DEFECT-FREE PRODUCTS THROUGH INTEGRATED DESIGN AND CONTROL

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Abstract

This paper describes the role of integrated design and control, together with six-sigma methodology, for the manufacture of virtually defect-free products. As will be shown, this can be achieved by utilizing statistical tools to quantify quality and more importantly, loss of quality and its cost. These tools assist in identifying the main sources of product variance, which are then eliminated or attenuated by appropriate integrated design of the manufacturing process and its control system. The design of an espresso machine is used as an example to illustrate the integrated approach.

Keywords

Product manufacturing; Integrated design and control; Six sigma; Espresso coffee.

Introduction

Espresso coffee is prepared in a machine that pumps cold water at high pressure (commonly 9 – 10 bar) into a boiler, which displaces near-boiling hot water through a cake of ground coffee. In a conventional machine, illustrated in Figure 1, the operator manually loads ground coffee into a metal filter housing, referred to as a *portafilter*, ensuring that the ground coffee is adequately packed, locks the portafilter under the hot water exit head, and activates the heater. A coffee cup, placed under the portafilter, is filled with the freshly extracted espresso coffee, which is produced by the leaching action of the high-pressure hot water as it passes through the ground coffee. The manufacturer of the espresso machine would like to guarantee that each cup of coffee processed by the machine has a consistent quality. It is noted that the quality of each cup of espresso depends on a large number of variables, among them, the grade and freshness of the coffee beans, the extent to which the beans have been ground, the degree to which the ground coffee is packed in the portafilter, the steam pressure, and the total amount of water used. Since many of the sources of product variability are out of the manufacturer's control, the development of an improved espresso machine would be driven by a desire to either reduce the level of influence of these sources or eliminate as many of them as necessary to ensure a satisfactory product.

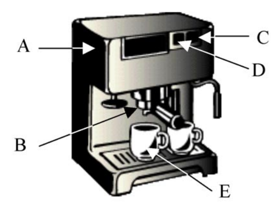

Figure 1. A typical espresso machine: (A) pressure vessel, (B) portafilter holding ground coffee, (C) on/off switch, with built in pressure indicator, (D) solenoid valve for espresso coffee, (E) cup holding espresso coffee.

Let $\underline{x}$ be a vector of process states, $\underline{y}$ be a vector of measured process outputs, and $\underline{z}$ be a vector of process quality variables or attributes of the manufactured product that needs to meet specifications, which in six-sigma methodology are referred to as *critical-to-quality* (CTQ) variables. In the framework of integrated product/process design and control, the degrees of freedom that are available to meet the CTQ targets are $\underline{u}$, a vector of manipulated variables, $\underline{d}$, a vector of uncontrolled, but possibly measurable, disturbances, and $\underline{\theta}$, a vector of design variables. The relationship between these variables is commonly expressed as follows:

$$\dot{\underline{x}} = \underline{f}\left\{\underline{x},\underline{u},\underline{d},\underline{\theta}\right\} \quad (1)$$

$$\underline{y} = \underline{g}\left\{\underline{x},\underline{u},\underline{d},\underline{\theta}\right\} \quad (2)$$

$$\underline{z} = \underline{h}\left\{\underline{x},\underline{u},\underline{d},\underline{\theta}\right\} \text{ or } \underline{z} = \underline{h}'\left\{\underline{y}\right\} \quad (3)$$

Note that Eq. (3) implies that the CTQ variables can be expressed either in terms of the process states, inputs and process parameters, or, more commonly, in terms of the process outputs. More generally, the process/product design involves not only the selection of continuous parameters, such as the steam pressure and total surface area of the coffee filter in the novel espresso machine, but also the structure of the product or process itself, commonly expressed mathematically in terms of binary operators. For the design of the espresso machine, these parameters could represent alternative configurations of the steam generation device or whether to permit one or two coffee filters to be positioned in the machine.

Traditionally, integrated process design and control has focused on the optimization of the parameters of the synthesized process and its desired operating point to minimize an objective function, formally defined as the nonlinear programming (NLP) problem:

$$\max_{\underline{d}\in \boldsymbol{D}} \min_{\underline{u}\in \boldsymbol{U},\underline{\theta}} J_2\left\{\underline{x},\underline{u},\underline{d},\underline{\theta}\right\}$$

Subject to:

$$\begin{aligned} &\dot{\underline{x}} = \underline{f}\left(\underline{x},\underline{u},\underline{d},\underline{\theta}\right) \\ &\underline{y} = \underline{g} \\ &\underline{y} \in \boldsymbol{Y} \\ &\underline{z} = \underline{h}\left\{\underline{x},\underline{u},\underline{d},\underline{\theta}\right\} \\ &\underline{z} \in \boldsymbol{Z} \end{aligned} \quad (4)$$

Here, the constraints are the state and output equations, as well as the CTQ variables. This NLP permits the simultaneous design of the process and its control system, subject to worst-case disturbance scenarios. Note that this formulation supports the definition of a partial control strategy, where the output variables are required to lie inside a hypercube, ***Y***, rather than meet specific setpoints. Eq. (4) can also be formulated in the steady-state mode, by expressing the first constraint in its stationary form.

In practice, however, the ability to hold the output variables within a prescribed hypercube is of limited interest, and, in general, is required only to ensure the stability of the process. Of greater interest is the need to meet CTQ requirements, implying the appropriate definition of the *y*-space hypercube in which the *z*-space meets the desired sigma level of the process.

This paper illustrates the amalgamation of integrated design and control with six-sigma methodology (Rath and Strong, 2000) in the manufacture of a novel espresso machine. As will be shown, the product quality, and more importantly, loss of quality and its cost, is quantified utilizing six-sigma methodology and its statistical tools. This exposes the most important sources of variance, to be eliminated or attenuated by appropriate redesign of the manufacturing process and its control system.

Six-sigma Methodology in Product Manufacturing

Cost of Defects

Six-sigma (6σ) is a structured methodology for eliminating defects, and hence, improving product quality in manufacturing and services. The methodology aims at identifying and reducing the variance in product quality, and involves a combination of statistical quality control, data-analysis methods, and the training of personnel. As described in detail in Seider et al (2004) and summarized in Figure 2, the sigma level of a process decreases with increasing product variance, as reflected by increased defects per million opportunities (DPMO). Note that defects can generally occur both above the upper control limit (UCL) and below the lower control limit (LCL).

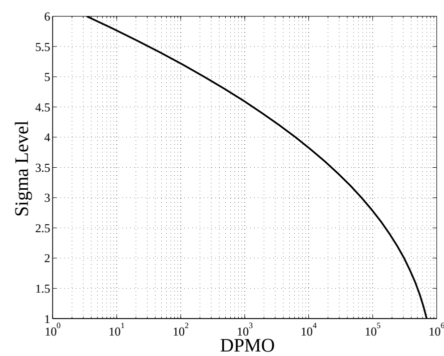

Figure 2. The relationship between DPMO and the sigma level

Although originally developed for the analysis of product manufacturing, it is also easy to compute the sigma level for a continuous process. For example, suppose that, on average, the primary product from a distillation column fails to meet its specifications during five hours per month of production. The sigma level for this process is computed by first estimating the DPMO:

$$\text{DPMO} = 10^6 \times \frac{5}{30 \times 24} = 6{,}944$$

Figure 2 gives the sigma level for this DPMO as 3.8. If improved operations were to reduce the specification violations to 0.5 hour per month, the DPMO would be reduced by a factor of 10, leading to an increase in the sigma level to 4.7. The increased sigma level is a consequence of the reduction in the variance in the CTQ variable, brought about by improved operation of the column, possibly achieved by enhancements to the process design and/or its control system.

The expected number of defects presented in Figure 2 applies to a single manufacturing step. Usually, the manufacture of devices involves a number of steps. For *n* steps, and assuming that all defective components of the device are removed from the production sequence at the step where they occur, the overall defect-free throughput yield, TY, is:

$$TY = \prod_{i=1}^{n}\left(1-\frac{\mathrm{DPMO}_i}{10^6}\right), \qquad (5)$$

where DPMO_i is the expected number of defects per million opportunities in step i. The fraction of the production capacity lost due to defects is 1 – TY. For example, consider the manufacture of a device involving 40 steps, each of which operates at 4σ. From Figure 2, the expected DPMO is 6,210 per step, so TY = $(1 - 0.00621)^{40}$ = 0.779. Thus, 22% of production capacity is lost due to defects, rendering the overall manufacturing operation a 2.3σ process. In contrast, if each of the 40 steps operate at 6σ, TY = $(1 - 3.4/10^6)^{40}$ = 0.99986, corresponding to about one faulty device for every 10,000 produced, and in this case, the overall operation is a 5.2σ process.

In the preceding discussion, it has been assumed that defective devices are eliminated in production, resulting only in reduced throughput yield. In the likely event that a fraction of the defects are undiscovered and lead to shipped devices that are faulty, the impact on sales resulting from customer dissatisfaction could be much greater. Noting that many manufacturing operations involve hundreds of steps (e.g., integrated-circuit manufacturing), it is clear that high levels of reliability, as expressed by low DPMO values, are required to ensure profitable manufacture. This is the driving force behind the extensive proliferation of six-sigma methodology.

Methods to Monitor and Reduce Variance

As described in detail by Rath and Strong (2000), an iterative five-step procedure is followed to progressively improve product quality. The five steps are: (a) Define, (b) Measure, (c) Analyze, (d) Improve, and (e) Control, referred to by the acronym, DMAIC:

(a) **Define**: First, a clear statement is made defining the intended improvement. Next, the project team is selected, and the responsibilities of each team member assigned. To assist in project management, a map is prepared showing the suppliers, inputs, process, outputs and customers (referred to by the acronym, SIPOC). A simplified block diagram usually accompanies a SIPOC, showing the principal steps in the process. At this stage, the main focus is on customer concerns, which are used to define critical-to-quality (CTQ) output variables.

As an example, Figure 3 shows a SIPOC for the preparation of espresso coffee. The quality of the coffee is considered to be the principal CTQ, and customer specifications define the LCL and UCL. Note that the control chart in Figure 4 identifies conditions under which acceptable coffee is prepared, which are constrained into a relatively tight operating window delineated by between 18-22% extraction of solubles, and a solubles concentration of between 1.15-1.35% (Sivetz and Desrosier, 1979).

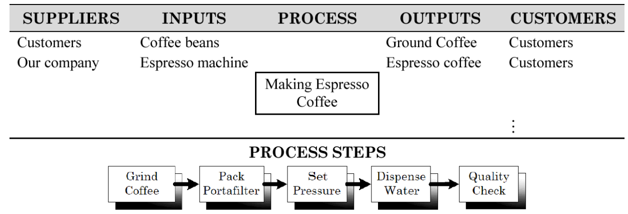

Figure 3. A SIPOC for the preparation of espresso coffee.

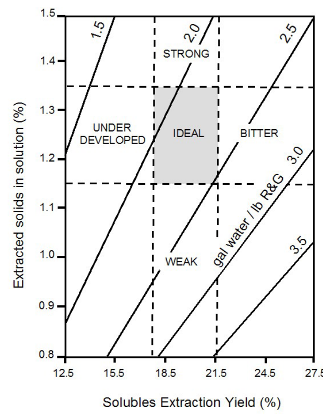

Figure 4. Coffee brewing control chart (developed by the Coffee Brewing Institute).

(b) **Measure**: The CTQ variables are monitored to check their compliance with the LCLs and UCLs. Most commonly, univariate statistical process control (SPC) techniques, such as the Shewart chart, are utilized. The data for the CTQ variables are analyzed and used to compute the DPMO and the sigma level of the process using Figure 2.

Returning to the espresso example, suppose this analysis indicates that using the existing machine, one cup in three on average has attributes that are outside the ideal operating window in Figure 4, indicating operation at lower than 2σ, with a target to reduce this to one in 250, that is, to attain 4σ performance.

(c) **Analyze**: When the sigma level is below its target, steps are taken to increase it, starting by defining the most significant causes for the excessive variability. This is assisted by a systematic analysis of the sequence of steps in the manufacturing process, and the interactions between them. Using this analysis, the common root cause of the variance is identified.

Continuing the espresso example, note that several factors contribute to an excessively high variance in product quality (llly, 2002; Sivetz and Desrosier, 1979):

(1) *Freshness of the ground coffee*. If the coffee is too stale, the taste of the coffee is affected.

(2) *Grade of the ground coffee*. If too coarse, the leaching is insufficient, affecting the taste of the coffee. If the coffee is ground too fine, the pressure drop across the packed grinds is too high, affecting the leaching detrimentally, and producing harsh bitter flavors.

(3) *Ground coffee packed evenly in the portafilter, to the correct degree*. The brew water finds the path of least resistance through the coffee. Uneven packing leads to channeling, in which the coffee in and in the proximity of the channels is over-extracted, and under-extracted elsewhere, resulting in a bitter and astringent beverage.

(4) *Correct amount of coffee loaded*. Insufficient coffee leads to over-extraction and to flat and watery espresso.

(5) *Sufficiently high water pressure*. This controls the temperature at which the leaching takes place.

(6) *Proper amount of water passed though the ground coffee*. As indicated in Figure 4, the degree of extraction is critical to ensure an acceptable product.

(7) *Quality of the water*. Since espresso coffee is 99% water, poor quality of the water used to extract the coffee (e.g. chlorination, organic content, hardness, alkalinity) has a detrimental effect on the quality of the product (Sivetz and Desrosier, 1979).

The reduction of all of the above sources of variance constitutes the main design challenge.

(d) **Improve**: Having identified the common root cause of variance, it is eliminated or attenuated by redesign of the manufacturing process or by employing process control.

For the espresso example, there are several solutions to reducing the sources of variance identified above. Equipping the espresso machine with a water filter reduces the variance in item (7). In some machines, a solenoid valve is installed to dispense a precise amount of water, thus attenuating the variance in item (6). Furthermore, increasing the degrees-of-freedom in the design by installing a pressure-control loop, ensures that the pressure is maintained between its required UCL and LCL, resolving item (5). Note, however, that items (1) to (4) constitute sources of variance that are not under the control of the manufacturer of the espresso machine, as described in the introduction. To eliminate these four sources of variance, the manufacturer of a novel espresso machine provides its users with vacuum-sealed containers of ground coffee having a built-in filter. On insertion into the machine, the container is perforated and used to prepare a single cup of coffee. Since the containers are vacuum-sealed, this ensures that the ground coffee is fresh, reducing the variance of source (1). The capsules of coffee need to be manufactured by a process with a high enough sigma level to ensure that items (2) and (4) are satisfied. Instead of relying on suitable packing of the ground coffee in the portafilter, a fixed flow resistance is installed in the portafilter to ensure the correct degree of coffee extraction, thus taking care of item (3). Moreover, the manufacturer controls the coffee supply, and consequently, the annual sales of coffee containers are likely to far exceed that of the machines.

(e) Control: After implementing steps to reduce the variance in the CTQ variable, the results are evaluated, and possible further improvements are considered. Thus, steps (b) to (e) in the DMAIC procedure are repeated to improve process quality in a stepwise fashion.

For the espresso example, it is evident that a manufacturer of espresso machines would not necessarily implement all of the alternatives identified previously for the reduction of CTQ variable variance, but rather, it would introduce first either the most practical, or the cheapest, or those with greatest impact.

Conclusions

This paper has introduced the potential advantages of combining six-sigma methodology, to quantify and assure product and process quality, with integrated design and control. As shown in the first example, this design methodology benefits from the analysis techniques of process system engineering, through integrated design and control procedures, that reduce the variance in the critical-to-quality variables by exploiting, and when necessary, increasing, the process degrees of freedom. While traditionally, product manufacturing has relied solely on statistical process control, the trend to improve profitability through increasing yields is driving many industries to embrace six-sigma methodology and advanced control strategies.

References

Illy, E. (2002). The Complexity of Coffee, Scientific American, June 2002, 72-77.

Rath and Strong (2000). *Six Sigma Pocket Guide*, Rath and Strong Management Consultants/AON Management Consulting, Lexington, Massachusetts.

Seider, W. D., J. D. Seader and D. R. Lewin (2004). *Product and Process Design Principles*, John Wiley and Sons, New York.

Sivetz, M. and N. W. Desrosier (1979). *Coffee Technology*, AVI Publishing Co., Westport.