ANALYSIS OF QUALITY COSTS FOR STATISTICAL QUALITY CONTROL PLANNING

N. Chiadamrong and C. Thaviwatanachaikul

Sirindhorn International Institute of Technology
Thammasat University, Thailand

ABSTRACT

Quality has become one of the most important force leading to organizational success and company growth in national and international markets. The return-on-investment from strong and effective quality programs is providing excellent profitability results in firms with effective quality strategies. Due to the wide variation in quality results, the search for the genuine keys to success in quality has become a matter of deep concern to management of companies. This paper suggests a way to quantifying quality costs. As a result, the appropriate quality strategies can be adjusted and set to match with each company situation based on the categorization of the quality costs suggested. This outcome can, then, be used as a guideline for manufactures in setting their suitable quality program, which establishes the proper balance between the costs and customer services.

1. INTRODUCTION AND BACKGROUND OF THE PROBLEM

The determination of both quality and quality costs actually takes place throughout the entire industrial circle. This is why real quality control cannot be accomplished by concentrating on inspection, process control or reliability studies alone. Costs of quality or sometimes called "*costs of poor quality*" are defined as those costs associated with the non-achievement of product or service quality as defined by the requirement established by the company and its contracts with customer and society¹. In addition, BS 6143 Part 2² and American Society for Quality Control (ASQC)³ defined them as costs incurred in ensuring and assuring quality as well as the loss incurred when quality is not achieved.

Under traditional cost accounting, quality costs are lumped into overheads, which are allocated to cost centers (usually departments) and then to products through predetermined overhead rates. For example, among various quality related costs, the rework and the unrecovered cost of spoiled goods caused by internal failures are charged to the factory overhead control account which accumulates the actual overhead costs incurred. Thus, the predetermined overhead rates should be adjusted to incorporate the normal levels of various quality related costs and excess quality related costs will be buried in overhead variances.

Oakland⁴ also claimed that quality related costs should be collected and reported separately and not absorbed into variety of overheads. After Feigenbaum⁵ categorized quality costs into prevention-appraisal-failure (PAF), it has been almost universally accepted for quality costing. The failure costs in this scheme can be further classified into two subcategories: internal failure and external failure costs.

However, this traditional PAF categorization has proven to fall short in registering the true quality costs and requires some modifications⁶. Since quality costs can be scattered among various accounts especially overheads, cost measures of the whole production system need to be updated. All quality activities and their associated costs needed to be related to the production activities. With traditional PAF categorization, there would be a lot of quality related activities and costs hidden in other manufacturing functions which would definitely undervalue the amount of the actual quality costs. In addition, such categorization does not provide mechanisms to quantifying and registering these hidden quality activities.

The ultimate purpose of quality improvement is to reduce quality costs through proper management of the quality control program. Statistical process control (SPC) and sampling plan have been widely used as a tool in industry for many years to reduce variability in processes and products. Typically, the output from a process is regularly sampled, measurement of key variables are taken, various statistics (such as mean and standard deviation) are calculated from the measurements and decisions on the maintenance of process performance are taken, usually to continue, to resample or to stop the process and make appropriate adjustments.

The content of SPC and sampling plan has been widely discussed in the literature both in their industrial applications and their experimental designs. Experimental design on quality processes is carried out to obtain a process that is robust and insensitive to external sources of variability. Unless we know which input variables are the important ones, it is very difficult to bring the process under control. Thus, such a design method is a critically important engineering tool for identifying influential process variables and determining the direction of adjustment on these factors to further improve process performance.

To provide a basis for this study in experimenting the quality cost under various quality schemes, some sources of empirical information are reviewed here. Burgess⁷ performed an experiment on the internal dynamics of conformance quality and costs. The experiment has enabled the rigorous examination of the main relationships connecting conformance quality and costs at the organization level. Xie *et al.*⁸ integrated SPC approach for manufacturing processes. Their method focuses on developing a framework for process monitoring when the process is subject to regular adjustments. Antony⁹ uses ANOVA and Taguchi approach to determine the optimal condition which provides the best settings of process variables under the multiple quality characteristics. Arentsen *et al.*¹⁰ integrate quality control with shop floor control. They suggest that not only the quality of products and processes must be controlled, but all the quality-related activities must also be controlled and attuned to the other manufacturing activities on the shop floor.

From the literature reviewed, it is found that much of the discussion about the quality improvement has been focused on the application and implementation of quality techniques. Less intention is, however, made to trace the hidden quality cost or find a way of measuring them. This is, in fact, the fundamental and essential knowledge for improving the shop performance as a whole. Without such reliable cost information, a wrong decision on setting the right quality program can be made since the cost and especially its source cannot be correctly identified.

2. PROPOSED METHODOLOGY FOR MEASURING QUALITY COSTS

The purpose of this paper is first to present a conceptual framework for measuring quality costs. The idea is that the measurement of quality is the price of non-conformance. Thus, considerable effort should be applied to measuring the hidden and opportunity costs of producing poor goods. This will involve measuring far more than just explicit costs of inspection, scrap and rework in terms of labor and materials. By obtaining more accurate value of the quality costs, the management will see an economic advantage and disadvantage in the installation of preventive systems. Since quality costs can be scattered among various accounts especially overheads, cost measures of the whole production system need to be updated.

Figure 1 presents a proposed classification of quality costs, which help track down actual quality related values. Main details of the economic cost model are shown in the Appendix. Under this proposed model, quality costs are classified by internal failure, external failure and explicit quality costs. As suggested by Porter¹¹, activities consume resources and product

Figure 1: Classification of quality costs.

consumes activities. Thus, a quality cost should be incurred at the point where the activity takes place. As a result, each internal failure cost is related and linked to a production activity. An opportunity costs also play an important role in measuring the quality costs. The opportunity costs can be defined as the potential profit that is lost or sacrificed when the choice of action requires the giving up of an alternative course of action¹². They are not usually entered in an organization's books and do not represent actual money. But they represent those economic benefits that are foregone as a result of pursuing some alternative course of action. Thus, if ignored, they would be valued at zero and a value of zero is surely less accurate than an informed estimate by a qualified individual and guesstimate of costs is certainly better than ignoring them. Waiting, idle and loss of goodwill costs are examples of such costs. Finally explicit quality costs are the costs incurred from obvious quality activities, which were wrongfully claimed as the total quality costs in the past.

In focusing on the connection between the factors of quality and costs, the appropriate level of statistical quality control planning needs to be set and adjusted according to the actual working condition of a company (i.e., defect rate and machine reliability). Too tight the quality program under a normally good condition will generate unnecessary quality activities and hence incur unnecessary appraisal costs. However, if the tight program is enforced in the unreliable machine condition, it would help screen out non-conformance parts, maintain machines in control and reduce failure costs. Thus, companies need to balance between their costs and services required in relation to their actual conditions. This paper will also reveal a guideline for the company based on their current situation in setting an appropriate level of their quality control. Statistical methods such as ANOVA and Duncan's multiple range test are introduced to identify important key factors and differentiate suitable strategies.

3. ILLUSTRATIVE EXAMPLE

Having identified the objective of the study, the next step is to put the proposed methodology to the test. This example is intended to illustrate the potential of the proposed approach.

3.1 System characteristics

The system is designed under a flow production line with four stations. Parts are produced and transferred between successive stations by forklift trucks in batches (25 units). At the end of each station, the process control is set to maintain the process performance. For simplicity, the *np* attribute chart is used. Even though attribute charts are generally not as informative as variable charts because there is typically more information in a numerical measurement than in merely classifying a unit as conforming or nonconforming. However, they do have important applications and useful in many processes where the quality characteristics are not easily measured on a numerical scale¹³. Then, before finished products are shipped to customers. The acceptant sampling plan with rectifying program is also used for final product inspection.

3.2 Parameter setting

During an operation, a fixed sub-group's sampling size (n) of one batch (25 units) is taken with both process control and sampling plan. This has been proved to be large enough to average at least 0.5 defective for np . In addition, a sample size of 25 units is very popular for percent charts, although various rules have been suggested for determining the minimum sample size⁵. At each checking point, two controllable factors: (1) lot size from which a sub-group is taken and (2) acceptant units, are experimented with two levels (i.e., tight and loose). This variation is used as a guideline in setting an appropriate level of the quality control under different levels of machine conformance. Thus, interested factors and their variation under consideration can be expressed as follows;

- (i) **Machine conformance factor (MCEFF):** four levels which are 85%, 90%, 95%, and 99%. It should be noted that these percentages of machine conformance level is a machine conformance level under the normal case. However the machine conformance level is worsen by 0.5% from an average of every 75 parts produced. This is due to the fact that machine performance is expected to worsen along with the number of units produced so that the good setting process control can help detect and adjust the process back to normal.
- (ii) **Lot size for the process control (LPROC):** two levels which are small (sampling one from every three batches) or big (sampling one from every seven batches). The small lot size denotes a quality control program that the process inspection is done more frequent with a shorter interval. This can bring a tighter process control in which the process deviation may be detected sooner but it can incur higher costs from the process inspection itself.
- (iii) **Acceptant units for the process control (APROC):** two levels which are tight or loose: Note that 0 and 1 unit are the acceptant units under the tight and loose case for 99%, 3 and 5 units for 95%, 5 and 9 units for 90% and 7 and 11 units for 85% machine conformance factor. The tight quality control requires the acceptant unit low so that an individual item in a sampled sub-group is facing a tighter control and the chart alarm is stricter to be signaled by the chart rule.
- (iv) **Lot size for the sampling plan (LSAMP):** two levels which are small (every three batches) or big (every seven batches). This is the same as the lot size of the process control where a sampling interval is varied according to the lot size.
- (v) **Acceptant units for the sampling plan (ASAMP):** two levels which are tight or loose: Note that 0 and 1 unit are the acceptant units under the tight and loose case for 99%, 3 and 5 units for 95%, 5 and 9 units for 90% and 7 and 11 units for 85% machine conformance factor. This is the same as the acceptant units of the process control where specification limit for lot rejection is controlled by the acceptant units.

3.3 Simulation model

Owing to the complexity of this manufacturing system, simulation is employed for analysis. All experimental models for the above manufacturing environment were developed using SIMAN simulation language¹⁴. With five factors under consideration, 64 ($4 \times 2 \times 2 \times 2 \times 2$) treatments are collected and analyzed. From preliminary runs, the moving average in output analysis reveals that a warm-up period of 410,000 minutes is required to be truncated before normal conditions are built up. Ten independently-seeded replications with 250,000 minutes in each replication are required, yielding independent observations between replications and bringing the confident interval (half-width) of the interested observation (flow time) within 5 percent of our point estimate for this value under 95% confident level.

3.4 Cost structure

Perhaps the weakness point of evaluating system performance based on costs is the system's reliable cost structure. Unfortunately, few credible data are available. Companies almost never publish such data. Attempts to conduct research on these costs have encountered several obstacles¹⁵. For example, the cost data are confidential. Even available, many seem to be mixed up and often expressed in intangible forms. With our hypothetical model, the following cost structure has been estimated. However, the sensitivity analysis of this cost structure is not presented here for suitability of the paper length.

(Approximately US\$1 = 40 baht)

- Direct labour cost is 250 baht per day per shift
- Direct material cost is 200 baht for both product types
- Indirect material cost is 50 baht per unit
- Utility cost of manufacturing machine is 7 baht per minute
- Utility cost of transporting equipment is 10 baht per minute
- Set up cost is 70 baht per minute
- Preventive maintenance cost per minute is 150 baht each machine
- Failure repairing cost per minute is 70 baht each machine
- Loss of goodwill is estimated at 200 percent of cost of goods sold
- Opportunity cost due to lost profit is estimated at 35% per planing period
- 20% depreciation rate per year is estimated with the percent value of each machine 10,000,000 baht
- Cost of sampling and charting in the process control is estimated at 300 baht per sampling
- Cost of sampling during product auditing is estimated at 150 baht per sampling
- Cost of chart alarm is 500 per an adjustable cause
- Inspection cost is 50 baht per unit

4. EXPERIMENTAL RESULTS

4.1 Categorization of quality costs

The proposed cost categorization has revealed interesting outcomes. It can be easily seen that costs related to the quality can be clearly identified and let us understand where they are scattered. Table 1 shows the distribution of quality costs. It is found

Table 1: Categorization of Quality Costs.

Policy	Internal failure: production related cost	Internal failure: opportunity cost	External failure: opportunity cost	Explicit quality cost	Total quality costs
85% TTBB*	210,941 Baht (11.32%)	366,350 Baht (19.65%)	1,013,666 Baht (54.40%)	273,494 Baht (14.67%)	1,863,451 Baht (100%)
85% TTBS#	284,499 Baht (28.42%)	358,901 Baht (35.85%)	12,667 Baht (1.27%)	344,894 Baht (34.46%)	1,000,961 Baht (100%)

* 85% machine conformance factor with tight acceptant units and large lot sizes on both the process control and the sampling plan.

85% machine conformance factor with tight acceptant units and large lot size for the process control and small lot size for the sampling plan.

Table 2: ANOVA Results.

Main factors			F-value		
	Internal failure: production related cost	Internal failure: opportunity cost	External failure: opportunity cost	Explicit quality cost	Total quality costs
MCEFF	2891.26	16.24	746.25	3950.92	1507.093
APROC	846.401	0.41(not sig)	28.46	59.58	8.03
LPROC	3416.142	1222.62	332.26	4081.34	202.74
ASAMP	828.523	14.43	1412.01	844.68	1342.5
LSAMP	626.604	139.15	882.82	3853.67	977.17
Selected interaction effects (select from the most significant effect)					
LPROCxLSAMP	424.247	25.55	569.99	506.26	569.99

All effects are significant under 95% significant level except the effect of APROC on the internal failure opportunity cost.

that if only explicit quality costs are used to represent the total quality costs, they would be measured as a small fraction in relation to an actual total figure. This causes possibilities of ignoring the importance of good quality programs and misleading the true value of quality costs. For instance, the explicit quality cost of TTBB policy appears to be lower than the TTBS policy's explicit cost but its total quality costs are a lot higher. This is due to the fact that the effect of the opportunity cost is considered. Even though, the internal opportunity costs are not much different between these two policies due to using the same lot size and hence the same sampling interval, their external opportunity costs are much different. Under traditional accounting practices, except the explicit quality cost, others would have been ignored or considered as any normal expenses without being aware of the quality problems. However, the problems and their associated costs can be easily highlighted and identified under the mechanism of this categorization.

4.2 ANOVA results

In easing of interpreting raw data from all 64 treatments, ANOVA is used to help identify key features and its results are presented in Table 2. Regarding the total quality costs, it is found that all interested factors are significant. Apart from the factor of machine conformance, which is clearly significant, the acceptant units of the sampling plan is very significant, followed by lot size of the sampling plan, lot size of the process control and acceptant units of the process control. This reinstates the significance of the sampling plan's factors over the factors of the process control to the total quality costs. This may

be due to the fact that the factors related to the sampling plan have the direct effect to the conformance of finished products in which any loose defects can generate a significant cost.

However, when the total costs are broken down to individual costs, it is found that the lot size of the process control clearly becomes the most significant factor to the internal failure costs (both production hidden and opportunity costs) and the explicit quality costs while the acceptant units of the sampling plan is clearly the most significant factor to the external failure opportunity costs. Lot size of the process control specifies frequency of charting intervals and controls possible time allowance of the process deviation before an inspection and further machine adjustment are made. Thus, by varying this factor, not only the internal failure costs such as rework costs but also the explicit quality costs such as inspection and sampling costs are affected.

The acceptant unit of the process control has only a clear impact on the internal failure: production related costs through reworking processes. However it has only a small or even no impact on other costs. On the contrary, the acceptant unit of the sampling plan, which specifies the toughness of the end line inspection before products are shipped to the customer, shows the strongest effect to the external cost. This is due to the fact that this factor controls an allowance of defective units to the customer and consequently becomes a direct input to the loss of customer goodwill cost.

4.3 Duncan's multiple range test results

Duncan's multiple range test is used to classify suitable combination of factors from each machine conformance level. Regarding the results from Table 3 and Figure 2 which show the distribution of total quality costs among different strategies, it is found that setting loose acceptant unit with big lot size (LLBB: too loose quality program) incurs very high cost due to a number of defectives are released to the customer. On the contrary, tight acceptant unit with small lot size (TTSS: too tight quality program) also incurs quite high cost due to its unnecessarily strict control. In addition, it is also noticeable that the patterns of the policies from different machine conformance factors are quite similar. If one policy performs well under 85% machine conformance, it will also perform equally well under other levels. However, when the machine conformance factor is improved (e.g., from 85% to 99%), there clearly appear to be less significant difference among these policies. Thus, it could also mean that there is also less difference in selecting any policy to implement.

The results also shows that setting acceptant units tight on both process and sampling plan with big lot size for the process control and small lot size for the sampling plan (TTBS) provides the lowest cost in all cases. The tight acceptant unit scheme works as a good precaution in screening out defects. Regarding the sampling interval, it shows that the process control should just be done in a longer interval (perhaps just occasionally checking) but the end line sampling plan should be done in a more frequent fashion. For the task of the end line sampling plan, allowing defective units to the next process and eventually to customer hand means high losses. As a result, the tight acceptant unit with shorter interval

Table 3: Duncan’s Multiple Range Test on Total Quality Costs (95% significant level).

Machine conformance factor	Policies classified and ranked in groups from low to high total quality costs
85%	1) TTBS 2) LTBS TLBS LLBS LTSS TTSS 3) LTBS TTBS TTBB LTBB 4) LLSS LLBS TLSS LLBB 5) TLBB
90%	1) TTBS 2) LTBS TLBS LLBS LTSS 3) TTSS LTBS LTBB 4) TTBS TTBB 5) TLSS LLSS TLBS LLBS LLBB 6) TLBB
95%	1) TTBS LTBS LLBS TLBS 2) LTSS TTSS LTBS LTBB 3) TTBB TTBS TLSS LLSS 4) TTBB TTBS TLSS LLSS 5) TLBS LLBS LLBB TLBB
99%	1) TTBS LTBS LLBS LTSS LTBB TTSS TTBB TLBS LTBS 2) LTSS TTBS LLSS TLBS 3) LLBS LLBB TLBB

Policy names are denoted by 4 letters. First two letters specify the acceptant units of the process control and the sampling plan, which are T (tight) or L (loose). The last two letters specify the lot size of the process control and the sampling plan, which are B (big lot size) and S (small lot size).

Figure 2: Distribution of total quality costs among strategies at different machine conformance levels.

should be set. On the other hand, the interval of the process control should just be set to match with the decline of the machine condition. Thus, with the long interval, the tight acceptant unit should be implemented otherwise defective units may not be detected and the chart alarm will not be signaled.

However, under good machine conformance factors (95% and 99%), it can be seen that in addition to implementing a long sampling interval of the process control (big lot size), we may also relax on the acceptant units of the process control without increasing the costs since parts are generally more conformed. So, there is a less danger in facing the chart alarm. Nevertheless, unlike the process control, the acceptant unit of the sampling plan should be set with care. If we need to set it loose, it will generally incur high external failure cost (since it is the last resource for inspection). Thus, it must only be used with more frequent samplings (sampling plan) in order to effectively prevent the loose defects. In addition, there is also a clear strong interaction between the lot size of the process control and the sampling plan (also shown in Table 1). This interaction can significantly vary the quality costs. In achieving low quality costs, the lot size of the process control should be set at a longer interval (big lot size) while the lot size of the sampling plan should be set at a shorter interval (small lot).

5. CONCLUSIONS

The proposed quality cost model has the potential to become an excellent tool in the overall management of business. It provides an indication of the health of management performance in many areas of a company. The view that traditional accounting practice on measuring quality costs are inaccurate and may even be of the wrong form is widely supported by quality managers. Everyone would like to have a valid model which they could use to access their present situation and predict the effects of changes. So far as is known there are insufficient data available to construct such a model, though there should be enough collective information available to make a reasonable hypothesis as to the shape and the relative proportions of the constituent costs.

By incorporating opportunity factors to determine the costs of quality, we could identify profitable strategies and uncover pathways to improvement. This opportunity cost can help to adequately show this importance, which the traditional PAF model would overlook. As we consider more and more the quality function, we will discover that the quality costs is mainly explained by the costs incurred to generate the needed quality as perceived by customers. Often, these costs may or may not have a tangible component. Thus, by approaching this uncertainty using opportunity costs, a company can have a measure of performance that provides valid paths to ferret out profitable strategies while increasing customer satisfaction. The findings suggest that the emphasis on costs of quality research needs to focus on opportunity costs.

This paper also highlighted the concept of quantifying the true cost of quality in which the costs of quality are a comprehensive system, not a piecemeal tool. If only explicit quality costs are used to represent the total, many consequences of having bad quality would be ignored and

this is definitely leading to the wrongful use of such information. Under the proposed cost categorization, the true costs of quality and where they are scattered among various accounts can be identified in which there is no such mechanism provided from the past methods.

Then, in setting the suitable quality program, one should set the level to minimize the total costs in order to balance between the costs and customer services. Acceptant units need to be set to match with the conformance level while the lot size, which controls sampling intervals, needs to be adjusted according to the consequence of passing defective units to the customer and the level of acceptant units set at that point. Even though, the machine conformance factor does not have a clear impact on the pattern of different strategies on their quality costs, it has shown a strong effect to the total costs. Then, Duncan's multiple range test can help classify suitable statistical process control strategies to each process's situation.

However, the results obtained from this study just revealed a preliminary outline of benefits from the proposed cost categorization. More experiments including the effect of different cost structures on outcomes of setting such suitable quality programs are still required. This sensitivity of input parameters, as they are usually not known, is another rich area to be researched. It would be incorrect to draw too many conclusions from this initial study. The research was done at only one environment. But as a pilot study, the research fulfils its purpose, which is to question some commonly held beliefs we have about quality costs and to demonstrate benefits from the proposed cost categorization.

6. REFERENCES

1. Besterfield, D.H., 1994, *Quality Control*, Forth edition, Prentice-Hall, New Jersey.
2. BS 6143 Part 2, 1990, *Guid to Determination and Use of Quality-related Cost*, BSI, London.
3. ASQC, 1971, *Quality Costs, What and How*, Second edition, ASQC Quality Press, Milwaukee, WI.
4. Oakland, J.S., 1993, *Total Quality Management*, Second edition, Butterworth-Heinemann Ltd, Oxford.
5. Feigenbaum, A.V., 1991, *Total Quality Control*, Third edition, McGraw-Hill, Singapore.
6. Dahlgaard, J.J., Kristensen, K. and Kanji, K.G., 1992, Quality costs and total quality management, *Total Quality Management*, 3, 3, pp. 211-221.
7. Burgess, F.T., 1996, Modeling quality-cost dynamics, *International Journal of Quality and Reliability Management*, 13, 3, pp. 8-26.
8. Xie, M., Goh, N.T. and Cai, Q.D., 2001, An integrated SPC approach for manufacturing processes, *Integrated Manufacturing Systems*, 12, 2, pp. 134-138.
9. Antony, J., 2001, Simultaneous optimization of multiple quality characteristics in manufacturing process using Taguchi's quality loss function, *International Journal of Advanced Manufacturing Technologies*, 17, pp. 134-138.
10. Arentsen, L.A., Tiemersma, J.J. and Kals, J.J.H., The integration of quality control and shop floor control, *International Journal of Computer Integrated Manufacturing*, 9, 2, pp. 113-130.

11. Porter, M.E., 1985, *Competitive Advantage: Creating and Sustaining Superior Performance*, Collier Macmillan Publishers, New York.
12. Son, Y.K., 1991, A framework for modern manufacturing economics, *International Journal of Production Research*, 29, 12, pp. 2483-2499.
13. Montgomery, C.D., 1997, *Introduction to Statistical Quality Control*, Third edition, John Wiley & Sons, USA.
14. Pegden, C.D., Shannon, E.R and Sadowski, P.R., 1995, *Introduction to Simulation Using SIMAN*, Second edition, McGraw-Hill, Singapore.
15. Gilmore, H.L., 1983, Consumer product quality control costs revisited, *Quality progress*, April, pp. 28-32.

APPENDIX

ECONOMIC COST MODEL FOR QUALITY COSTS

In constructing the cost model, one should be aware of its practicality. The model should neither oversimplify to the point where the model becomes trivial nor carry so much detail that it becomes clumsy and contributes little or nothing to understanding the problem. According to Pareto's law, 80 percent of system behavior can be explained by the action of 20% of its components. The model presented here only includes those aspects relevant to the study objectives. Thus, the quality costs should include:

1. INTERNAL FAILURE: PRODUCTION RELATED COSTS

These are costs registered as production expenses, but have incurred from poor quality. They are normally scattered among various accounts and need to be related with production activities. The production related costs could be actual expenses hidden among production activities or opportunity costs, which do not represent actual money but surely have some economic values.

1.1. Hidden quality costs

Quality costs hidden among production activities include:

- a. Material cost (C_{mat})
(Direct and indirect material cost due to defective units)

$$C_{mat} = \sum_{j=1}^J \sum_{i=1}^I [(CMT_d(i) + CMT_{id}(i) \times NP_{rwk}(i, j))] \quad (1)$$

Where:

$CMT_d(i)$ = Cost per unit of direct raw materials of product i

$CMT_{id}(i)$ = Cost per unit of indirect materials of product i

$NP_{rwk}(i, j)$ = Number of rework products of product i at machine j

- b. Machine cost ($C_{m/c}$)
(Machine operating cost due to reworks)

$$C_{m/c} = \sum_{j=1}^J \sum_{i=1}^I [UTC(j) \times TM_{rwk}(i, j)] \quad (2)$$

Where:

$UTC(j)$ = Utility cost per unit time, i.e. electrical, water, coolant, of running machine j

$TM_{rwk}(i, j)$ = Total machine time of processing rework part i at machine j

- c. Labor cost (C_{labour})
(Direct labor cost for rework units)

It is assumed that only direct labors, who are paid by working time, are affected by poor quality products.

$$C_{labour} = \sum_{j=1}^J \sum_{i=1}^I [CL_d(i, j) \times TL_{rwk}(i, j)] \quad (3)$$

Where:

$CL_d(i, j)$ = Direct labor cost per unit time of processing product i at machine j

$TL_{rwk}(i, j)$ = Total labor time from operating rework part i at machine j

- d. Set-up cost (C_{setup})
(Set-up cost caused by rework parts)

$$C_{setup} = \sum_{j=1}^J [SC(j) \times TS_{rwk}(j)] \quad (4)$$

Where:

$SC(j)$ = Set-up cost per unit time of machine j

$TS_{rwk}(j)$ = Total set-up time caused by rework parts at machine j

- e. Material handling cost (C_{mh})
(Transportation cost of transporting parts back for rework)

$$C_{mh} = \sum_{j=1}^J \sum_{i=1}^I \sum_{r=1}^R [TC(i, j, r) \times TH_{rwk}(i, j, r)] \quad (5)$$

Where:

$TC(i, j, r)$ = Transportation cost of transporter r for transferring part i to machine j

$TH_{rwk}(i, j, r)$ = Total transportation time of transporter r for transferring rework part i to machine j

1.2. Opportunity costs

Opportunity costs are considered as potential economic benefits that are lost or sacrificed when the products are non-conformance. Regarding internal production activities, waiting and idle costs can be considered as the loss, which is sacrificed due to implementing the quality program.

a. Waiting cost (C_{waiting})

If parts are held for quality processes such as inspection or reworking at any points in the process, there will be a loss which incurs from not quickly processing those parts and making them into a profit. Thus, the waiting cost is a cost associated with those parts that are waiting for service somewhere in manufacturing processes. It could also be considered as the cost of work-in-process inventory. In this model, a WIP contribution is an increment of the time spent in a queue multiplied by the corresponding value added through the most recent operation completion. The waiting cost can be calculated as:

(Waiting opportunity cost per unit time) $\times$ (Total waiting time of parts due to quality control processes)

$$C_{\text{waiting}} = v \times \sum_{j=1}^J \sum_{i=1}^I \left\{ \left(UC_i + \left[\frac{C_{m/c}(i, j, -1) + C_{\text{labour}}(i, j, -1) + C_{\text{setup}}(i, j - 1) + C_{\text{mht}(i, j)}}{NP(i, j)} \right] \right) \times TP(i, j) \right\} \quad (6)$$

Where:

v = Opportunity cost per unit time

UC_i = Unit cost of materials for product i

$TP(i, j)$ = Total waiting time due to quality processes for part i at machine j

$NP(i, j)$ = Number of part i being processed through machine j

b. Idle cost (C_{idle})

Idle cost is the cost associated with the under-utilization of manufacturing equipment. It shows inefficiency of the company planning in utilizing available resources. Due to quality control's processes, parts may need to be held for process inspection and rework. Thus, rather quickly pushing parts forward to the next operation, machines and equipment of the next operation may need to wait and be idle until the inspection and reworking processes finish. Thus, under-utilization of these machines and equipment can be presented as:

(idle opportunity cost per unit time) $\times$ (total idle time of the equipment due to quality control processes)

$$C_{\text{idle}} = v \times \sum_{j=1}^J [U_{\text{without}Q}(j) - U_{\text{with}Q}(j)] \times T \times E(j) \times P(j) \times O(j) \quad (7)$$

Where:

v = Opportunity cost per unit time

$U_{\text{without}Q}(j)$ = Machine j normal utilization when there is no quality control's processes

$U_{withQ}(j)$ = Machine j utilization while quality control's processes are implemented

T = Planning period

$E(j)$ = Efficiency of machine j

$P(j)$ = Present value of machine j

$O(j)$ = Depreciation rate (%) of machine j during the planing period

Refer to the value of the opportunity cost, as suggested by Son¹², the opportunity cost per unit time (v) can be considered according to the sales and market condition. If there is demand, the cost may be considered as lost profit since opportunities of making and selling more products are foregone. In this case, it is based on the company's profit rate, which can be calculated from the company's accounting record. However, if there is no demand, the loss may only be considered as a capital tied up. Thus, it should only be based on the company's cost of capital or internal rate of return.

2. EXTERNAL FAILURE: OPPORTUNITY COST (C_{efo})

This is another type of opportunity lost costs when the product does not perform satisfactorily after it is supplied to the customer. It is lost since future sales are forgone due to the supply of bad quality products. Typically, the customer dissatisfaction cost would be very high (higher than a normal replacement cost) since there is a high chance that the customer would not come back to buy that product again and all future sales would be lost. Thus, the external failure costs can be represented by:

(Cost of dissatisfying a customer by selling a defective part)

$$C_{efo} = ND \times CDS \quad (8)$$

Where:

ND = Number of defective units sold to the customer

CDS = Cost of dissatisfying a customer

3. EXPLICIT QUALITY COSTS

These are explicit costs associated with quality as previously defined in the traditional accounting system. These explicit costs just reveal a small fraction in relation to the total costs of the poor quality's consequences.

a. Prevention: Process control (C_{pc})

The cost of a process control includes:

(Control chart sampling cost) + (Sub-group's inspection cost) + (Chart alarm cost)

$$C_{pc} = \sum_{j=1}^J \sum_{i=1}^I [CSP(i, j) \times NSG_p(i, j)] + \sum_{j=1}^J \sum_{i=1}^I [CIS(i, j) \times NB(i, j) \times NSG_p(i, j)] + \sum_{j=1}^J [C_{ca}(j) \times N_{ca}(j)] \quad (9)$$

Where:

$CSP(i,j)$ = Cost of sampling and charting part i at machine j

$CIS(i,j)$ = Cost of inspection per unit of part i at machine j

$C_{ca}(j)$ = Cost of adjusting machine j back to normal condition

$NSG_p(i,j)$ = Number of sub-groups taken during the planning period

$NB(i,j)$ = Sub-group sample size

$N_{ca}(j)$ = Number of chart alarms occurring during the planning period

b. *Appraisal: Acceptant sampling plan (C_{ap})*

Cost of a typical sampling plan can be calculated as:

(Sampling cost) + (Sampled sub-group inspection cost) + (100% inspection cost)

$$C_{ap} = \sum_{j=1}^J \sum_{i=1}^I [CSA(i,j) \times NSG_a(i,j)] + \sum_{j=1}^J \sum_{i=1}^I [CIS(i,j) \times NB(i,j) \times NSG_a(i,j)] + \sum_{j=1}^J \sum_{i=1}^I [CIS(i,j) \times NR(i,j)] \quad (10)$$

Where:

$CSA(i,j)$ = Cost of sampling part i at machine j

$NSG_a(i,j)$ = Number of sub-groups taken during the planning period

$NR(i,j)$ = Number of units from the remaining lot required for 100% inspection during the planning period