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MATHEMATICAL MODELLING FOR THE COST OF QUALITY: A CASE OF STEEL PLANT ACTIVITIES

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Abstract

Quality has become the measure of overall performance and global competence, and high quality process performance is becoming of crucial importance in the manufacturing sector. All quality improvement programs aim for customer satisfaction at the optimum cost. For this, a realistic estimate of cost of quality (COQ); the overall costs of producing quality products is essential. COQ analysis enables organizations to capture and eliminate the consequences of poor quality. But many of the organizations do not use it effectively due to the lack of an efficient COQ tracking system. This paper presents a mathematical model for the estimation of COQ per unit product with a specific quality level. A case study, carried out in a steel plant in India, based on process interruptions such as breakouts in continuous casting of steels is presented. The economic importance of opportunity losses is emphasized.

Keywords: Cost of Quality (COQ), COQ models, Opportunity costs, Continuous casting of steels, Case Study

1. Introduction

Quality is one of the best sources of competitive advantage and many manufacturing companies promote quality as the central customer value [1]. The goal of continuous improvement programs is to meet customer needs at the lowest cost. To achieve this goal, the COQ; costs required to attain quality, must be identified, measured and reduced. Companies can lose money because they fail to use significant opportunities to reduce their COQ [2], [3] [4]. Generally, COQ is understood as the sum of conformance plus non-conformance costs, where cost of conformance is the price paid for prevention of poor quality such as inspection and quality appraisal, and cost of non-conformance is the cost of poor quality caused by product and service failure such as rework and returns [5], [6]. The objective of a COQ process is to capture the total value of poor quality in the organization and provide a vehicle that justifies the elimination of poor quality [7]. A realistic estimation of COQ is an essential element of any quality initiative [8]. However, only a minority of organizations follows formal COQ approaches because quality costs are hard to measure. This paper presents a mathematical model for the estimation of COQ, with a specific quality level, applied to a continuous casting steel plant. The significance of opportunity losses is emphasized.

2. COQ background

The concept of quality costs was first mentioned by Juran and denoted as the cost of poor quality [9]. According to Crosby, COQ is the price of nonconformance. COQ refers to the costs associated with providing poor quality product or service to the customers and it may range from 15%-30% of business costs [10].

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2.1 Categorization of COQ

1. *Prevention costs*: Costs incurred to prevent poor quality such as quality planning, process reviews and training.
2. *Appraisal costs*: Costs incurred to determine the degree of conformance to quality requirements such as inspection and testing.
3. *Internal failure costs*: Costs associated with defects found before the customer receives the product or service such as scrap, rework and material downgrades.
4. *External failure costs*: Costs associated with defects found after the customer receives the product or service like processing customer complaints, returns and warranty claims.

Opportunity and intangible costs are hidden failure costs that can only be estimated such as profits not earned or revenue lost (e.g. unused capacity and poor delivery of service) [11].

2.2 COQ models

COQ models are classified into four groups.

1. P-A-F models: Prevention costs + Appraisal costs + Failure costs
2. Crosby's model: Cost of conformance + Cost of nonconformance
3. Opportunity or intangible cost models: [Prevention costs + Appraisal costs + Failure costs + Opportunity costs]
4. Process cost models: Cost of conformance + Cost of nonconformance

Most COQ models are based on the P-A-F classification and the basic suppositions of the P-A- F model are that investment in prevention and appraisal activities will reduce failure costs, and that further investment in prevention activities will reduce appraisal costs [12] [13].

3. Continuous casting of steels

Continuous casting, in the steelmaking industry, is the key process (carried out in continuous casting machine) whereby the liquid steel is converted into solid steel such as slab, bloom or billet for subsequent rolling operations in a hot strip mill. During continuous casting, certain difficulties such as process stoppages and product quality problems are encountered. Full economic benefits of continuous casting could be achieved, if the process quality is very high and the process stoppages are kept to a minimum [14].

4. COQ model development

The proposed COQ model is an improvised version of the COQ model developed by Zugarramurdi et.al (2007) for food plants [12]. It consists of two sub-models; the controllable costs sub-model and the consequential costs sub-model [15]. The controllable costs sub-model consists of prevention costs and appraisal costs, and it has six items (Table 1). Each component of the prevention costs is affected by the coefficient 'ζ' and that of the appraisal costs by 'ξ' for different quality levels.

Table1. Controllable costs sub-model

Controllable costs
Prevention costs
1. Quality planning costs, P_{C_1}
2. Quality training program costs, P_{C_2}
3. Preventive maintenance costs, P_{C_3}
Appraisal costs
1. In-plant inspection and testing costs, A_{C_1}
2. Laboratory analysis costs, A_{C_2}

3. In-process inspection costs, A_{C_3}

The consequential costs sub-model includes the costs of failures (internal and external) and opportunity losses, and it has six components (Table 2). Each component of the internal failure costs and the external failure costs is affected by the coefficients 'β_F' and 'δ_F' respectively and those that of opportunity costs by 'θ_{C_1}'and 'θ_{C_2} for different quality levels [10].

Table2. Consequential costs sub-model

Consequential costs
Internal failure costs
1. Scrap costs, IF_{C_1}
2. Costs of low labour productivity and low process yield, IF_{C_2}
3. Cost of inefficient usage of plant capacity, IF_{C_3}
External failure costs
1. Warranty claims, complaints, returned and recalled products, EF_{C_1}
Opportunity costs
1. Cost of poor delivery service, O_{C_1}
2. Cost of unused capacity, O_{C_2}

The details of the parameters used in the proposed model are given in Table 3.

Table 3. Quality, market and production parameters

Quality parameters
Q_m : Raw material quality (dimensionless parameter)
Q_p : Product quality (dimensionless parameter)
$Y^*_{Q_m}$: Yield for optimum quality level Q^*_m (t product/ t raw material)
$X^*_{Q_m}$: Productivity for optimum quality level Q^*_m (t product/ h-worker)
Z_{cip} : Number of critical inspection points
Market parameters
P_{Q_m} : Purchase price of raw material (Rs/ t)
S_{Q_p} : Selling price for quality level Q_p (Rs/ t)
$S^*_{Q_p}$: Selling price for optimum quality level Q^*_p (Rs/ t)
Production parameters
O : Annual production capacity (t product)
U : Actual annual production (t product)
Q_d : Quantity demanded by the customers (t product)
Q_s : Quantity supplied to the customers (t product)
R_i : Raw material sampling inspection rate (t raw material/ h)
W : Average labour rate for trained workers (Rs/ h) I_F : Total fixed investment (Rs)

X_{Q_m} : Productivity for quality level Q_m (t product/ h-worker)
Y_{Q_m} : Yield for quality level Q_m (t product/ t raw material)
L : Total labour cost (Rs/ t product)
NB: [t- metric tonnes, h- hours, Rs- Indian rupees]

4.1. Controllable costs sub-model

Prevention costs

The most important elements under the prevention costs category for continuous casting steel plants are the following:

1. Quality planning costs, P_{C_1}

These costs include the expenses of designing, developing and implementing quality plan, audit system, quality measurement system and control equipment. It can be estimated as follows:

$$P_{C_1} = \zeta_{P_1} I_F / O \quad (1)$$

The coefficient ζ_{P_1} can be estimated as a percentage of I_F, and it represents about 3–5% of the fixed investment for a steel plant working at very high quality.

2. Quality training costs, P_{C_2}

The costs incurred for formal training and education programmes related to quality comes under this category.

Expression (2) is used to calculate P_{C_2}. The ζ_{P_2} coefficient could be defined as a percentage of total labour cost. For steel plants, the average training cost spent is around 10–20% of the total labour cost.

$$P_{C_2} = \zeta_{P_2} L Q_p \quad (2)$$

3. Preventive maintenance costs, P_{C_3}

The product defects and recalls can be reduced by preventive maintenance. Besides, an additional supervision is followed by preventive maintenance.

To estimate P_{C_3}, expression (3) is used:

$$P_{C_3} = [\zeta_{P_3} I_F / O + \zeta_{P_4} L] Q_p \quad (3)$$

In steel industry, maintenance costs range from 5% to 10% of I_F. Taking into account the additional investment (3–5% of I_F), introduced with expression (1), coefficient ζ_{P_3} resulted as 0.1–0.5% of I_F. The additional supervision cost is estimated as a fixed percentage of direct labour costs (L) and in steel plants it is of the order of 5–10% of L. This cost is introduced in expression (3) by the ζ_{P_4} coefficient.

Appraisal costs

Appraisal costs are the costs incurred for checking the degree of conformance of the products and raw materials.

1. In-plant inspection and testing costs, A_{C_1}

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These are the costs of inspection and testing of incoming material and to the salaries of inspection personnel. A_{C_1} can be computed by the following expression

$$A_{C_1} = (\xi_{A_1} W / R_i Y_{Q_m}) Q_p \tag{4}$$

The analysis of the parameter ξ_{A_1} indicates the inspection activities performed in the actual plan in relation to those that should be done for the ideal quality.

2. Laboratory analysis costs, A_{C_2}

These costs are the costs of testing of purchased raw material, semi-finished or finished products for ensuring quality. These can be estimated as a percentage (about 0-15%) of labour cost (L) as shown in Eq. (5).

$$A_{C_2} = \xi_{A_2} L Q_p \tag{5}$$

3. In-process inspection costs, A_{C_3}

These costs include the costs related to personnel engaged in the in-process evaluation of product conformance to quality requirements. A_{C_3} is a function of the number of critical inspection points (Z_{cip}) and can be estimated as,

$$A_{C_3} = \xi_{A_3} Z_{cip} L Q_p \tag{6}$$

4.2. Consequential costs sub-model

Internal failure costs

The internal failures result from low raw material quality and lack of an adequate quality plan. They are estimated as the decrease in selling price (less quality), labour inefficiency (less productivity) and raw material (less yield) .

1. Scrap costs, IF_{C_1}

These costs include the costs of rejects, wastage, reprocessing and repair due to poor quality. These items also include losses resulting from the difference between an optimum selling price and a reduced price. IF_{C_1} is evaluated by expression (7)

$$IF_{C_1} = (S^*_{Q_p} - S_{Q_p})(1 - Q_p)^2 \tag{7}$$

Where, $S_{Q_p} = \beta_F S^*_{Q_p}$

The coefficient β_F depends on the quality levels.

2. Costs of low labour productivity and process yield, IF_{C_2}

IF_{C_2} include the cost of personnel and idle facilities resulting from product defects, disrupted production schedule, and yield losses due to poor raw material quality.

$$IF_{C_2} = W(1/X_{Q_m} - 1/X^*_{Q_m}) + P_{Q_m}(1/Y_{Q_m} - 1/Y^*_{Q_m}) \tag{8}$$

3. Cost of inefficient usage of plant capacity, IF_{C_3}

This cost is accounted for using poor quality raw material and results in a reduction in production capacity because of the decline in the overall yield.

$$IF_{C_3} = S_{Q_p}(Y^*_{Q_m} - Y_{Q_m}) / Y^*_{Q_m} \tag{9}$$

External failure costs

External failure costs include costs of warranty claims, processing complaints, returned and recalled products. External failure costs, EF_{C_1} can be computed as a percentage of selling price as follows,

$$EF_{C_1} = \delta_F S_{Q_p} \tag{10}$$

The coefficient δ_F differs for different quality levels.

Opportunity costs

1. Opportunity loss due to poor delivery service, O_{C_1}

Cost of lost opportunity due to poor delivery service is the cost of failure in meeting the demand of customers. This can be estimated as a function of the demand and supply of the products as follows,

$$O_{C_1} = [(Q_d - Q_s)/Q_s]S_{Q_p} \tag{11}$$

Where $(Q_d - Q_s)/Q_s = \theta_{C_1}$ (12)

The coefficient θ_{C_1} depends on various quality levels.

2. Opportunity loss due to unused capacity, O_{C_2}

This loss is accounted for the steel plants that are incapable of producing the products due to various reasons and can be computed as follows,

$$O_{C_2} = [(O - U)/O]S_{Q_p} \tag{13}$$

Where $(O - U)/O = \theta_{C_2}$ (14)

The coefficient θ_{C_2} depends on different quality levels.

4.3. Total COQ

The total COQ can be estimated by adding all items of controllable costs sub-model and consequential costs sub-model. Eq. (15) represents the total COQ (COQ_T) per unit of product, as a function of product quality level (Q_p).

$$COQ_T(Q_p) = \sum_{i=1}^{n} P_{C_i}(Q_p) + \sum_{j=1}^{n} A_{C_j}(Q_p) + \sum_{k=1}^{n} IF_{C_k}(Q_p) + \sum_{l=1}^{n} EF_{C_l}(Q_p) + \sum_{m=1}^{n} O_{C_m}(Q_p) \quad \text{Where i,j,k,l,m} = 1,2,\ldots,n \tag{15}$$

5. Case study

The proposed model has been applied to a continuous casting steel plant which produces various steel products with export quality [16]. The plant operates 365 days with a capacity of 3.6 million tonnes of liquid steel per year and faces the problems like downtime due to process interruptions such as breakouts, and sometimes unable to meet the demand of customers, both resulting in opportunity losses.

A relationship between raw material and final product quality was obtained to estimate the costs associated with a specific quality level [17]. The quality characteristics of the input raw materials and the final products were analyzed and the quality range was chosen as 0-1; for the worst (0) to the best quality (1) (Table 4). Eq.16 shows the relationship found between raw material and product quality.

$$Q_p = 0.983Q_m + 0.002 \quad (16)$$

Table 4. Raw material quality level

Quality level	$Q_m \times 100$
Poor	≤ 24
Fairly good	$25-48$
Good	$49-71$
Very good	$72-94$
Extra quality	≥ 95

5.1. Controllable costs

1. Prevention costs

Generally, steel plants need 1% of I_F to plan and implement a quality system. 5% was used for the ζ_{P_1} value corresponding to optimum quality. I_F for a steel plant with 3-4 million tonnes capacity is about 12,000 crores rupees. When the level of product quality is decreased from extra quality to poor, the training costs also decreases. Maintenance cost for the steel plant is estimated at 5-10% of I_F and the coefficient ζ_{P_3} was determined between 3% and 10% of maintenance costs. The maximum value of ζ_{P_4} for additional supervision cost was 10% of the direct labour costs for extra quality.

2. Appraisal costs

The parameter ξ_{A_1} shows the inspection activities performed in the actual plan in connection with the activities that should be done to reach optimum quality, in which case ξ can be as high as 1. About 0.003 tonnes raw material is inspected per hour (R_i) and the average labour rate is Rs 50/h. The number of critical inspection points Z_{cip} in steel plant is taken as 6; at ladle, tundish, during continuous casting, hot rolling, cold rolling and macro analysis.

5.2. Consequential costs

Process yield and labour productivity can be related as a function of raw material or product quality [18]. The linear relationship between yield and product quality for steel plant is found as follows

$$Y_{Q_m} = (14.28Q_p + 27.30) \quad (17)$$

Expression (17) shows the linear relationship between labour productivity and product quality.

$$X_{Q_m} = 0.04197\,Q_p + 0.04631 \quad (18)$$

Raw material price and selling price are estimated as a function of quality. Then, expressions (7) to (14) were used to estimate internal failure costs, external failure costs and opportunity costs.

5.3. Total COQ

The controllable costs, consequential costs, and total COQ per unit of product for different quality levels resulting from the application of the proposed model were estimated and plotted in Figure 1. The optimum COQ is found to be for the product quality level 0.93.

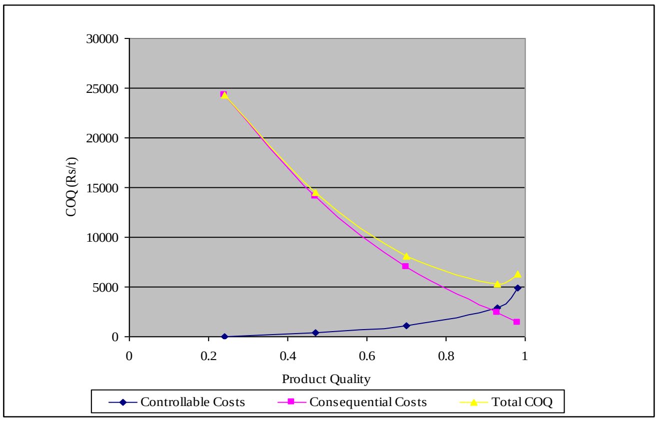

Figure 1. Total COQ, controllable costs and consequential costs as a function of product quality

The proportion of variance accounted for the opportunity cost model and the P-A-F model shown in Figure 2 is observed as 0.252.

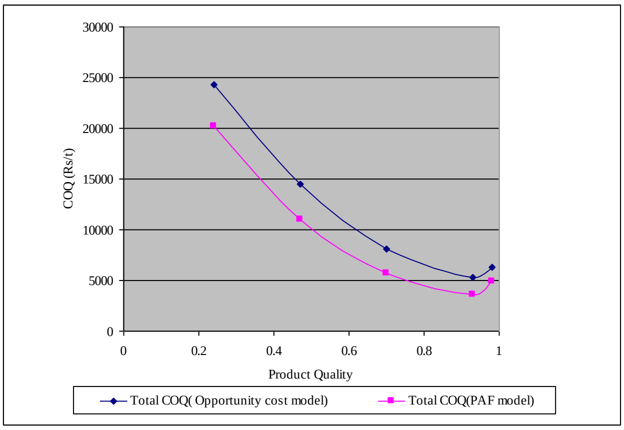

Figure 2. Comparison between PAF model and opportunity cost model

6. Conclusions

A mathematical model to estimate the COQ for a continuous casting steel plant has been proposed. The COQ per unit product has been estimated (by using the proposed model) for a steel plant based on a case study conducted. The economic importance of the opportunity losses is emphasized.

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