xi) \leq 1: \quad b(\xi) \cong \frac{\xi}{\xi^*} \tag{6}$$

where, ξ and ξ^* denote a noise intensity ($0 \leq \xi \leq 1$) and assumed noise intensity ($\xi^* = 1$) respectively.

For, example, the assumption 3.1 represents as follows:

$$\begin{cases} \xi \approx 0: & a(\xi) \approx 1 \quad b(\xi) \approx 0 \quad (Stable) \\ \xi \approx 1: & a(\xi) \approx 0, \quad b(\xi) \approx 1 \quad (Unstable) \end{cases} \tag{7}$$

$$\frac{dF}{dt} = \int_{x \in S} \frac{\delta F}{\delta \varphi} \cdot \frac{\partial \varphi}{\partial t} dx \leq 0 \tag{8}$$

To establish Equation (8), it must be needed as follows:

$$\frac{\partial \varphi}{\partial t} = -\tau \frac{\delta F}{\delta \varphi} \tag{9}$$

where, $\tau > 0$.

Now, let the special solution of Equation (9) to φ^*. We define $h(\theta)$ and $g(\theta)$ as follows[10]:

Definition 3.5. *$h(\theta)$ and $g(\theta)$*

$$h(\theta) \equiv \theta^2(3 - 2\theta) \tag{10}$$

$$g(\theta) \equiv \theta^2(1 - \theta)^2 \tag{11}$$

Therefore, we can derive the free energy $\varphi(\theta,\xi)$ as follows[10]:

$$\varphi(\theta,t) \equiv a\cdot h(\theta)+b\cdot\{1-h(\theta)\}+cg(\theta) \tag{12}$$

where, $0\le\varphi(\theta,t)\le 1$.

As shown Figure 6, $\varphi^*(\theta,t)$ denotes the boundary width function as follows:

$$\varphi^*(\theta,t)=\left\{\begin{array}{ll}1 & (Stable\quad phase)\\ 0 & (Unstable\quad phase)\end{array}\right. \tag{13}$$

where, $0\le\varphi(\theta,t)\le 1$ and $\varphi(\theta,t)$ denotes a order parameter[2, 6, 10].

4. **Stochastic partial differential equation for order parameter variable.** We define the free energy $F(\varphi^*)$ using the order parameter φ^* again.

Definition 4.1.

$$F(\varphi^*)\equiv\int_S\Big[\frac{r}{2}(\nabla\varphi^*)^2+W(\varphi^*)\Big]d\theta \tag{14}$$

where, $\theta\in S$.

The boundary condition of Equation (14) is as follows.

$$\frac{\partial\varphi^*}{\partial\theta}=0 \tag{15}$$

Moreover, Equation (9) for φ^* instead of φ is as follows:

$$\frac{\partial\varphi^*}{\partial t}=-\tau\frac{\delta F}{\delta\varphi^*} \tag{16}$$

From Equations (14) and (15), Equation (16) is as follows:

$$\Big[\frac{\delta F}{\delta\varphi^*}\Big]=-r\Delta\varphi^*-\frac{1}{2}\varphi^*(1-(\varphi^*)^2) \tag{17}$$

By substituting Equation (17) into Equation 16, we obtain as follows:

$$\frac{\partial\varphi^*}{\partial t}=r\Delta\varphi^*+\frac{1}{2}\varphi^*(1-(\varphi^*)^2) \tag{18}$$

where, let $\tau=1$.

However, in actual products, fluctuations occur due to the effects of temperature and humidity. A definite model can not be performed with a definite model like Equation (18). Therefore, in this paper, we model the influence of temperature and humidity with white noise and introduce the following stochastic model instead of definite model Equation (18)[2].

$$\frac{\partial\varphi^*}{\partial t}=r\Delta\varphi^*+\frac{1}{2}\varphi^*(1-(\varphi^*)^2)+(1-\varphi^*)^2\frac{\partial B}{\partial t} \tag{19}$$

where, B denotes a Wiener process. The initial condition and boundary condition are as follows:

$$\frac{\partial\varphi^*}{\partial\theta}\Big|_{\theta=0,1}=0,\quad \varphi^*(\theta,0)=0,\quad \varphi^*(\theta,0)=1 \tag{20}$$

Then, the free energy F of the boundary width is derived as follows:

$$F(\varphi^*)=\int_{\theta\in S^*}\Big\{W(\varphi^*)+\frac{1}{2}r\Big|\nabla\varphi^*\Big|^2\Big\}d\theta \tag{21}$$

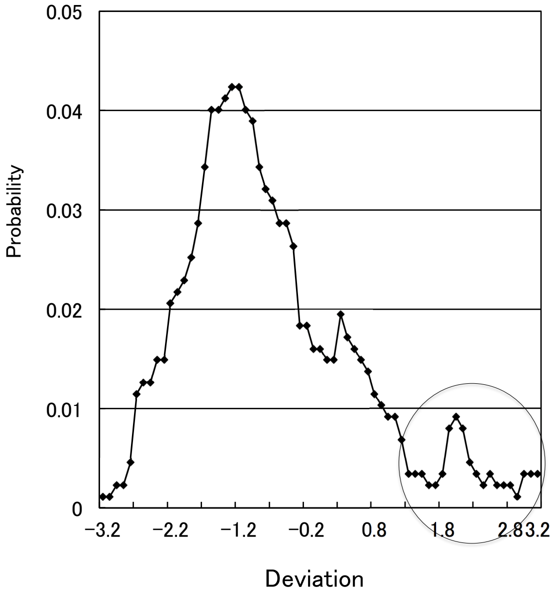

Figure 7. Product measurement value probability distribution before improvement

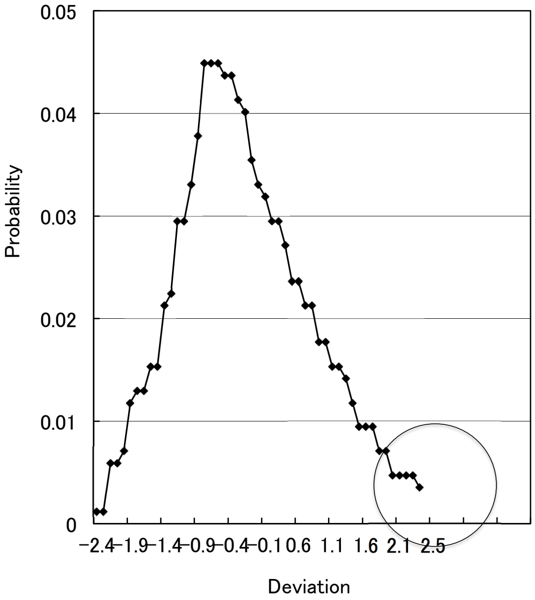

Figure 8. Product measurement value probability distribution after improvement

Table 1. Product measurement probability value

	Average	Volatility
Figure 7	18.7	1.88
Figure 8	17.9	1.41

The solution of Equation (21) can obtain as follows:

$$\varphi^*(\theta,t)=\varphi_0^*(\theta)+\int_0^t\Delta\varphi^*(\theta,t)dt+\int_0^t\hat{W}(\varphi^*(\theta,t))dt+\int_0^t(1-(\varphi^*)^2)dB(\theta,t) \qquad (22)$$

where, the boundary condition denotes Equation (20).

Here, $\hat{W}(\varphi(\theta,t))$ is derived as follows[2]:

$$\hat{W}(\varphi(\theta,t))=\frac{1}{2}\varphi^*(1-(\varphi^*)^2) \qquad (23)$$

5. Numerical simulation.

5.1. **Initial trouble improvement of the product.** Figures 7 and 8 show the product measurement value probability distribution before and after our proposed improvements, respectively. The average values and standard deviations are shown in Table 1. Based on the results illustrated in Figures 7 and 8, we were able to minimize the probabilistic fluctuation due to noise in the vicinity of the quality boundary within the quality distribution of the product group. As a result, the error rate decreased from 3% to 0.5%, representing a significant improvement. This case study of a specific product provides evidence that this approach can be widely used for quality improvement in electronics manufacturing in climates with variable temperature and humidity.

Table 2. Expected loss function for nonstandard quality

	a	b	c	r	V
Figure 9	0.5	0	0	-	-
Figure 10	0.5	0	0	1	0
Figure 11	0.5	1	0	-	-
Figure 12	0.5	1	0	1	6
Figure 13	0.5	0	1	-	-
Figure 14	0.5	0	1	1	-6

5.2. **Potential function and Normalized boundary deviation.** Figure 9 shows the unstable phase with two stable phases. However, the stable phase is a parabolic form. Figure 11 shows the left side stability. Figure 13 shows the right side stability. The potential function model equations of Figures 9, 11 and 13 are derived as follows:

$$\begin{aligned} W(\theta) &= a \cdot g(\theta) + b \cdot h(\theta) + c \cdot (1-\theta) \\ g(\theta) &\equiv \theta^2(1-\theta), \quad Double-well\ function \\ h(\theta) &\equiv \theta^2(3-2\theta), \quad Energy\ density\ distribution \end{aligned}$$

Figure 10 shows the normalized boundary deviation by applying phase field method and shows the unstable to deviation width. Figure 12 shows the normalized boundary deviation by applying phase field method and shows the low value stability against deviation width. Figure 14 shows the normalized boundary deviation by applying phase field method and shows that boundary directionality occurs with respect to the deviation width. Figures 10, 12 and 14 are derived as follows:

$$F(\theta) = \int \left[\frac{r}{2}(\nabla\theta)^2 + W(\theta)\right]$$

$$\varphi^*(\theta, t) \cong \frac{1}{2}\Big(1 - \tanh\Big(\frac{\theta - Vt}{2}\Big)\Big)$$

where, θ denotes the special solution of following equation.

$$\frac{\partial\theta}{\partial t} = -\tau\frac{\delta F}{\delta\theta}$$

6. **Conclusions.** In this study, we performed a theoretical analysis of the product performance near quality boundaries. Specifically, we utilized GL free energy theory to account for stochasticity during analysis of the potential function near a product quality boundary to reduce troubles in the initial stage of product shipment. Using parts susceptible to $1/f$ noise resulted in malfunctioning products in our actual data. When strictly examining these devices, quality defects occurred at a rate of about 3%. We have corrected stochastic fluctuations caused by noise near the quality boundary as much as possible. As a result, when examining the quality distribution of a product lot, quality was improved. By improving the electronic circuit, the probability of abnormal functioning of the product due to high temperature and high humidity was suppressed from 3% to 0.5%. Although we focused on a specific product, our results support the theoretical basis of this approach for quality improvements in a broad range of products.

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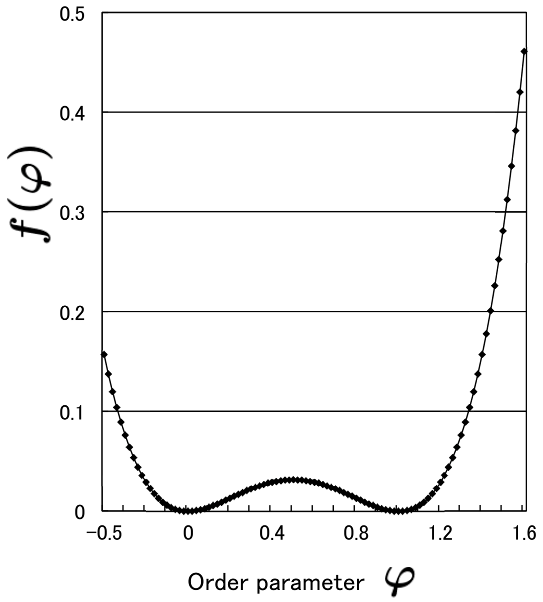

Figure 9. Potential function by applying phase field method

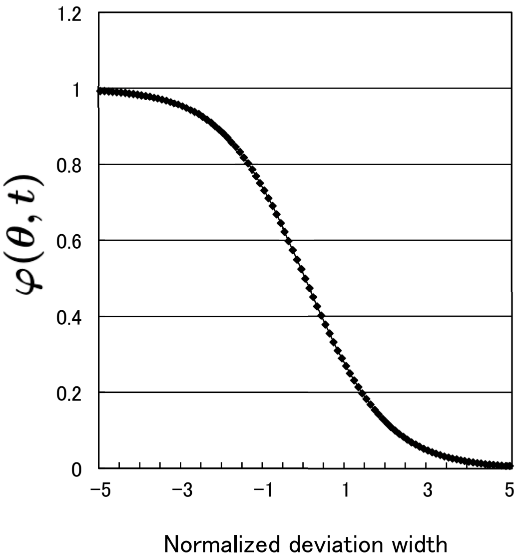

Figure 10. Normalized boundary deviation by applying phase field method

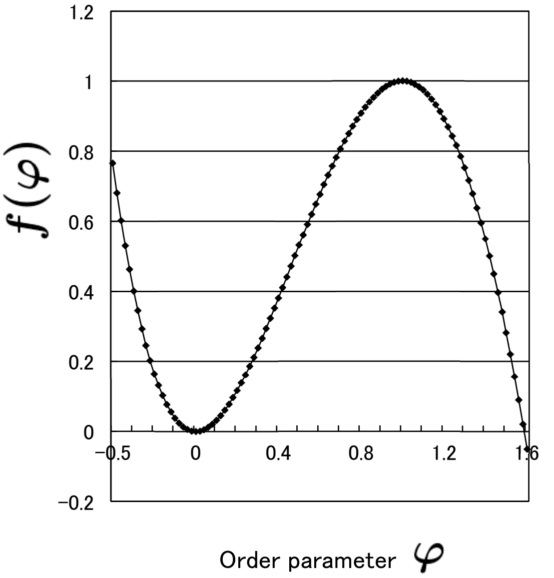

Figure 11. Potential function by applying phase field method

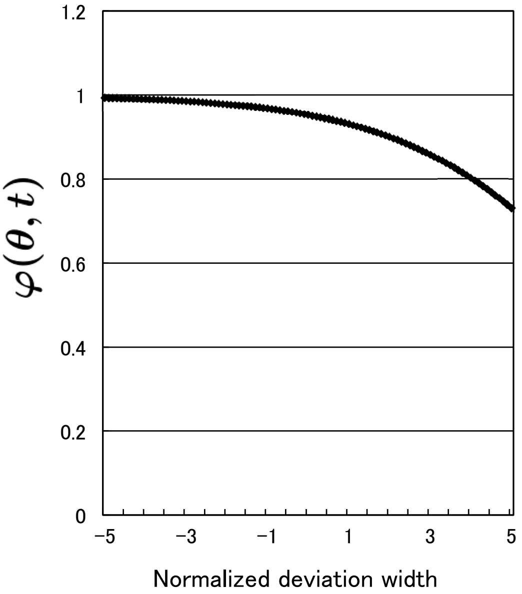

Figure 12. Normalized boundary deviation by applying phase field method

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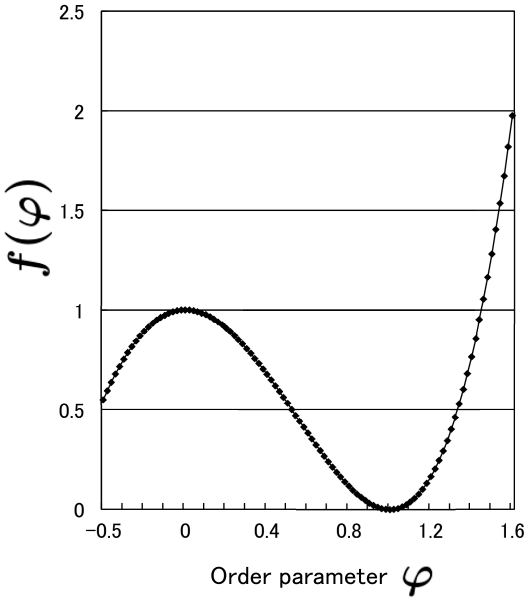

FIGURE 13. Potential function by applying phase field method

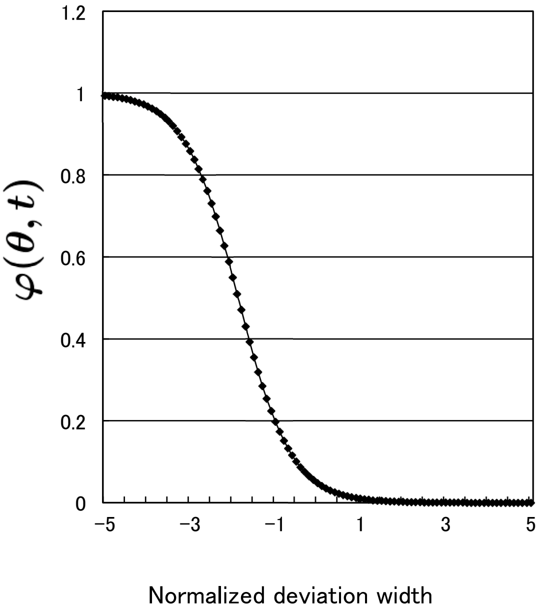

FIGURE 14. Normalized boundary deviation by applying phase field method

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