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A PRODUCIBILITY MEASURE FOR QUALITY CHARACTERISTICS WITH DESIGN SPECIFICATIONS

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Key Words

Producibility; Multiple quality characteristics; Process capability indices; Geometric mean; Product/process design; Classification of quality characteristics; Manufacturing cost; Meal-Ready-to-Eat pouches.

Introduction

A product life cycle consists of three phases: product/ process design, actual production, and postproduction service and support. Traditionally, the early design phase of a product rarely interacts with the other phases. However, the actual production and the after-sale customer service are phases that actually constitute the major cost of a product during its life cycle. Consequently, a product design that does not integrate these phases often requires additional redesigns due to manufacturing cost, variations in product quality, and excessive postproduction support. *Producibility* is a measure of the desirability of a product and process design in terms of the consistency of quality and the economy of production (1). The purpose of this article is to develop a producibility vector which takes into account both the quality and cost requirements of the product.

Although several types of process capability indices are extensively explored and are well summarized in Ref. 2, it appears that Harry and Lawson (3) were the first to work on the producibility research which considers the process capability indices. Their work was later included in the *Producibility Measurement Guidelines* by the Department of the Navy (4). However, Harry and Lawson's work does not consider the global aspects of multiple quality characteristics and the manufacturing cost. In this article, we incorporate both the process capability and the manufacturing cost into a producibility vector.

The quality characteristics of a product need to be clearly defined before performing process capability studies. In most cases, products have more than one important characteristic. Furthermore, there may exist interactions among different characteristics which make process capability difficult to evaluate. In this article, we consider products with multiple quality characteristics. We classify quality characteristics of a product into three categories: critical, major, and minor (5). Each one has a different effect on the product's functionality. Based on this classification, we develop a measure of the process capability for multicharacteristic products.

Manufacturing cost is also an important factor which is considered in the producibility measure. Recent work on quality attempted to represent product quality in terms of cost by developing a cost-objective function to be minimized. However, product quality is difficult, if not impossible, to assess accurately in terms of cost, as poor product quality not only diminishes customers' goodwill, which is already difficult to measure, but also causes loss to the entire society (6).

In this article, we develop a producibility vector which includes both the process capability indices and the manufacturing cost per unit of production.

Producibility: Elements and Definitions

We explain the categories of the quality characteristics and the manufacturing cost to develop the producibility vector.

Classification of the Quality Characteristics

We classify product characteristics into the following three categories (5):

Critical: Those characteristics that could cause damages to human, environment, or any irrecoverable impact when the corresponding specifications are violated

Major: Those characteristics that cause the product to malfunction but do not cause damages as critical characteristics do when the corresponding specifications are violated

Minor: Those characteristics that diminish the product's usability while not causing damages and malfunctioning as critical and major characteristics do when the corresponding specifications are not met

Each quality characteristic under consideration is assigned to one of these mutually exclusive categories.

Manufacturing Cost

There are several cost elements that should be taken into account in order to estimate accurately the manufacturing cost per unit. They include production efficiency, raw materials, personnel, capital and equipment, and utilities. These cost elements can serve as a guideline for manufacturing cost estimation. Because other relevant elements might be included, the user of the producibility vector should develop an appropriate manufacturing cost estimation for his/her manufacturing environment (7).

Producibility Vector

We develop a producibility vector that includes measures of the process capability and the manufacturing cost as related to the design of the product and its processes. We first present the vector, then demonstrate step-by-step procedures for evaluating its elements. The proposed five-element producibility vector is expressed as

$$PV = [PCI_{critical}, PCI_{major}, PCI_{minor}, PCI_{overall}, MC],$$

where

PCI	=	process capability index
$PCI_{critical}$	=	minimum value of the calculated PCIs for all critical characteristics
PCI_{major}	=	minimum value of the calculated PCIs for all major characteristics
PCI_{minor}	=	minimum value of the calculated PCIs for all minor characteristics

$\mathrm{PCI}_{\mathrm{overall}}$ = overall process capability index of all quality characteristics; the weighted geometric mean of PCIs for all quality characteristics
MC = manufacturing cost per unit of production

The process capability index (PCI) can be estimated using C_p, C_{pk}, C_{pm}, or C^*_{pm}, dependent on the situation and the needs of the study (2). However, it should be noted that once an adequate index is chosen for a particular quality characteristic, the same index should be used throughout for calculations related to the same characteristic. This is very important, especially when conducting comparative producibility studies for different product and process designs.

As indicated, the first three elements are the minimum PCIs for the three types of quality characteristics. We choose the minimum PCI value for each type of characteristic, because a low PCI value for any one quality characteristic will result in the rejection of the product/process design, regardless of the PCI values of other characteristics.

Windham (8) suggests a weighted arithmetic mean of the capability indices of all characteristics as a measure of the overall performance of the quality characteristics. The three different types of quality characteristics should be weighted according to the relative importance of the characteristics. We choose a weighted geometric mean of all PCIs to calculate the overall quality performance of the product, as the geometric mean is more sensitive than the arithmetic mean to small values. This is desirable because a smaller PCI value diminishes producibility considerably. This index is useful for selecting better product/process design after screening poor designs with a low $\mathrm{PCI}_{\mathrm{critical}}$ or $\mathrm{PCI}_{\mathrm{major}}$ value.

In implementing the producibility vector, the producer may wish to emphasize the role of PCIs relative to the manufacturing cost, because high quality is demanded and low cost is expected (4).

Suppose a product has n quality characteristics; n_1 are critical; n_2 are major; and n_3 are minor; that is;

- Critical characteristics: $X_1, X_2, \ldots, X_{n_1}$
- Major characteristics: $Y_1, Y_2, \ldots, Y_{n_2}$
- Minor characteristics: $Z_1, Z_2, \ldots, Z_{n_3}$
- $n = n_1 + n_2 + n_3$

The PCI for each category of characteristics is calculated as

$$\mathrm{PCI}_{\mathrm{critical}} = \min_{1\le i\le n_1}\{\mathrm{PCI}_{X_i}\},$$

$$\mathrm{PCI}_{\mathrm{major}} = \min_{1\le i\le n_2}\{\mathrm{PCI}_{Y_i}\},$$

$$\mathrm{PCI}_{\mathrm{minor}} = \min_{1\le i\le n_3}\{\mathrm{PCI}_{Z_i}\}.$$

In order to calculate the weighted geometric mean of the PCI values for all characteristics, we assign weights to each type of characteristic. We use w_1, w_2, and w_3 to represent the relative importance for critical, major, and minor characteristics, respectively. The weight ratio can be assigned by consensus with the practitioners based on their needs and situations in the early stage of product/process design. Derringer (9) advises that the weight ratio can be best assigned from the consensus meeting in the early stage of product and process design. The overall PCI is obtained as

$$\begin{aligned}\mathrm{PCI}_{\mathrm{overall}} &= \left[\left(\mathrm{PCI}_{X_1}\cdots\mathrm{PCI}_{X_{n_1}}\right)^{1/n_1}\right]^{w_1/\Sigma w_i}\left[\left(\mathrm{PCI}_{Y_1}\cdots\mathrm{PCI}_{Y_{n_2}}\right)^{1/n_2}\right]^{w_2/\Sigma w_i} \\ &\quad\times\left[\left(\mathrm{PCI}_{Z_1}\cdots\mathrm{PCI}_{Z_{n_3}}\right)^{1/n_3}\right]^{w_3/\Sigma w_i} \\ &= \left[\left(\mathrm{PCI}_{X_1}\cdots\mathrm{PCI}_{X_{n_1}}\right)^{w_1/n_1}\left(\mathrm{PCI}_{Y_1}\cdots\mathrm{PCI}_{Y_{n_2}}\right)^{w_2/n_2}\right. \\ &\quad\left.\times\left(\mathrm{PCI}_{Z_1}\cdots\mathrm{PCI}_{Z_{n_3}}\right)^{w_3/n_3}\right]^{1/\Sigma w_i}.\end{aligned}$$

Examples

In this section, we use the processes designed for producing Meal-Ready-to-Eat (MRE) pouches as examples to demonstrate the proposed producibility vector. The quality specifications of the MRE pouches are given in a series of military standard documents. We are particularly interested in the production of beef stew and ham slice MRE pouches (10,11).

Beef Stew Pouches

A beef stew pouch has three components: beef cubes, gravy, and vegetables. The proportion of these components and the minimum weight requirements are given in Ref. 10. For example, the military standards specify minimum weight requirements for the net weight of the pouch and drained weights for beef and vegetables. There are specifications for the fat content, the salt content, and the connective tissue in the beef. In addition to the finished product specifications, an in-process specification is provided and it should be kept during production. For example, the maximum net weight (e.g., 250 g) is a critical factor on which the thermal process is based to ensure thorough sterilization of the food pouches. Although this requirement is not listed as one of finished product specifications, it is certainly an important in-process specification which ensures the final weight requirements. We summarize the military specifications (10) as follows:

Net Weight: Individual pouch ≥ 212.6 g
Average of 20 pouches ≥ 226.7 g
Individual pouch ≤ 250 g*
Beef Drained Weight: Individual pouch ≥ 56.7 g
Average of 20 pouches ≥ 68.0 g
Vegetable Drained Weight: Individual pouch ≥ 34.0 g
Average of 20 pouches ≥ 45.3 g
Salt Content: $0.5\% \leq$ individual pouch $\leq 1.8\%$
Connective Tissue: ≤ 10.0 g

Among the specifications of the quality characteristics, the maximum net weight is the only one that is considered *critical* because any pouch exceeding the maximum weight could cause a failure of the thermal sterilization process and may subsequently threaten the user's health. The remaining quality characteristics specifications, including the minimum net weight requirement for the net weight, are considered *major*, except the connective tissue which is regarded as *minor*. It is interesting to observe that the above specifications are somewhat different from usual specifications. For the net and drained weights, there are not only specifications for individual pouch but also for the average of a sample of 20 pouches. To calculate the PCI value for the minimum net weight, we take the minimum value of the PCI values for the individual and the average specifications. For example, the PCI value for the net weight minimum requirement is calculated as

$$\mathrm{PCI}_{\mathrm{min\_net}} = \min\left[\frac{T_{\mathrm{net}} - 212.6}{3\hat{\sigma}_{\mathrm{net}}};\ \frac{T_{\mathrm{net}} - 226.7}{3\hat{\sigma}_{\mathrm{net}}/\sqrt{20}}\right],$$

where the first term in the brackets of the right-hand side is the lower specification for the individual pouch and the second term is for the "average of 20" pouches. T_{net} is the target fill weight of beef stew and $\hat{\sigma}_{\mathrm{net}}$ is the estimated standard deviation of the individual pouch net weight. In a similar manner, we calculate the PCI values for other quality characteristics.

It can also be observed that for the minimum weight requirement, one cannot indefinitely increase the PCI values by increasing the target fill weight. If the target fill weight is increased, the manufacturing cost will increase because of the additional raw material required. For the net weight specifications, increasing the PCI value for the minimum net weight requirement also diminishes the PCI value for the maximum net weight requirement, which is a critical quality characteristic. The proposed producibility measure will clearly demonstrate these trade-offs. Before we calculate the producibility measure, we first determine the relationships among the ingredients of the beef stew and the effects of the ingredient fill weights on the contents of connective tissue and salt. The beef stew is made of three ingredients: gravy, beef, and vegetables. There are three target fill weights that can be chosen by the manufacturer: target pouch fill weight, target beef fill weight, and target vegetable fill weight. Once these three fill weights are determined, the product characteristics are then calculated as

Gravy fill weight
= (Target pouch fill weight) - (Target beef fill weight) - (Target vegetable fill weight),

Target beef drained weight
= (Beef retort yield)(Target beef fill weight)
= (85%)(Target beef fill weight).

The retort process requires heating the pouch to 250°C for a specified time to ensure its safety for human consumption.

Target vegetable drained weight
= (Vegetable retort yield)(Target vegetable fill weight)
= (135%)(Target vegetable fill weight),

Target salt content (%)

$$= 100\%\,\frac{(1.23\%)(\text{Target gravy fill weight}) + (2.36\%)(\text{Target beef fill weight})}{(\text{Target pouch fill weight})},$$

Target weight of connective tissue
= 6.5%(Target beef drained weight).

We conduct experiments to estimate the standard deviation for each quality characteristic. The results are shown in Table 1. It is found that changes in the target fill weights have no effect on the estimated standard deviations for the listed quality characteristics. We now study two sets of the target fill weights shown in Table 2.

In the actual production, the mean values of the quality characteristics can be adjusted to be equal to the corresponding target values. The calculated PCI values are shown in Table 3. The results in Table 3 are demonstrated by calculating two PCI values for design A as follows:

$$\mathrm{PCI}_{\mathrm{max\_net}} = \frac{\mathrm{USL} - T}{3\hat{\sigma}} = \frac{250 - 232}{3(4.57)} = 1.313,$$

$$\mathrm{PCI}_{\mathrm{min\_net}} = \min\left[\frac{232 - 212.6}{3(4.57)};\ \frac{232 - 226.7}{3(4.57)/\sqrt{20}}\right] = 1.415.$$

*In-process specification.

Table 1. Estimated Standard Deviation of the Quality Characteristics for the Beef Stew Pouches

QUALITY CHARACTERISTIC	ESTIMATED STANDARD DEVIATION
Net weight (g)	4.57
Beef drained weight (g)	4.45
Vegetables drained weight (g)	8.33
Salt content (%)	0.107
Connective tissue (g)	0.507

Table 2. Target Fill Weights for the Beef Stew Pouches

DESIGN	POUCH FILL WEIGHT	BEEF FILL WEIGHT	VEGETABLE FILL WEIGHT
A	232 g	85 g	51 g
B	231 g	87 g	49 g

Table 3. PCIs for the Beef Stew Pouches

	CRITICAL	MAJOR				MINOR	
DESIGN	MAX. NET WEIGHT	MIN. NET WEIGHT	BEEF DRAIN WEIGHT	VEGET. DRAIN WEIGHT	SALT CONTENT	CONNECT. TISSUE	UNIT COST
A	1.313	1.415	1.165	1.395	1.328	3.487	1.192
B	1.386	1.342	1.292	1.287	1.263	3.414	1.199

We can now calculate the elements of the producibility vector. Again, we use design A as an example:

$$PCI_{critical} = \min[1.313] = 1.313$$
$$PCI_{major} = \min[1.415,\ 1.165,\ 1.395,\ 1.328] = 1.165$$
$$PCI_{minor} = \min[3.487] = 3.487$$

To calculate the overall PCI, we use the relative importance ratio 6 : 3 : 1 based on discussion with the producer of the pouches. Thus,

$$PCI_{overall} = [(1.313)^6(1.415 \times 1.165 \times 1.395 \times 1.328)^{3/4} \times (3.487)^1]^{1/10} = 1.451.$$

Table 4 shows the producibility measures for designs A and B. The last entry of the measure represents the manufacturing cost per pouch. Details of the manufacturing cost calculations are beyond the scope of this article. From Table 4, design B shows a better producibility measure than design A, because design B has higher PCI values for the critical and major characteristics and for the overall performance than design A, and a large (greater than 3) PCI value for minor characteristics, whereas the manufacturing costs for the two designs are almost equal.

Ham Slice Pouches

Similar to the above example, we evaluate different filling and slicing designs for the production of ham slice pouches. There are four different design settings:

A: Hand Fill, Automatic Slicing
B: Hand Fill, Automatic Slicing/Sizing
C: Robot Fill, Automatic Slicing
D: Robot Fill, Automatic Slicing/Sizing

Table 4. Comparison of the Producibility Between Two Designs for the Beef Stew Pouches

DESIGN	PV $[PCI_{critical}, PCI_{major}, PCI_{minor}, PCI_{overall}, MC]$
A	[1.313, 1.165, 3.487, 1.451, 1.192]
B	[1.386, 1.263, 3.414, 1.487, 1.199]

Table 5. Yields, Inspection Efficiency, and Proportion Defective for the Ham Slice Pouches

DESIGN	$Yield_{first}$	$Yield_{second}$	INSPECTION EFFICIENCY	PROPORTION DEFECTIVE	PCI_{defect}
A & B	96.3%	99%	99%	4.71%	1.067
C & D	94.4%	99%	99%	6.61%	0.745

There are two filling designs: hand fill and robot fill. Two workers are required to place ham slices into the open pouches in order to meet the line speed of 60 pouches/min. When a robot is used to place the ham slices, it requires no workers. For both hand fill and robot fill, two workers are required to unpack the ham boxes and place the ham loafs on the slicer. These two workers are also responsible for sorting out broken slices or slices with unsatisfactory air pockets.

There are also two different designs for the ham slicing process. In the first design, the automatic slicing device cuts off ham slices from the ham loaf. In the second design, the slicer is also equipped with a sizing device that cuts off the surface of the ham loaf to obtain more consistent shapes and weights of ham slices. The second design, however, increases the raw material cost by 10 cents per pound filled.

Ham slice pouches are subjected to two 100% inspections: one before and the other after the retort process. The robot appears to produce more defective pouches. This is due to the inaccruracy of the robot arm. The target fill weight for the slicing device is higher than the slicing/sizing device because the variations in the net weight and drained weight are higher without sizing. We assume the inspections to be 99% effective; that is, among 100 defective pouches, 99 of them will be sorted out by the two inspections. Proportion defective (%) of finished pouches is calculated using the following formula:

$$\text{Proportion defective (\%)} = (1 - \text{Yield}_{\text{first}} \times \text{Yield}_{\text{second}}) \times \left(\frac{1}{\text{Inspection effectiveness}}\right) \times 100\%,$$

where $Yield_{first}$ is the yield from the first 100% inspection and $Yield_{second}$ is the yield from the second 100% inspection. The results obtained from the experiments are shown in Table 5.

Because the pouch defective is an attribute characteristic, we cannot use the usual capability indices to estimate the producibility vector. Instead, we use a modification of the odds ratio proposed by Kotz and Johnson (2). Let the upper bound of the proportion defective be $w_u = 0.05$. We propose a process capability index for the pouch defective as

$$PCI_{defect} = \frac{w_u/(1 - w_u)}{w/(1 - w)},$$

where w is the actual proportion of the pouch defective. The PCI_{defect} for both designs A and B is

$$\frac{0.05/(1 - 0.05)}{0.047/(1 - 0.047)} = 1.067.$$

The PCI_{defect} for all designs are shown in the last column of Table 5. Because the PCIs for designs C and D are less than 1, designs C and D are not acceptable filling and slicing designs.

The target value for the net weight is 150 g and for the drained weight is 127.5 g. The specifications for the net weight and the drained weight of the ham slice pouches (11) are

Net Weight:	Individual pouch	≥113.4 g
	Average of 20 pouches	≥127.6 g
	Individual pouch	≤ 180 g (in-process specification)
Drained Weight:	Individual pouch	≥ 102.1 g
	Average of 20 pouches	≥107.7 g

Again, we conduct experiments to collect data for estimating the standard deviations. The results are shown in Table 6.

Based on the above specifications and estimated standard deviations, we calculate the PCI values as given in Table 7.

Table 6. Estimated Standard Deviations of the Quality Characteristics for the Ham Slice Pouches

DESIGN	NET WT. S.D.	DRAINED WT. S.D.
A & C	7.795	7.692
B & D	3.199	5.851

Table 7. PCI Values for the Ham Slice Pouches

	CRITICAL		MAJOR		
DESIGN	MAX. NET WT.	POUCH DEFECT	DRAIN WT.	MIN. NET WT.	UNIT COST
A	1.283	1.098	1.101	1.565	1.389
B	3.126	1.098	1.447	3.814	1.422
C	1.283	0.745	1.101	1.565	1.424
D	3.126	0.745	1.447	3.814	1.443

Table 8. Comparison of the Producibility of Four Designs for the Ham Slice Pouches

DESIGN	PV [$PCI_{critical}$, PCI_{major}, PCI_{minor}, $PCI_{overall}$, MC]
A	[1.098, 1.101,—, 1.227, 1.389]
B	[1.098, 1.447,—, 2.005, 1.422]
C	[0.745, 1.101,—, 1.079, 1.424]
D	[0.745, 1.447,—, 1.762, 1.443]

We use the importance ratio 2 : 1 between the critical and major characteristics based on a consensus meeting with the producer of the pouches to calculate the overall PCIs for the designs. The producibility indices and the manufacturing costs for the designs are shown in Table 8. From this table, design B, which requires hand fill with slicing/sizing, appears to be the best design, as it dominates other designs in terms of PCIs and has a manufacturing cost only 3.3 cents higher than design A, which is second best. As mentioned earlier, designs C and D cannot be selected, as their PCI values for critical characteristics are less than 1.

Conclusions

This article develops a producibility vector which assesses the producibility of a product/process design with given specifications in terms of process capability and manufacturing cost. Quality characteristics are classified into three categories according to their relative importance and the PCI for each category is calculated. As an overall measure of the product/process design performance, we propose $PCI_{overall}$, which is the weighted geometric mean of the PCIs for all quality characteristics. Manufacturing cost is also considered and is included as the fifth element of the producibility vector. The vector can be used for determining a good design which has high process capability and low manufacturing cost. We demonstrate the application of this vector to the production of beef stew and ham slice pouches.

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