The dynamics of quality costs in continuous improvement

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Abstract

Purpose – The ideals of total quality view contradicts with the traditional prevention-appraisal-failure (PAF) model. The PAF model, based on the "higher quality-higher cost" notion, fails to explain the "higher quality-lower cost" premise of total quality. The purpose of this study is to examine the behaviour of quality costs and investigate the two contradicting views.

Design/methodology/approach – Based on the literature, a generic descriptive model is developed to examine the dynamics of quality costs and quality level over time. Through illustrative examples, the behaviour of quality costs is demonstrated and relevant implications are highlighted.

Findings – The proposed model supports continuous improvement regardless of the effectiveness of the firm's quality improvement programs. When the quality improvement program is highly effective, the "higher quality-lower cost" phenomenon is observed; whereas, in a less effective quality improvement program, the authors observe the "higher quality-higher cost" phenomenon, which still calls for increased improvement effort necessary for quality sustainability.

Research limitations/implications – The proposed model explains well the dynamics of quality costs, however, it can be further enhanced by incorporating the dynamics of the effectiveness of the firm's quality improvement program and its relation to quality level and quality costs.

Practical implications – The proposed model is a useful tool especially for quality improvement planning and budgeting decisions.

Originality/value – Balancing between the two contradictory views of quality costs, this study provides a deeper understanding of the relationship of quality costs and quality level.

Keywords Quality management, Continuous improvement, Quality costs, Total quality, Dynamics

Paper type Research paper

Introduction

Total quality and continuous improvement have attracted significant attention especially in the last two decades. As far as quality costs are concerned, the "quality is free" notion based on the ideals of total quality and zero defects, has contradicted the optimal quality model's premise which was dominant prior to the emergence of total quality management (TQM). The optimal quality model also known as the prevention-appraisal-failure (PAF) model demonstrates the trade-off between prevention-appraisal and failure costs, and proposes a cost-minimizing quality level by balancing the two. The total quality view supported by some empirical evidence (Ittner, 1996) proposes that firms can achieve quality improvement over time while concurrently decreasing prevention-appraisal costs. Even though the ideals of total

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quality have become popular, its "higher quality-lower cost" premise has become the subject of debate among both academicians and practitioners, particularly in recent years, necessitating re-examination of the subject.

There have been a number of analytical and empirical studies examining the behaviour of quality costs and quality level. In addition, there are some cross-country studies surveying quality-costing practices, how companies define their quality cost categories, and how quality costs data are reported. Lindsay and Bishop (1964) provide one of the first studies for optimal inspection allocation utilizing dynamic programming. White (1965) characterizes the optimal multistage inspection plan for an ordered production process using dynamic programming. Ballou and Pazer (1985) analyse the cost-quality implications of process improvement versus inspection enhancement in a serial production process. The effect of quality improvement speed on the quality costs is studied by Foster and Adam (1986). Highlighting some benefits of continuous improvement, Schneiderman (1986) argues that it is not contradictory to the trade-off model's premise that an optimal quality level exists. Plunkett and Dale (1988) survey quality cost models used in the literature concluding that they are inaccurate and misleading, questioning the existence of an optimal quality level, and casting serious doubts on the PAF model's concept of the optimal quality level. Son and Hsu (1991) derive a quality cost function incorporating quality control, cost accounting, and manufacturing inputs and constructed a model quantifying quality costs. Dahlgaard *et al.* (1992) develop a model of quality management system incorporating quality costs. Narasimhan *et al.* (1993) examine the dynamic influence of price and perceived quality on sales, and investigate the effect of continuous quality improvements on optimal pricing Narasimhan *et al.* (1996). Love *et al.* (1995) perform an empirical study using a dynamic model and find that the short run quality control problem is consistent with the optimal quality view whereas the long-run quality control problem is consistent with the total quality view. Burgess (1996) examines quality costs models in the literature and tests the dynamics of quality costs and quality level utilizing a simulation approach. In an empirical study based on time series behaviour of quality costs reported by 49 plants, Ittner (1996) finds that majority of the plants achieved on-going reductions in non-conformance costs while maintaining or reducing their prevention and appraisal costs. Li and Rajagopalan (1998) support the total quality view while relying on the PAF model and construct a dynamic model of decision making for process improvement and quality assurance efforts. While their dynamic model incorporates quality learning, they assume that production volume, process improvement, and appraisal efforts of the firm are determined by their proposed optimal control model. Lorente and Rodriguez (1998)) formulate analytical models examining different views on total quality cost identified in the literature and explain how quality improvement (defined as agreement to design specifications) relates to cost reduction. Shah and FitzRoy (1998) examine issues related to collecting, measuring, reporting and uses of quality cost data, and provide empirical evidences of relationship between quality cost components. Veatch (2000) formulates a dynamic quality model for a production system with multiple inspection locations and sampling. Kogan and Raz (2002) demonstrate an efficient algorithm determining the optimal intensity, sequence and timing of inspection effort on a finite planning horizon. Zantek *et al.* (2002) empirically validate procedure for measuring the effect of each stage's performance on the output quality of subsequent stages in a production system.

A recent case study from the Thai automotive industry via a system dynamics-based simulation model to investigate the potential effects of different market pricing conditions on optimal quality spending is presented by Visawan and Tannock (2004).

Even though the dynamic relationship of quality costs and quality level have been the subject of some studies in the literature, most of these studies have focused on optimal allocation of inspection efforts on a finite planning horizon. These studies focus mainly on costs of inspection while ignoring the other quality cost components. The dynamics of quality costs over time have been rarely discussed in those studies. The growing debate over the validity of the total quality premise has created confusions that are affecting continuous improvement efforts in many quality improvement programs. While those with strong belief in zero defects disregard trade-offs between prevention-appraisal and failure costs altogether, many managers, after devoting substantial resources to quality improvement efforts, are turning their attention again to the cost-minimizing optimal quality. Measurements such as return on quality are being utilized for determining the optimal level of quality improvement activities. In light of this, the need for examining the behaviour of quality costs using a dynamic model rather than a static approach, that dominated the quality cost literature, has become apparent.

Emerging in the literature is a balanced view of quality costs that does not contradict the core premise of either the optimal quality or the total quality (Love *et al.*, 1995; Burgess, 1996; Lorente and Rodriguez, 1998; Visawan and Tannock, 2004). This paper is motivated by these studies attempting to further examine the relationships between quality costs and quality level utilizing an analytical methodology built on the findings in the literature. We propose a generic descriptive modelling structure, which allows us to explain the dynamic behaviour of quality costs and quality level. The proposed model is robust in that it succeeds to effectively demonstrate aspects of both the total quality and optimal quality premises. Our analytical approach is related to the study by Li and Rajagopalan (1998) who also examine the dynamic relationship between quality costs and quality level. However, their model is based on the assumption that the firm will optimise its quality improvement efforts over time. Our proposed model, due to its descriptive nature, does not depend on any assumptions on a firm's dynamic allocation of its quality improvement efforts. This approach allows managers to better assess the impact of quality improvement efforts over time under different dynamic scenarios of allocating quality improvement costs.

The remainder of this paper is organized as follows. First, quality cost categories and components are presented. Second, the traditional PAF model of quality costs is discussed. Third, we propose our dynamic model that explains the behaviour of and the relationship between quality costs and quality level. Fourth, the dynamics of quality costs and quality level are illustrated through examples. Fifth, we discuss managerial implications of our findings. Finally, we offer concluding remarks and suggest opportunities for future research.

Categories of quality costs

The first categorization of quality costs is traced back to the publication of Juran's Quality Control Handbook (1951). The Juran's minimum cost model, originally known as the economic conformance level (ECL) model classifies quality costs into two categories of conformance and non-conformance. The concept of "quality costs" has had different meanings to different people. It refers as much to the cost of achieving a desired quality level as those costs incurred as a consequence of not achieving it. For some people, it implied the cost of conformance (or improving quality). Yet, for others it meant the cost of non-conformance (or poor quality). The quality costs categories that are widely used today were made by Feigenbaum (1956; 1961). He further refined the conformance cost into prevention and appraisal costs, and the non-conformance cost into internal and external failure costs. Prevention costs are incurred to keep the appraisal and failure costs to their minimum. Appraisal costs include all the incurred costs to ensure that a product or service conforms to specifications. Internal failure costs are those incurred by defective product or service before delivery to customers and deal with the failure to meet explicit requirements or implicit needs of customers. External failure costs are associated with quality problems in product or service after it is delivered to customers such as warranty costs and business loss due to customer dissatisfaction. Examples of common quality costs for each of the four categories are shown in Table I. For more details about quality cost categories and their components, see Atkinson *et al.* (1994), Campanella (1999), and Gryna *et al.* (2007). Harrington (1987) provides a comprehensive list of quality costs with 101 prevention costs, 73 appraisal costs, 139 internal failure costs, and 50 external failure costs.

Although, little credible quality cost data are provided by companies and there are various definitions of quality cost components (Shah and FitzRoy, 1998; Mandal and Shah, 2002), nevertheless some studies report quality cost figures expressed in terms of some percentages. In the quality cost literature, there are several measures typically used to benchmark a firm's effectiveness of its quality expenditures. These include total quality cost as percentage of sales turnover, total manufacturing cost, material cost, and hours of labour. Some firms use internal failure cost compared to average percentage of production cost, warranty cost as average percentage of sales volume, supplier appraisal costs as percentage of material costs, appraisal costs as percentage of production cost, and quality improvement cost as percentage of total quality cost.

Quality costs represent a sizeable amount of a firm's total manufacturing cost. According to Wheelwright and Hayes (1985), IBM's quality costs represented 30 per cent of its manufacturing costs in the early 1980s. In a study of a machine tool company, Burns (1976) finds that quality-related costs account for 5 per cent of sales turnover. Another study conducted in the steel industry reports that costs of quality represented 38 per cent of sales turnover (Moyer and Gilmore, 1979). In the literature, the cost of quality is ranged between 5 per cent and 30 per cent of sales turnover. In

Prevention costs	Appraisal costs	Internal failure costs	External failure costs
Process control Product and service design and redesign Process design Supplier relations, audit and screening Preventive maintenance Training and quality circles	Raw material inspection In-process inspection Final inspection Inspection material and services Quality audit	Scrap Rework Equipment repair Process downtime Re-inspection of products	Warranty charges Litigation and liability Complaint handling Returns Rework on returns Lost sales Penalties and allowances

Table I.
Common quality costs by categories

manufacturing, it has been reported that the annual failure costs (internal and external) are about 15 per cent of sales turnover, varying from about 5 to 35 per cent depending on product complexity. Whereas in the service organizations, the annual failure costs average about 30 per cent of operating expenses, ranging from 25 to 40 per cent depending on the organization (Gryna *et al.*, 2007). Many authors (Garvin, 1988; Taguchi and Clausing, 1990) have pointed out that external failure costs may be up to ten times the internal failure costs or other quality costs.

Some studies have surveyed categories of quality costs in terms of percentages of total quality cost. It is reported that prevention is the least expensive while failure is the most expensive quality cost components. According to Burns (1976), prevention, appraisal, and failure (internal and external) costs account for 3.3 per cent, 40.3 per cent, and 56.4 per cent of total quality cost, respectively, while Moyer and Gilmore (1979) report 6 per cent, 14 per cent, and 80 per cent. These observations are empirically supported by Carr and Ponoemon (1994). Using data from 49 plants of 21 companies, Ittner (1996) further reports 18.4 per cent, 27.3 per cent, and 55.1 per cent on average for prevention, appraisal, and failure costs, respectively.

The prevention-appraisal-failure (PAF) model

Originally developed in 1950s, the PAF model attempts to achieve an optimal level of quality by balancing the trade-offs between prevention-appraisal (conformance) and failure (non-conformance) costs. The main premises of the model include:

- Quality level is determined by conformance to specifications.
- As quality level increases, the failure cost decreases at a decreasing rate.
- As quality level increases, the prevention-appraisal cost increases at an increasing rate.
- Total quality cost is the sum of prevention-appraisal and failure costs.
- The optimal quality level is determined by minimizing the firm's total quality cost.

Let quality level (q) be defined as the proportion of non-defective items of a single product. Let also defect rate (d) be defined as the proportion of defective items. Then $q = 1 - d$. Based on the PAF model's premises, prevention-appraisal cost, denoted as $C(q)$, is an increasing convex function in q, and failure cost, denoted as $N(q)$, is an decreasing convex function in q. The convexity of $N(q)$ is empirically supported in that most of the decrease in external and internal failures occurs at the earlier years of a quality improvement program (Giakatis *et al.*, 2001). Total quality cost, denoted as $TC(q)$, is the sum of the two costs and is then convex in q as depicted in Figure 1.

According to this model, a firm with less than optimal quality level (q^* in Figure 1) can make substantial savings in internal and external failure costs by making small investments in relatively inexpensive prevention and appraisal activities. Differently stated, for a quality level below q^*, marginal decrease in failure cost would be more than marginal increase in prevention-appraisal cost. Likewise, as the firm continues with its quality improvement efforts and incurs additional prevention and appraisal costs, its gains from reduced failures diminishes. Therefore, the firm's improvement efforts will cease to be economical after the quality level reaches q^*. This "higher quality-higher cost" behaviour of PAF model contradicts with the pursuit of total

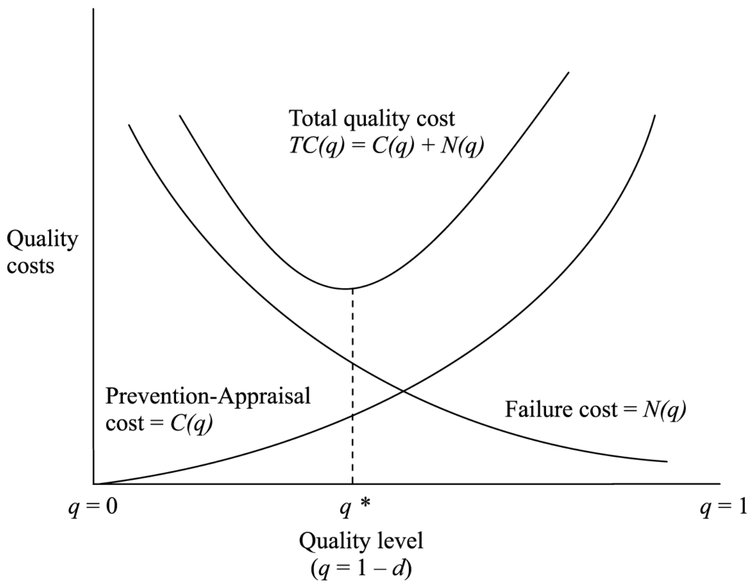


Figure 1.
The PAF model

quality or zero defects in the continuous improvement philosophy. This static nature of the PAF model appears simplistic. It does not consider dynamic behaviours of quality costs and the firm's quality level over time.

In the framework of the PAF model, quality is determined in terms of conformance to specifications. Other key dimensions of quality (Garvin, 1987; 1988) that are increasingly recognized in the contemporary quality management era are excluded in this optimal quality model. The meaning of quality has continued to evolve in an era characterized by high consumer expectations and sophistication as a result of intense global competition. Garvin identifies eight dimensions of quality and stresses the need for and the importance of strategic quality planning. These dimensions of quality are: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. Defined by the producer of a product or service (as opposed by the customer), conformance is the most classical definition of quality and is more easily measurable than most of other quality dimensions. In the quality cost literature, conformance is typically used to measure the quality level. In our dynamic model proposed in the next section, we also make the same assumption, $q = 1 - d$, while recognizing the importance of other dimensions of quality. If quality means satisfaction of customer's requirements, therefore achieving the desired quality level will depend on successfully conforming to the product specification during production.

The dynamic model

Unlike the static PAF model, a dynamic approach can provide opportunities for better understanding the behaviour of quality costs and quality level over time. Our proposed model synthesizes some aspects of PAF model with those in the total quality framework and provides an integrative approach for explaining the relationships between the firm's quality level and quality costs over time.

In our model, we refer to sum of prevention and appraisal costs as (quality) improvement cost, the sum of internal and external failure costs as (quality) failure cost, and the sum of improvement and failure costs as total quality cost. Let *Q(t)*, *F(t)*, *I(t)*, and *TC(t)* be quality level, failure cost, improvement cost, and total quality cost at time *t*, respectively. Then $TC(t) = I(t) + F(t)$. Let also *A(t)* be the sum of the adjusted improvement costs for times 1, 2, 3, ..., *t*. This definition of *A(t)* is based on the premise that improvement efforts made in the previous periods have diminishing effects on the quality level at time *t*. We refer to *A(t)* as the effective quality capital. Here *Q(t), F(t),* and *A(t)* are state variables; whereas, *I(t)* is control variable. The dynamic relationship between quality level and quality costs can be shown as in Figure 2.

As illustrated in the model shown in Figure 2, the quality level at time *t* is dependent upon all the improvement efforts made over times 1, 2, ..., *t*. In other words, *Q(t)* is a function of *I(t)*, *I(t-1)*, ... *I(1)*. However, the effect of *I(t)* on *Q(t)* is different from those of *I(t-1)*, *I(t-2)*, ..., *I(1)*. To account for differences in the effects of improvement costs on quality level at time *t*, we introduce a firm-specific factor ($0 \leq \alpha \leq 1$) to reflect the effectiveness of the quality improvement program on quality level. Specifically, we use α to reflect the effects of improvement costs *I(t)*, *I(t-1)*, ..., *I(1)* upon the firm's quality level *Q(t)*. Thus, the effective quality capital *A(t)* for period 1 through *t* can be shown, (see Table II).

Therefore, *A(t)* can be defined as:

$$A(t) = I(t) + \alpha I(t-1) + \alpha^2 I(t-2) + \cdots + \alpha^{t-1} I(1) = \sum_{k=0}^{t-1} \alpha^k I(t-k). \quad (1)$$

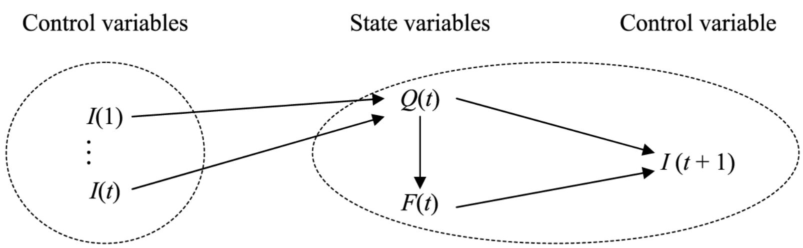


Figure 2.
Dynamics of quality costs and quality level

Table II.

Time	*A(t)*
1	*I(1)*
2	*1(2)* + α*I(1)*
3	*1(3)* + α*I(2)* + α^2*I(1)*
.	.
.	.
.	.
t	$I(t) + \alpha I(t-1) + \alpha^2 I(t-2) + \ldots + \alpha^{t-1} I(1)$

Note that quality level $Q(t)$ is an increasing concave function of effective quality capital $A(t)$ and thus is an increasing concave function of improvement costs $I(t), I(t-1), \ldots, I(1)$ as shown below.

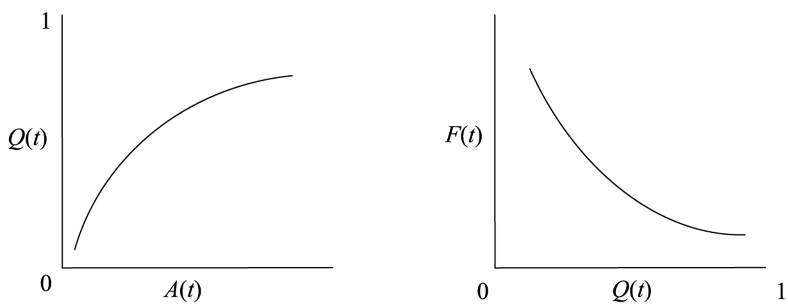
$$Q(t) = f[A(t)] = f[I(t) + \alpha I(t-1) + \alpha^2 I(t-2) + \cdots + \alpha^{t-1} I(1)]$$

$$= f[\sum_{k=0}^{t-1} \alpha^k I(t-k)]. \quad (2)$$

Thus, if any of $I(t), I(t-1), \ldots, I(1)$ increases, the marginal increase in $Q(t)$ will decrease, which shows the Pareto effect of improvement costs on the quality level over time. The quality level $Q(t)$ is determined also by the firm's effectiveness of the quality improvement program α, which governs the speed and sustainability of quality improvement over time.

What determines the effectiveness (α) of a quality improvement program? A broad range of activities collectively and synergistically help a firm to enhance its quality improvement program's effectiveness. Culture of quality, quality-related training, supply chain design and management, quality planning, design for quality, process design and planning, process control, quality audits are among the fundamental preventive measures that determine the sustainability of a firm's quality gains. While prevention cost is the least expensive quality cost component as discussed earlier, a small amount of investment in preventive measures results in substantial savings in internal and external failures as a result of enhanced quality.

Extending on the PAF model's behaviour of quality costs which indicates that prevention-appraisal cost is an increasing convex function in quality level, we conversely construct the quality level $Q(t)$ as an increasing concave function of effective quality capital $A(t)$. As discussed earlier and shown in Figure 2, in our model the quality level $Q(t)$ is determined by the firm's improvement efforts $I(t), I(t\text{-}1), \ldots, I(1)$. Thus, we assume that $Q(t) = f[A(t)]$ is an increasing concave function in $A(t)$ as depicted in Figure 3(a). Concavity of $Q(t)$ implies diminishing marginal quality improvement and is consistent with the Pareto effect (Juran, 1979). According to Pareto principle, poor quality is mainly accounted by a few quality problems, which implies that gains from quality improvement are substantial at the early stage of the quality



(a) Relationship between effective quality capital and quality level

(b) Relationship between quality level and failure cost

Figure 3.
Relationship between quality costs and quality level

improvement program when the few critical quality problems are detected and eliminated. By the assumption of $Q(t) = f[A(t)]$, our dynamic model does not merely incorporate absolute amounts of failure and improvements costs as they relate to the quality level. Rather, the model is constructed to reflect diminishing effects of improvement efforts upon quality level over time. As we shall show later, our robust dynamic model explains the total quality as well as the optimal quality views about relationships between quality cost and quality level.

Furthermore, consistent with the premises of the PAF model and Pareto principle, we assume that failure cost $F(t) = h[Q(t)]$ is a decreasing convex function in $Q(t)$ as depicted in Figure 3(b). Convexity of $F(t)$ implies diminishing marginal failure costs as quality level of the firm increases. This is to say that as quality level increases, the amount of savings from the reduced failures diminishes.

In summary, as shown in Figure 3(a) and (b), our dynamic model is similar to the PAF model in that failure cost $F(t)$ is a decreasing convex function of quality level $Q(t)$. Whereas, our model differs from the PAF model in that quality level $Q(t)$ is a function of effective quality capital $A(t)$ as opposed to simply improvement (prevention-appraisal) cost $I(t)$ in the PAF model.

The "higher quality-lower cost" phenomenon: illustrative examples

To construct illustrative examples, we need a functional form of quality level $f(x)$ which satisfies the following properties:

(1) quality level $f(x)$ is concave in effective quality capital x;

(2) quality level $f(x)$ is a percentage, i.e. $0 \leq f(x) \leq 1$;

(3) quality level $f(x)$ is increasing in effective quality capital x.

Properties (1) and (3) are valid due to the Pareto phenomenon that the marginal increase in quality level decreases as the effective quality capital increases. Properties (2) and (3) imply that $lim_{x\to\infty} f(x) = 1$, where $f(0) = 0$. Hence, we use the following functional form for $Q(t) = f[A(t)]$ satisfying the three properties stated above as widely used in the management science literature (Little, 1970; Lodish *et al.*, 1988; Li and Rajagopalan, 1998):

$$f(x) = \frac{ax^b}{n + ax^b}, \tag{3}$$

where $a, n > 0$ and $0 < b \leq 1$ are firm-specific parameters.

We consider a functional form of failure cost $h(y)$ which satisfies the following properties:

(1) failure cost $h(y)$ is convex in quality level y; and

(2) failure cost $h(y)$ is decreasing in quality level y.

Property (1) is also consistent with the Pareto phenomenon that the marginal decrease in failure cost decreases as quality level increases. Property (2) implies that $lim_{y\to\infty} h(y) = 0$ with $h(0) = \theta$, where θ is the firm's failure cost when its quality level y is 0. Hence, for the failure cost $F(t) = h[Q(t)]$, we formulate the following functional form satisfying the two properties as stated above:

$$h(y) = \theta\left(1 - \frac{cy^d}{m + cy^d}\right), \quad (4)$$

where θ, c, $m > 0$ and $0 < d \leq 1$ are firm-specific parameters.

As an illustrative example, let's assume that for a firm $I(1) = 6\%$ of its manufacturing cost, $a = 1$, $b = 0.9$, $n = 0.01$, $\theta = 0.24$, $c = 1$, $d = 1$, and $m = 5$. Let's also assume that $I(t) = (0.95)I(t-1)$, which means 5 per cent reduction in improvement cost at each time period. By a numerical example, we show the "higher quality-lower cost" phenomenon that *Q(t)* can increase even when *I(t)* decreases for a certain period of times. Note that in our model, the improvement cost *I(t)* and failure cost *F(t)* are expressed as percentages of the firm's manufacturing cost as used in practice and in the literature (Wheelwright and Hayes, 1985). Table III provides the result for 12 time periods under two values for the firm's effectiveness α of the quality improvement program. The selection of the two values for α is to compare the cost behaviour under two different effectiveness levels for the firm's quality improvement program. The higher value of α indicates a higher level of effectiveness.

Interestingly, the *I(t)* and *Q(t)* results for $\alpha = 95\%$ support the "higher quality-lower cost" behaviour embodied in the continuous improvement philosophy; while the "higher quality-higher cost" behaviour of the optimal quality model can be observed for $\alpha = 80\%$. In Table IV(a) for $\alpha = 95\%$, quality level *Q(t)* is continuously increasing while the firm's improvement cost *I(t)* decreases. In Table III(b) for α =80%, *I(t)* and *Q(t)* decrease simultaneously from period 5 onward. These results corroborate with earlier findings in the literature (Dale and Plunkett, 1991; Love *et al.*, 1995; Burgess, 1996; Ittner, 1996; Lorente and Rodriguez, 1998: Visawan and Tannock, 2004).

As can be seen in Figures 4(a) and 4(c), while the effective quality capital *A(t)* and quality level *Q(t)* increase steadily over time for $\alpha = 95\%$, we see a mixed behaviour of them when $\alpha = 80\%$. For $\alpha = 80\%$, *A(t)* and *Q(t)* increase till period 4 and then begin declining from period 5 onward.

The behaviour of the failure cost is also affected by the firm's effectiveness α of its quality improvement program. The higher α is, the smaller the firms' failure cost at each time period is, as shown in Figure 4(b). As improvement cost *I(t)* decreases, the firm's failure cost behaviour depends on α: while we see a steady decrease in the failure

	(a) Results for $\alpha = 95\%$				(b) Results for $\alpha = 80\%$			
Time	*I(t)*	*A(t)*	*Q(t)*	*F(t)*	*I(t)*	*A(t)*	*Q(t)*	*F(t)*
1	0.0600	0.0600	0.8883	0.2038	0.0600	0.0600	0.8883	0.2038
2	0.0570	0.1140	0.9341	0.2022	0.0570	0.0960	0.9239	0.2026
3	0.0542	0.1625	0.9512	0.2016	0.0542	0.1152	0.9346	0.2022
4	0.0514	0.2058	0.9602	0.2013	0.0514	0.1229	0.9381	0.2021
5	0.0489	0.2444	0.9657	0.2012	0.0489	0.1229	0.9381	0.2021
6	0.0464	0.2786	0.9694	0.2010	0.0464	0.1180	0.9359	0.2022
7	0.0441	0.3087	0.9720	0.2009	0.0441	0.1101	0.9321	0.2023
8	0.0419	0.3352	0.9740	0.2009	0.0419	0.1007	0.9268	0.2025
9	0.0398	0.3582	0.9754	0.2008	0.0398	0.0906	0.9201	0.2027
10	0.0378	0.3781	0.9766	0.2008	0.0378	0.0805	0.9120	0.2030
11	0.0359	0.3952	0.9775	0.2008	0.0359	0.0709	0.9023	0.2033
12	0.0341	0.4095	0.9782	0.2007	0.0341	0.0618	0.8909	0.2037

Table III. Results of the dynamic model

Table IV.
Three improvement cost strategies and quality levels

Time	(a) Improvement cost $I(t)$ for S_1	$I(t)$ for S_2	$I(t)$ for S_3	(b) Quality level for $\alpha = 95\%$ $Q(t)$ for S_1	$Q(t)$ for S_2	$Q(t)$ for S_3	(b) Quality level for $\alpha = 80\%$ $Q(t)$ for S_1	$Q(t)$ for S_2	$Q(t)$ for S_3
1	0.0600	0.0460	0.0341	0.8883	0.8621	0.8271	0.8883	0.8621	0.8271
2	0.0570	0.0460	0.0359	0.9341	0.9194	0.8994	0.9239	0.9139	0.8929
3	0.0542	0.0460	0.0378	0.9512	0.9414	0.9281	0.9346	0.9331	0.9185
4	0.0514	0.0460	0.0398	0.9602	0.9532	0.9437	0.9381	0.9431	0.9323
5	0.0489	0.0460	0.0419	0.9657	0.9605	0.9536	0.9381	0.9490	0.9411
6	0.0464	0.0460	0.0441	0.9694	0.9656	0.9605	0.9359	0.9529	0.9472
7	0.0441	0.0460	0.0464	0.9720	0.9693	0.9656	0.9321	0.9556	0.9519
8	0.0419	0.0460	0.0489	0.9740	0.9721	0.9696	0.9268	0.9576	0.9555
9	0.0398	0.0460	0.0514	0.9754	0.9743	0.9727	0.9201	0.9590	0.9585
10	0.0378	0.0460	0.0542	0.9766	0.9761	0.9753	0.9120	0.9601	0.9610
11	0.0359	0.0460	0.0570	0.9775	0.9775	0.9775	0.9023	0.9609	0.9633
12	0.0341	0.0460	0.0600	0.9782	0.9787	0.9793	0.8909	0.9615	0.9652
Total	0.5516	0.5516	0.5516	11.5223	11.4501	11.3524	11.0431	11.3089	11.2145

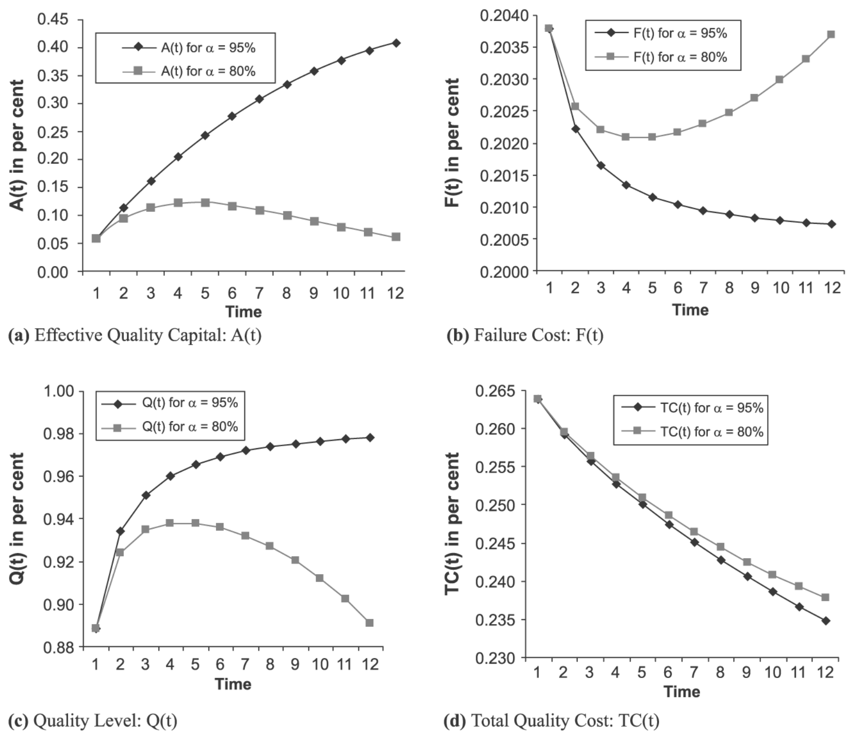


Figure 4.
Results of the dynamic model: quality costs and quality level

cost over time for $\alpha = 95\%$, the failure cost begins to increase from period 6 onward for $\alpha = 80\%$.

As can be seen in Figure 4(d), the firm's total quality cost *TC(t)* is steadily decreasing for both $\alpha = 95\%$ and $\alpha = 80\%$. For $\alpha = 95\%$, the "higher quality-lower cost" notion is observed in that the steady increase in quality level occurs while total quality cost decreases. Note however that in the case of $\alpha = 80\%$, this notion is temporarily observed in that the quality level increases up to time period 4 after which it decreases. As can be seen in Figure 4(c), the "higher quality-lower cost" phenomenon is observed up to time period 4, while beginning with time period 5 the optimal quality model's premise of "higher quality-higher cost," is evident. It is emphasized that the dynamic model developed in this paper is robust in that it provides flexibility in describing the behaviour of quality cost and quality level from both total quality and optimal quality perspectives.

As can be seen in Figure 5(a) and (b), the quality level *Q(t)* is increasing concave in the effective quality capital *A(t),* and the failure cost *F(t)* is decreasing convex in the quality level *Q(t).* Note that similar results are found for $\alpha = 80\%$, but the graphs are not shown.

Implications of these results for quality management practices include:

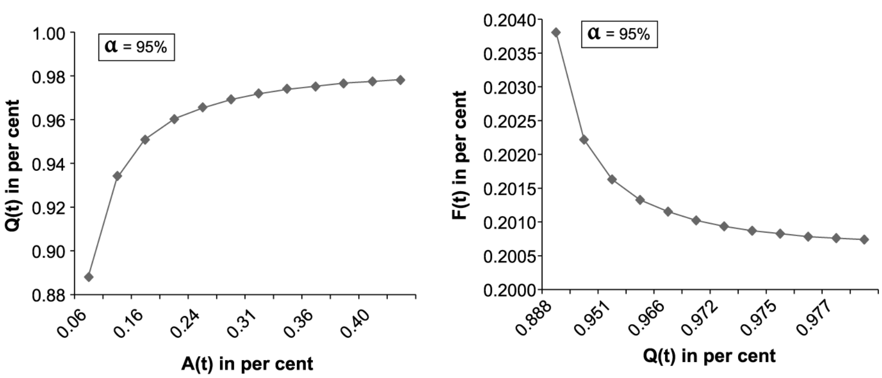
(1) The increase in quality level at each time period depends on α, the effectiveness of the firm's quality improvement program.

(2) A firm with a higher α, where the quality improvement program is highly effective, enjoys more sustainable benefits from previous periods' quality improvement efforts.

(3) A firm with a lower α, a less effective quality improvement program must keep up with its quality improvement efforts because its quality gains are not sustainable. By increasing quality improvement effectiveness through proactive quality improvement measures the firm will enjoy its full potential in the pursuit of zero defects.

(4) Most of the firm's savings in failure cost occur in the early years of its quality improvement program. To sustain the savings, the firm must continue with its quality improvement efforts.

(5) The firm's quality level at a given time period is determined by a continuum of its quality improvement efforts made already by the firm and not merely by its amount of improvement costs at that time period.



(a) Effective Quality Capital & Quality Level: A(t) & Q(t)

(b) Quality Level & Failure Cost: Q(t) & F(t)

Figure 5.
Results of the dynamic model: quality costs and quality level

(6) The "higher quality-lower cost" premise is valid for a firm with highly effective quality management program, while it may not be valid in the cases where the firm's quality management program itself needs some improvements to be more effective.

Dynamic effects of improvement costs on quality

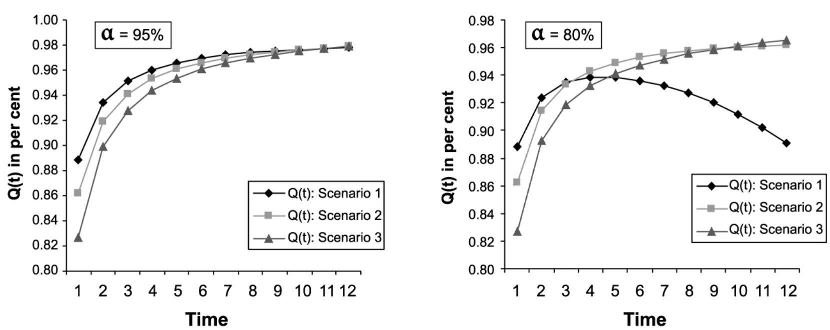
For illustrative purpose, the effects of firms' improvement efforts on quality level over time are examined in the context of three strategies related to the firm's allocation of a fixed total amount (0.5516) of improvement cost over $t = 1, 2, 3, \ldots, 12$. The three improvement cost strategies are:

- Strategy 1 (S_1): The firm decreases improvement costs over time.
- Strategy 2 (S_2): The firm keeps constant improvement cost over time.
- Strategy 3 (S_3): The firm increases improvement costs over time.

The effects of the three improvement cost allocation strategies on quality level of the firm are shown in Table IV, under two different values of firm's effectiveness of quality improvement program as before, i.e. $\alpha = 95\%$ and $\alpha = 80\%$.

Figure 6 illustrates the quality levels under each improvement cost allocation strategy for $\alpha = 95\%$ and $\alpha = 80\%$.

To be sure, these results provide interesting insights about how the firm's approach in allocating its quality improvement efforts impacts the resulting quality level over time. As can be seen in Table IV and Figure 6, when the firm's quality improvement program is highly effective ($\alpha = 95\%$), all three improvement cost allocation strategies deliver steadily increasing quality levels for the twelve periods shown in our example. However, among the three strategies, S_1 results in the highest quality level up to $t = 10$, while S_2 and S_3 deliver the highest quality level at $t = 11$ and $t = 12$, respectively. It is to be noted that on a finite planning horizon (such as the one of 12 time periods used in our example), S_1 results in the highest total quality level (11.5223). Note also that the quality level under S_1 will begin to decrease at some time period after $t = 12$, if the firm continues to decrease its improvement cost. In other words, under the decreasing improvement cost strategy, there will always be a turn point after which the firm's quality level will begin to decline, even when a firm has a highly effective quality improvement program.



(a) Quality Level: Q(t) **(b)** Quality Level: Q(t)

Figure 6.
Quality levels under three improvement cost allocation strategies

When the firm's quality improvement program is less effective ($\alpha = 80\%$), not all three strategies result in steady increase in quality level for the 12 time periods. Under S_1, the turn point occurs at $t = 5$, whereas the turn point takes place for neither S_2 nor S_3. Among the three strategies, S_1 results in the highest quality level up to $t = 3$, S_2 delivers the highest quality level for $t = 4, 5, \ldots, 9$, and S_3 achieves the highest quality level for $t = 10, 11, 12$. Again, we note that on the finite planning horizon S_2 results in the highest total quality level (11.3089). Note also that the turn point of quality level for $\alpha = 80\%$ occurs much earlier than that for $\alpha = 95\%$.

To clarify, as our example shows, turn points take place under S_2 and S_3, for neither $\alpha = 95\%$ nor $\alpha = 80\%$. This is true regardless of any values of α, which can be shown formally. It is obvious to see no turn points under S_2:

$$A(t) = I_c + \alpha I_c + \alpha^2 I_c + \cdots + \alpha^{t-1} I_c,$$
$$A(t+1) = I_c + \alpha I_c + \alpha^2 I_c + \cdots + \alpha^{t-1} I_c + \alpha^t I_c = A(t) + \alpha^t I_c,$$

where I_c denotes the constant improvement cost for each period. Thus, $A(t) \leq A(t+1)$ for any t. Recall that $Q(t)$ is an increasing function of $A(t)$. It follows that $Q(t) \leq Q(t+1)$ for any t.

The implication under S_3 is immediate. In this case, quality level will increase since $I(t) \leq I(t+1)$ for any t.

Therefore, depending upon the firm's improvement cost allocation strategy and its quality improvement program effectiveness; there may be a turn point after which the quality level will decline. More specifically, we note the following observations for each of the three improvement cost allocation strategies:

- *Decreasing improvement cost strategy*. Regardless of how effective the firm's quality improvement program is, there will always exist a turn point from which the quality level begins to decline. The higher the effectiveness of the firm's quality improvement program, the later the turn-point will occur.
- *Constant improvement cost strategy*. Regardless of how effective a firm's quality improvement program is, there will exist no turn point. The firm's quality level will never decline and may increase.
- *Increasing improvement cost strategy*. Regardless of how effective a firm's quality improvement program is, there will exist no turn point. The firm's quality level will always increase.

These observations imply that quality management systems striving for total quality through continuous improvement and effective preventive measures will succeed in delaying or practically never experiencing a turn point in the quality level of their products and services.

For firms with highly effective quality improvement program, quality gains achieved from improvement efforts during early stages has sustainable impact on the quality levels of the subsequent time periods. For these firms as observed in our illustrative example, the allocation strategy of decreasing improvement costs delivers the largest total quality level and this strategy is recommendable only for a short period of times. However, the continuation of this strategy for a longer period of times will eventually result in the decline of quality level. Thus, overall, a constant or increasing improvement cost strategy ensures continuous increase in quality level over long run. However, for firms with less effective quality improvement programs, the decreasing improvement cost strategy delivers the lowest total quality level and the decline in the quality level will begin to occur very soon and therefore, this strategy is not recommendable for either short or long term.

Conclusion

There have been some misconceptions about quality costs and their relations to quality level both in practice and in theory.

Many managers today pursue quality improvement relentlessly without fully considering the relationships between quality cost and quality level. Slogans such as "quality is free," may have limited (if not blinded) some managers' cost-consciousness. According to Hayes *et al.* (2005, p. 302) "changing attitudes and practices takes a long time, as does integrating all the programs that attack different sources of quality problems into a cohesive whole". This is certainly truer in the age of pursuing competitive edge in an era characterized by Fine's (1998) "Clockspeed."

The discipline of quality management still is evolving. While there has been substantial amount of research studies dealing with design and implementation of quality systems, the dynamics of quality costs however, have not widely been analysed. A better understanding of the dynamics of quality costs, the relationships between the effectiveness of a firm's quality improvement efforts and the quality level over time can help managers to better explain sometimes conflicting cost behaviours that historically have been distractive to practitioners and researchers.

To that end, utilizing a descriptive approach we developed a generic mathematical model to examine the dynamics of quality costs and quality level over time. The traditional PAF model based on the "higher quality-higher cost" notion fails to explain the total quality model's fundamental premise of "higher quality-lower cost." This paper demonstrated that depending on the level of effectiveness of the firm's quality improvement efforts there could be mixed results. Balancing between the two models, the dynamic model developed in this paper supports continuous improvement regardless of the level of effectiveness of the firm's quality improvement programs. When the quality improvement program is highly effective, the "higher quality-lower cost" phenomenon is observed. Whereas in a less effective quality improvement programs, we observe the "higher quality-higher cost" phenomenon, which still calls for increased improvement effort necessary for quality sustainability. Consistent with the Pareto effect embodied in the continuous improvement philosophy, this paper shows that most of the firm's savings in failure cost occur in the early years of quality improvement program. Nevertheless, to sustain the savings the firm must continue with its quality improvement efforts. These findings have important use especially for the quality improvement planning and budgeting decisions.

For future research, we suggest development of the firm's long-run average quality cost function to be used as a performance measure for assessing the quality improvement program. Under the performance criterion of long-run average quality cost, it would be interesting to determine analytically improvement costs over time based on firm-specific functional expressions of quality level and failure costs. While our model combined prevention and appraisal costs into improvement cost, it will be interesting to separately examine the behaviours of prevention and appraisal costs, and their relationships to quality level and failure costs. Finally, we suggest that our generic model be enhanced by incorporating the dynamics of the effectiveness of the firm's quality improvement program and its relation to quality level and quality costs.

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