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Title Page

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Abstract

While various techniques for improving product quality have been proposed, the supply chain network is often taken for granted. This paper considers quality control within a three-level supply chain and provides interesting findings that differ from the existing literature. Results suggest a curvilinear relationship between quality improvement efforts in the supply chain and brand owner profit: maximum efforts by the supplier and manufacturer do not guarantee optimal profit for the brand owner. Furthermore, two quality control methods - appraisal and certification - are examined. The quality control methods are found to affect both finished product quality and brand owner profit, but their impacts are moderated by the external failure cost of finished products. Results also suggest that no one particular quality control method dominates in terms of improving finished product quality or raising firm profitability. The optimal quality control method depends on the external product failure cost and other contextual factors in the supply chain.

Keywords: Inspection; Quality management; Simulation; Three-level supply chains
JEL Classifications: C63, D81, D82, L14, L15.

1. Introduction

Providing quality products is a challenge and each member of a supply chain plays a role in its assurance from raw materials through components to finished goods. Since superb product quality enhances consumer value, satisfaction, and loyalty, and provides the basis for firm profitability (Bowersox et al., 2007), firms have employed various quality management methods. For example, organizations in over 100 countries have adopted ISO 9000 (ISO.org, 2011). Corporations such as Motorola, Inc. and General Electric Company have implemented Six Sigma programs (Kotelnikov, 2008). Bayerische Motoren Werke AG (BMW) adopted computer-aided inspection (CAI) technology to ensure product quality at its engine manufacturing factory in Steyr, Austria (Higgins, 2003). Despite numerous efforts like these, quality management in supply chains remains mission unaccomplished.

Multi-level supply chains represent a reality in most industries. For instance, Apple outsources its hard drive production of iPods to Toshiba Cooperation in Japan. Most other major components of the iPod, such as the click wheel, lithium battery, media decoder, and controller chip, are outsourced to contract manufacturers as well (Varian, 2007). Unfortunately, just one quality issue at one stage of the supply chain can result in significant costs. For example, quality issues caused by a supplier of paint to an outsourced manufacturer lead to a massive recall of toys by Mattel (Merle, 2007). And while most previous studies have focused on quality issues within a two-level (dyadic) supply chain (Ahire et al., 1996; Benjaafar et al., 2007; Cachon and Lariviere, 2005; Das et al., 2000; Scannell et al., 2000; Schmitz, 2005), questions about quality management in more than two-level supply chains remain largely unaddressed. Studies of dyadic relationships, however, do not represent the complexity, nor the reality, of a typical supply chain.

In a multi-level supply chain, final product quality reflects quality at each individual level of the supply chain, and the entire supply chain must be aligned to deliver. Since longer and more complicated supply chains are likely to reduce visibility and control of product quality across firms, quality management methods that have been widely studied in a single firm or a buyer-supplier context may not be as effective in multi-level systems. For instance, quality management in a single firm tends to focus on the trade-offs between the cost of effort for improving product quality and the failure cost (tangible or intangible) incurred by bad quality. Hence, the optimal quality effort level could be more easily identified in that environment. However, as seen in cases such as Toyota's recalls, the bigger problem in quality management under supply chain environment is how to induce the members at different levels in a supply chain to exert effort to provide high quality products for final customers.

Within a three-level supply chain framework, this research aims to address the following questions: 1) How do quality improvement efforts by supply chain members at different levels affect the effectiveness and efficiency of quality management methods? 2) What are the impacts of different control methods on quality management in a three-level supply chain? 3) How do these impacts vary depending on contextual factors (such as external failure costs) in the supply chain?

This paper makes significant contributions to both the research literature and the practice of logistics management by extending quality management from dyadic to three-level supply chains. The effectiveness and efficiency of two quality management methods are investigated within a three-level supply chain. Results suggest that, under either method, simply exerting more quality improvement effort does not result in high brand owner profitability within the supply chain. Furthermore, differing from traditional quality studies that merely consider cost as an outcome of product quality (Cachon and Zhang, 2006; Tagaras and Lee, 1996), this paper examines how external failure costs affect the quality level of finished products. Specifically, the interactions of quality control methods and external failure costs within a supply chain on overall product quality are investigated.

The remainder of this paper is organized as follows. The following section reviews the relevant literature. The research methodology is described in the third section. Then, the analysis is presented and the managerial implications are drawn. Finally, conclusions and future research directions are discussed in the last section.

2. Literature review

In the existing literature, several approaches have been proposed to improve product quality including supplier selection, inspection, and process control (Anderson et al., 1995; Ahire et al., 1996; Cachon and Zhang, 2006; Flynn et al., 1995; Kaynak and Hartley, 2008; Meena et al., 2011; Voss et al., 2009). However, these quality control approaches are investigated only within a two-level supply chain, substantially simplifying the supply chain control and decision mechanisms with regard to quality assurance. Many quality challenges, such as those faced by Mattel, arise because the supply chain network is much more complex, and the relationships are much more diverse, than those of a dyad. Based on previous research, this paper extends the quality management literature by considering a three-level supply chain framework.

Tagaras and Lee (1996) analyzed both input component quality and the manufacturing process to investigate the tradeoff between quality and cost in a "vendor-vendee relationship." They suggest that looking only at the manufacturing process is not sufficient. Input component quality, the manufacturing process, and quality costs should be jointly considered in order to secure quality finished products. Their perspective provides a theoretical foundation for this research. In this paper, a supply chain includes a brand owner, a manufacturer, and a component supplier, where both the manufacturer's and the supplier's work contribute to the quality of the finished product.

Zhu et al. (2007) focused on interactions between a buyer who owns the brand and provides the product design and a supplier who is in charge of the manufacturing process. They argue that the buyer's investment in the supplier's quality improvement process significantly raises the quality level and the profit of both parties. Based on their results, this research allows the brand owner to invest in quality improvement by compensating both the manufacturer and the component supplier, thereby inducing them to exert quality improvement effort.

Balanchandran and Radhakrishnan (2005) investigated a warranty contract in a two-level supply chain where a final product consists of components made by both the buyer and the supplier. The effectiveness of the warranty contract was found to depend on information from both inspection and external failure. In addition, Hwang et al. (2006) compared inspection and certification method in terms of the supplier quality efforts and product quality. They found that the use of certification increases despite the increasing effectiveness of inspection. However, their findings in a buyer-supplier (two-level) supply chain may be not generalizable to a more realistic supply chain structure involving more members.

Although there are studies dealing with multi-level supply chain management, few of them ever investigate the quality issues or the impact of competing quality management methods in those settings. Building upon previous work, this research considers a three-level supply chain where members decide their respective levels of effort to manage product quality through not only manufacturing but also procurement. This modeling framework extends previous research and generates important results that provide insightful implications of supply chain behaviors on quality management.

3. Research method

Understanding quality issues in multi-level supply chains is complicated by the multiple dependencies among members at different levels. We allow for curvilinear relationships with uncertainty between quality effort levels and resultant costs as suggested in prior literature (Tagaras and Lee 1996, Balanchandran and Radhakrishnan 2005), in order to capture the imperfect production process at different levels of the supply chain. Such relationships typically leave the three-level systems virtually intractable analytically. As a consequence, simulation is used in this research to model such complexities, such as product and payment flows in a supply chain.

3.1. Product quality within a three-level supply chain

As mentioned above, this analysis considers a supply chain framework consisting of a brand owner[①], a manufacturer, and a supplier. As shown in Figure 1, the brand owner, such as Mattel,

[①] The brand owner is simply the label for the firm that is responsible for acquiring, marketing and distributing the finished products to the final customers. The findings in this study apply equally well whether the finished products are branded or not.

outsources production to the contract manufacturer, who produces the final product with parts procured from the component supplier. Since a finished product is the outcome of two sequential quality processes (the component input and the manufacturing process), the quality of the final product depends on the quality performance of both the manufacturing and the procurement processes.

< Insert Figure 1 here >

Neither component inputs nor the production process are perfect in this three-stage supply chain, but the supplier and the manufacturer are able, at a cost, to exert effort to improve quality. However, their actual effort levels are unobservable to the brand owner.

Following the quality framework of Balanchandran and Radhakrishnan (2005), the supplier's quality improvement effort, q_s , is modeled as the probability that the component performs the desired functions (i.e., the component has acceptable quality). The manufacturer's quality improvement effort, q_m , represents the probability that its work performs the desired functions. All variables used in the analysis are described in Table 1. Details about the simulation are provided in the Appendix.

< Insert Table 1 here >

3.2. Supply chain quality control methods

Within a three-level supply chain framework, this research considers the application of two competing quality management methods which have been widely implemented in industry and studied in dyadic supply chains (e.g. Balanchandran and Radhakrishnan, 2005; Hwang, et al., 2006; Starbird, 1997). The first is quality appraisal, which is a traditional quality control method defined as an inspection process of incoming items. The second, more recent method is supplier certification, which has become wide-spread due in part to ISO 9000. This method requires that the buyer evaluate and certify the seller's capability and facilities (rather than its physical products) based on an established process (such as ISO 9000 or a certified supplier process). Once the seller passes the evaluation and certification is granted, no further inspection is needed for component shipments, and shipments are immediately accepted for use in the production of finished goods. Many successful firms such as Toyota have used supplier certification to eliminate expensive, non-value-added inbound inspections. The quality appraisal and supplier certification methods are largely mutually exclusive of each other since they are rarely used simultaneously.

3.2.1. Appraisal control method

Using quality appraisal, the manufacturer inspects components delivered from the supplier. The inspection process is imperfect and does not identify all defective units. Specifically, the probability of identifying a defective unit in the manufacturer's inbound process is denoted as θ, and after the manufacturer identifies the percent defective in a shipment, it makes a recovery effort to fix the defective components before converting them into finished products.

As shown in Figure 1, depending on the outcome of the component inspection, the supplier is paid an amount of c if the component passes the inspection and c_s if it does not. Similarly, the brand owner pays the manufacturer for each unit of finished product depending on the outcome of the product: w if no product defects are identified by customers and w_m if defects are detected by customers. (In practice, the manufacturer is likely to receive full payment when it delivers finished product to the brand owner. Then, the brand owner would charge back a penalty in the case of product defects. For the purpose of model simplification and without loss of generality, it is assumed that the manufacturer is paid after customers have had a chance to identify any defects.) Since high quality components and finished products are more desirable, $w > w_m$, $c > c_s$.

The simulation steps for the quality appraisal process are shown on the left side of Figure 2.

< Insert Figure 2 here >

3.2.2. Certification control method

Under supplier certification, the brand owner requires that the manufacturer only source from suppliers that have obtained external certification such as ISO 9000 (Hwang et al., 2006). The brand owner pays the manufacturer a unit price, w or w_m, for the finished product depending on the finished product quality, q_m. The manufacturer pays supplier a unit price, c or c_s, depending on the component quality q_s. Since NO inspection is performed within the supply chain, the brand owner only realizes quality issues through external product failures reported by end customers, such as product returns and recalls. Once there are external product failures, the brand owner investigates and identifies the cause of the failure as either the supplier's or the manufacturer's fault. This process of assigning responsibilities is not perfect either, resulting in the possibility of external failures being incorrectly assigned.

The brand owner pays the manufacturer w or w_m per unit for non-defective and defective products identified with manufacturing defects, respectively. The manufacturer in turn pays the supplier c or c_s per unit for non-defective and defective components. In the case of supplier certification, the simulated events are shown on the right side of Figure 2.

3.3. Simulation parameters

In order to investigate the impact of quality control methods on product quality and firm profit within the supply chain, certain contextual factors are fixed (such as component inspection effectiveness θ, the price of the finished product for end customers *r*, and the external failure cost *l)* at specific levels in the simulation in order to avoid confounding issues. The cost of external failures is allowed to vary in a later analysis in order to investigate the impact of contextual factors on quality and profit performance. Daily demand from end customers for finished products (D) is assumed to be a constant 1,000 units, and a unit of finished product requires two component units from the supplier. Input parameter values for the simulation model as shown in Table 2 are selected based on industry practices. Further sensitivity analysis based on these input parameter values suggests that the result pattern is largely unchanged and thus demonstrates the robustness of the essence of our findings in the paper.

< Insert Table 2 here >

3.4. Experimental design

The experimental design consists of the two quality control methods and six decision variables made by firms in the supply chain. These include the set of pricing decisions for good and defective components (c, c_s) and for good and defective finished products (w, w_m), and the set of quality improvement efforts for component supplier and manufacturer (q_s , q_m). c_s and w_m are each set at a low level, since they represent either no or very low payments for defective component or products. The decision variables (*c*, *w*) are each tested at five different levels, while quality improvement efforts (q_s , q_m) are each tested at nine different levels. The combination of these two quality control methods and six decision variables results in 16,200 ($2\times5^2\times9^2\times2^2$) scenarios. Such a large number of scenarios offer the opportunity of searching for optimal quality improvement efforts in a complicated environment. Later, the analysis is extended to investigate how changes in contextual factors (e.g. external failure cost) influence quality levels and firm performance, leading to many multiples of the 16,200 scenarios.

Table 3 presents the experimental design including two quality control methods, three sets of component prices, three sets of manufactured product prices, and four sets of quality improvement efforts, which results in the 16,200 combinations.

< Insert Table 3 here >

3.5. Model validation, verification, and simulation

To ensure that the computer-based simulation model accurately portrays supply chain operations, validation of both the conceptual models and the results was performed. Related literature and industry practice has provided extensive validity to the three-level supply chain model (Balanchandran and Radhakrishnan, 2005; Hwang et al., 2006; Tagaras and Lee, 1996). A careful walk-through of the conceptual models shown in Figure 2 was conducted before the development of the computer-based model (Law, 2005; Manuj et al., 2009). Simulation output validation was performed after model verification, as explained below.

PHP, a general-purpose scripting language, was used to build the simulation models. In order to ensure that the computer program correctly reflected the conceptual model, verification was conducted for the two quality control methods respectively. Simulated entities were traced throughout each scenario in the experimental design. A log file recorded every single activity in the simulation. Product flows were tracked and analyzed. The computer-based model was found to consistently follow the logic of the conceptual model.

After the simulation was run, the results were also validated. All variable values at each level of the supply chain, such as failure rate, cost, and revenue, were verified by comparing them with the manually calculated values for the first 50 days of the simulation. Then, sensitivity analysis was performed to test the impact of the model factors on the simulation results.

Each scenario was run for 1,000 days and replicated 5 times. The first 200 days in each replication was truncated to eliminate the initial transient data. Thus, for each replication, data from day 201 to day 1000 (800 observation days) were recorded. This sample size provided sufficient statistical power and is similar to prior work in the literature (Boyer et al., 2009; Nachtmann et al., 2010).

3.6. Output measures

The selection of the quality management methods employed in a supply chain is often made by the brand owner. Hence, as indicators of the effectiveness and efficiency of quality management respectively, the simulation had two main outputs: the failure rate of finished products and the profit of the brand owner which includes the loss of customer good will if the products fail. The quality improvement efforts, failure rates, and brand owner profit were recorded for each replication, and then their means were calculated for each of the 16,200 scenarios. At the end, the best scenario was selected in terms of maximizing brand owner profit while assuring that the manufacturer and the supplier put forth their appropriate quality improvement efforts in the supply chain.

4. Results

4.1. Quality improvement efforts and profit of brand owners

This section examines how the quality improvement efforts exerted by the supplier and manufacturer affect brand owner profit. Figure 3 shows the relationship between the manufacturer's quality improvement effort and the brand owner profit under the two quality control methods**.** Given a fixed level of supplier quality improvement effort, with an increase in the quality improvement effort by the manufacturer, brand owner profit demonstrates an overall increase. This result confirms that the brand owner prefers high product quality for profit maximization.

However, the relationship between manufacturer quality improvement effort and brand owner profit is not increasing in a linear fashion. In terms of maximization of brand owner profit, manufacturer quality improvement effort reaches the optimal at 0.9 under quality appraisal and at 0.95 under supplier certification in terms of the brand owner profit, not at the maximum level of 1, because high quality improvement effort increases not only brand owner revenue but also manufacturer and supplier quality improvement costs and, consequently, raises prices of finished products paid by the brand owner. Similar results are obtained for the relationship between supplier quality improvement effort and brand owner profit when the manufacturer quality improvement effort is fixed at a certain level. *The results indicate that high quality improvement efforts exerted by the supplier and the manufacturer generally contribute to the brand owner profit, but the maximum efforts are not necessarily associated with maximum brand owner profit.*

< Insert Figure 3 here >

In order to investigate which quality control method leads to a higher brand owner profit, box-plots are drawn for finished product failure rates and brand owner profit under quality appraisal and supplier certification (see in Figure 4). It is unclear which quality control method dominates for either higher finished product quality or brand owner profit as their ranges overlap. Therefore, other contextual factors must be jointly considered with quality control methods. These extensions are examined next.

< Insert Figure 4 here >

4.2. External failure cost and quality control methods

The previous section discussed how quality improvement efforts and quality control methods affect brand owner profit given a fixed external failure cost. In reality, however, external failure costs may not be constant. For example, the external failure cost incurred by Toyota due to brake failures is vastly different from those due to failures of non-critical components such as radios or windshield wipers. Thus, to generalize this study, the impact of external failure costs on quality outcomes and profit under the two quality control methods is explored.

To this end, the external failure cost is allowed to change in the range of l = (0, 10, 20, 30, and 40) as shown in Table 3; consequently, the number of scenarios increases from 16,200 to 81,000 (i.e. 5×16,200). After running the simulations, an optimal decision set with maximum brand owner profit was selected for each external failure cost value, leading to the best brand owner profit with the corresponding finished product failure rate, as shown in Table 4.

< Insert Table 4 here >

In each of the 81,000 scenarios, all data after the initial transient period were recorded. Then, the average values of all input and output variables (such as quality improvement efforts, finished product failure rate, and brand owner profit) for each scenario were calculated and aggregated. Both Multivariate Analysis of Variance (MANOVA) and Univariate Analysis of Variance (ANOVA) were used to study the main effects of external failure cost and quality control methods and their interactive effect on two dependent variables: finished product failure rate and brand owner profit. ANOVA is applied to test these effects on two dependent variables independently, while MANOVA is conducted on the two dependent variables simultaneously since finished product failure rates and brand owner profit are likely to be correlated (Chen et al., 2007; Closs et al., 2010; Nachtmann et al., 2010).

Table 5 summarizes the MANOVA and ANOVA results. These analyses indicate that the main effects of external failure costs and quality control methods, and their interactive effect, are all significant. These results confirm that there is no one method of quality control that dominates in terms of providing better finished product quality and higher brand owner profit in all scenarios. In fact, the differences of these two supply chain quality control methods depend on the extent of external failure costs, as highlighted in Figures 5 and 6.

< Insert Table 5 here >

First, the main and interaction effects of external failure cost and quality control methods on finished product quality are shown in Figure 5. When the external failure cost increases, the finished product failure rate decreases under both quality appraisal and supplier certification. However, *supplier certification leads to a lower finished product failure rate than quality appraisal when the external failure cost is low, while quality appraisal provides a lower finished product failure rate than supplier certification when the external failure cost is high.* This result implies that increased external failure cost provides more motivation for firms in the supply chain to exert high quality effort under quality appraisal than under supplier certification.

< Insert Figure 5 here >

Second, the main and interaction effects of external failure cost and quality control methods on brand owner profit are illustrated in Figure 6. When external failure cost increases, brand owner profit decreases under both quality appraisal and supplier certification. Furthermore, brand owner profit decreases faster under quality appraisal than supplier certification. *Supplier certification leads to lower brand owner profit than quality appraisal does when the external failure cost is low, while supplier certification leads to higher brand owner profit than quality appraisal does when the external failure cost is high.*

< Insert Figure 6 here >

These two figures imply that when the external failure cost is low, quality appraisal is more efficient (with higher brand owner profit) but less effective (with higher finished product failure rate) than supplier certification. In contrast, when the external failure cost is high, supplier certification is more efficient (with higher brand owner profit) but less effective (with higher finished product failure rate) than quality appraisal.

This interesting result may be due to the fact that supply chain quality performance depends on quality improving efforts and effective inspection of component quality. When the external failure cost is low, investing in quality improvement has limited potential to improve supply chain profitability. Therefore, the manufacturer and supplier tend to rely on inspection to reduce overall product failure rate while avoiding expensive quality improvement efforts, leading to efficient supply chain quality operations (higher brand owner profit). Using supplier certification, the manufacturer and supplier can only invest in quality improvement in their respective operations to avoid the penalties from external failures. While this leads to higher finished good quality, it is not necessarily efficient due to the limited savings from reduced external failures. However, when the external failure cost is high, under supplier certification, the manufacturer and supplier are more motivated and justified to increase quality improvement efforts (and their related costs) to reduce the high external failure costs, leading to more efficient operations (higher brand owner profit) than those under quality appraisal. However, without component inspection, the overall finished product quality under supplier certification is not improved as effectively as it is under quality appraisal.

As summarized in Table 6, with the changes in external failure cost, there is no one particular quality control method that dominates in terms of increasing both brand owner profit and overall product quality. When the external failure cost is small, quality appraisal leads to a higher brand owner profit, but a lower overall product quality, than supplier certification does. When the external failure cost is high, supplier certification leads to a higher brand owner profit, but a lower overall product quality, than quality appraisal does.

< Insert Table 6 here >

5. Managerial implications

Intuitively, a brand owner would always prefer that its supplier and manufacturer exert full quality improvement effort in order to maximize its profit. However, as shown in Figure 3, the optimal quality improvement efforts achieved in the supply chain is not necessarily at its highest level. High quality improvement effort not only increases the quality of finished product and the brand owner revenue, it also raises the costs incurred by the brand owner, such as the price paid for the finished product, the related compensation for the efforts of the supplier and the manufacturer, and external failure costs associated with product quality. Thus, the positive impacts of quality improvement efforts taken by the supplier and the manufacturer on the brand owner profit are not linear. For the brand owner, high quality improvement effort does not guarantee maximum profit.

The MANOVA and ANOVA results suggest that quality control methods significantly affect both finished product quality and brand owner profit. Thus, supply chain managers should take into account the quality control methods employed when addressing quality management issues. However, quality control methods are not the only factors that brand owners need to consider to improve finished product quality and profit. Their impact is highly dependent on the extent of the external failure cost. Results suggest that quality appraisal is the appropriate option for the brand owner to increase profitability when the external failure cost is low, but supplier certification is preferred when external failure cost is high.

Moreover, this paper provides a new perspective on the relationship between product quality level and quality costs. Quality costs are generally viewed as the outcome of the quality level. On the contrary, this study suggests that external failure costs should to be considered an input factor that contributes to product quality. Furthermore, its interactive effect with quality management methods on finished product quality and brand owner profit should also be recognized by firms.

6. Conclusions, contributions, and future research

Managing quality in supply chains has become a major challenge in the age of globalization. One of the main reasons is the nature of quality dependencies in the supply chain, which complicates quality decisions among partners as the supply chain becomes longer with outsourcing and offshoring. In this paper, quality management models are developed in a three-level supply chain (i.e. a brand owner, a manufacturer, and a supplier) employing different quality control methods. The objective is to better understand supply chain quality decisions and their impact on supply chain member performance.

A curvilinear relationship between quality improvement effort in the supply chain and brand owner profit is found in this simulation study. Maximum levels of quality improvement effort by the supplier and the manufacturer do not guarantee optimal profit for the brand owner. Thus, pursuing maximum quality improvement effort at all cost is not necessarily an appropriate quality management strategy for the firm's bottom line.

Moreover, the impacts of quality control methods on product quality and brand owner profit are moderated by the external failure cost. When the external failure cost is low, quality appraisal leads to a higher level of profit for the brand owner than supplier certification does. When the external failure cost is high, supplier certification dominates quality appraisal.

The paper makes significant contributions to the logistics management literature. First, a three-level supply chain is proposed to focus on the interdependency between quality improvement efforts of supply chain members. The models incorporate the interests of supply chain members to exert quality improvement efforts. Second, this paper studies different supply chain quality control methods—appraisal and certification. Third, this paper provides a new perspective on the relationship between quality level and costs. Whereas quality costs are typically regarded as a consequence of product quality, this research finds that external failure cost affects the quality level of finished products. Fourth, the interactive impacts of quality control methods and external costs in the supply chain on the overall product quality and profit performance are investigated. The impact of quality control methods is found to be moderated by the external failure cost of the supply chain.

These contributions are significant because, despite the importance of quality management in logistics management, it is understudied particularly from a supply chain perspective. This research is aimed at improving the understanding of quality management in supply chains based on a simulation approach. Results provide new insights and implications to the literature and practice.

Opportunities for future research can be summarized in three primary areas. First, inclusion of dynamic analysis can be considered as results may vary. If dynamic analysis is applied, firm quality performance and reputation could be carried over time. The optimal quality output may change when long term profit is considered. Second, other contextual factors can be considered in addition to external failure costs. Varying cost parameters associated with quality improvement efforts at the supplier and the manufacturer will make the quality models more realistic—the resulting outcomes, however, are not apparent. Finally, it would be interesting to examine more complicated supply chain networks (such as supply chains with multiple firms at each echelon) as considerable ambiguity remains regarding their effect. Unfortunately at this point, allowing multiple firms at each echelon or allowing more than three echelons in the supply chain will increase the analysis complexity exponentially, even if just using the simulation technique. By taking these additional complexities into account, future analyses of quality management in supply chains will continue to evolve toward more realistic applications and insightful theories.

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Appendix

This appendix provides additional details of the simulation. PHP, a general-purpose scripting language, was used to build the simulation models. Stata 11 was used to analyze the simulation records and generalize the test results of MANOVA and ANOVA.

Following the frameworks of Hwang, et al. (2006) and Balanchandran and Radhakrishnan (2005), the supplier's quality improvement effort, q_s, is modeled as the probability that the component performs the desired functions (components with acceptable quality) with a corresponding quality cost of $S(q_s) = \alpha_0 + \alpha_1 q_s + \alpha_2 q_s^2 + \varepsilon_s$, where ε_s is a random variable representing the uncertain nature of supplier quality cost. This random variable follows a normal distribution with mean 0 and standard deviation 0.5. The manufacturer's quality improvement effort, q_m, represents the probability that its work performs the desired functions with a corresponding quality cost of $M(q_m) = \beta_0 + \beta_1 q_m + \beta_2 q_m^2 + \varepsilon_m$, where ε_m is a random variable representing the uncertain nature of manufacturer quality cost, which follows a normal distribution with mean 0 and standard deviation 0.5.

Using quality appraisal, as shown in Figure 2, firms interact with their direct customer and supplier in the supply chain through the following sequence of events:

(1) The brand owner and manufacturer agree on the unit prices of the product $\{w, w_m\}$. The manufacturer and supplier agree on the unit component prices $\{c, c_s\}$.

(2) The supplier chooses its quality enhancement effort $\{ q_s \}$.

(3) The manufacturer receives the component from the supplier and inspects it. If the component is identified as good, the manufacturer pays c to the supplier. If the unit is identified as defective, the supplier is only paid c_s.

(4) The manufacturer then exerts its committed quality improvement effort in the production process (q_m) and sells the finished product to the brand owner.

(5) The brand owner receives the finished good from the manufacturer and sells it to the consumer for r per unit. If the product fails due to defects, the consumer returns it for full refund and the brand owner incurs the external failure cost of (r+l).

(6) If the finished product incurs no failure in the market, the brand owner pays w to the manufacturer. For each unit of failure, the brand owner pays w_m to the manufacturer.

The portion of defective finished product in total supply is $F=(1-q_s)(1-\theta)+[q_s+(1-q_s)\theta](1-q_m)=1-[q_s+(1-q_s)\theta]q_m$, while the portion of good finished product is $[q_s+(1-q_s)\theta]q_m$.

Using supplier certification, as shown in Figure 2, the firms interact with others in the supply chain through the following sequence of events:

(1) The brand owner and manufacturer agree on the unit price of the product $\{w, w_m\}$. The manufacturer and supplier agree on the unit component price $\{c, c_s\}$.

(2) The supplier chooses its quality enhancement effort { q_s }.

(3) The manufacturer receives the component.

(4) The manufacturer then exerts its committed quality improvement effort in the production process (q_m) and sells the finished product to the brand owner.

(5) The brand owner receives the finished good from the manufacturer and sells it to the consumer for r per unit. If the product fails due to defects, the consumer returns it for full refund and the brand owner incurs the external failure cost of (r+l).

(6) If the finished product incurs no failure in the market, the brand owner pays *w* to the manufacturer. For each unit of failure, the brand owner pays w_m to the manufacturer if the brand owner identifies the manufacturer as the cause of the defective products.

(7) The manufacturer in turn pays *c* to the supplier for good finished products and pays c_s to the supplier if the brand owner identifies the supplier as the cause of the defective products.

The proportion of external failures that are identified as the fault of the manufacturer and the supplier, respectively, are e_m and e_S:

$$e_s(q_s, q_m) = a(1-q_s) + (1-b)(1-q_m)q_s \,,$$

$$e_m(q_s, q_m) = (1-a)(1-q_s) + b(1-q_m)q_s \,,$$

where $a \in (0,1]$ and $b \in [0,1]$. *a* is the probability that the supplier is correctly held responsible for the external failures, and *b* is the probability that the manufacturer is correctly held responsible for poor work. The parameters {*a*, *b*} denote the precision of the identification technology, with higher *a* and *b* indicating higher precision.

Under both appraisal and certification methods, in order to maintain the business with the component supplier and the manufacturer and induce high quality from them, the brand owner has to structure its payment scheme to satisfy a set of requirements which provide enough incentive for the manufacturer to exert the necessary effort to raise its quality. By the same token, the manufacturer has to design its payment scheme to the supplier in such a way that it offers the supplier sufficient incentive to exert the necessary effort to raise its component quality. (1) The price for a good component (finished product) needs to be greater than the price for a defective component (finished product): $c > c_s$, $w > w_m$. (2) In order to ensure that the revenue received by the manufacturer covers its cost of components, the price for a unit of finished product needs to be greater than the cost of two units of components (recall that a unit of finished product requires two unit of components): $w > 2c$, $w_m > c_s$. Thus, in the simulation model, prices of component parts are set as c = (6, 8, 10, 12, 14) and c_s = (0, 3), prices of finished product at the manufacturer are set as w = (30, 34, 38, 42, 46) and w_m = (0, 10), and the quality improvement effort at both the supplier and the manufacturer is set as q_m = (0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1) and q_s = (0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1).

TABLES

Table 1. Variable descriptions

Variable	Description
q_s	Quality improvement effort made by component supplier, which indicates the probability that the component performs the desired functions (components with acceptable quality).
q_m	Quality improvement effort made by manufacturer, which indicates the probability that the manufacturing process performs the desired functions.
$S(q_s)$	Quality cost incurred by component supplier.
ε_s	Random factor in quality cost for component supplier. It follows the distribution: Normal (0, 0.5).
$M(q_m)$	Quality cost incurred by component supplier.
ε_m	Random factor in quality cost for manufacturer. It follows the distribution: Normal (0, 0.5).
θ	Inspection effective rate which indicates the probability of identifying a defective components when manufacturer inspects them.
a	Probability that supplier is correctly held responsible for external failures (because of unqualified components).
h	Probability that manufacturer is correctly held responsible for poor work despite good component provided.
F	Total number of defective finished products.
c	Price paid by manufacturer to component supplier for each unit of component that passes inspection.
c_s	Price paid by manufacturer to component supplier for each unit of component that fails inspection.
w	Price paid by brand owner to manufacturer for a unit of finished product that does not fail in the market.
w_m	Price paid by brand owner to manufacturer for a unit of finished product that is identified by end customers as defective in the market.
e_m	Manufacturer's fault identified by brand owner in case of external failure of finished product.
e_S	Supplier's fault identified by brand owner in case of external failure of finished product.
r	Price of a unit of finished product sold by brand owner to end customers.
l	External failure cost incurred by brand owner for a unit of defective finished product identified and returned by end customers.

Table 2. Simulation parameters

Parameters	Symbol	Quality Appraisal	Supplier Certification
Inspection effectiveness	θ	0.9	N/A
Price for finished product charged by brand owner	r	50	50
External failure cost for defective finished product paid by brand owner	l	20	20
Demand for finished products	D	1,000	1,000
Fault identified for supplier	a	N/A	0.8
Fault identified for manufacturer	b	N/A	0.9
Quality cost at supplier	$\alpha_0 = 1,\ \alpha_1 = 1,\ \alpha_2 = 12,\ \varepsilon_s$ follows Normal (0,1)		
Quality cost at manufacturer	$\beta_0 = 2,\ \beta_1 = 4,\ \beta_2 = 25,\ \varepsilon_m$ follows Normal (0,1)		

Table 3. Experimental design

Factor	No. of Levels	Level
Price for good finished product w	5	(30, 34, 38, 42, 46)
Price for defective finished product w_m	2	(0, 10)
Price for good component c	5	(6, 8, 10, 12, 14)
Price for defective component c_m	2	(0, 3)
Quality improvement effort of manufacturer q_m	9	(0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1)
Quality improvement effort of supplier q_s	9	(0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1)
External Failure Cost l	5	(0, 10, 20, 30, 40)
Quality Control Method	2	Quality Appraisal, Supplier Certification

Table 4. Best levels of finished product quality and brand owner profit

External Failure Cost	Quality Appraisal		Supplier Certification	
	Finished Product Failure Rate	Brand Owner Profit	Finished Product Failure Rate	Brand Owner Profit
0	0.23	7952	0.20	6,340
10	0.14	6416	0.12	5,660
20	0.14	4656	0.10	4,685
30	0.04	3776	0.10	4,060
40	0.04	1776	0.09	2,906

Table 5. Multivariate and univariate ANOVA test results

Main & Interactive Effects	Multivariate ANOVA	Univariate ANOVA	
	Finished Product Failure Rate and Brand Owner Profit	Finished Product Failure Rate	Brand Owner Profit
External Failure Cost	6,211***	1,254***	6,818***
Quality Control Method	11,128***	22,257***	11,667***
External Failure Cost × Quality Control Method	442***	889***	426***

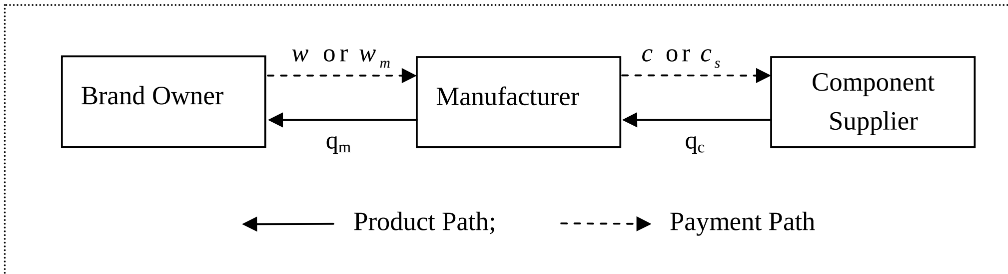
Note: the numbers shown in the cells are F-statistics.

*** Significant at the 1% level.

Table 6: Appropriate quality control methods for a given set of conditions

External Failure Cost		Finished Product Quality	Brand Owner Profit
	High	Appraisal Control Method	Certification Control Method
	Low	Certification Control Method	Appraisal Control Method

FIGURES



Note: Symbols below the solid arrows indicate the quality of components and the manufacturing process. Symbols above the dotted arrows indicate the payments for components and finished products.

Figure 1. Three-level supply chain

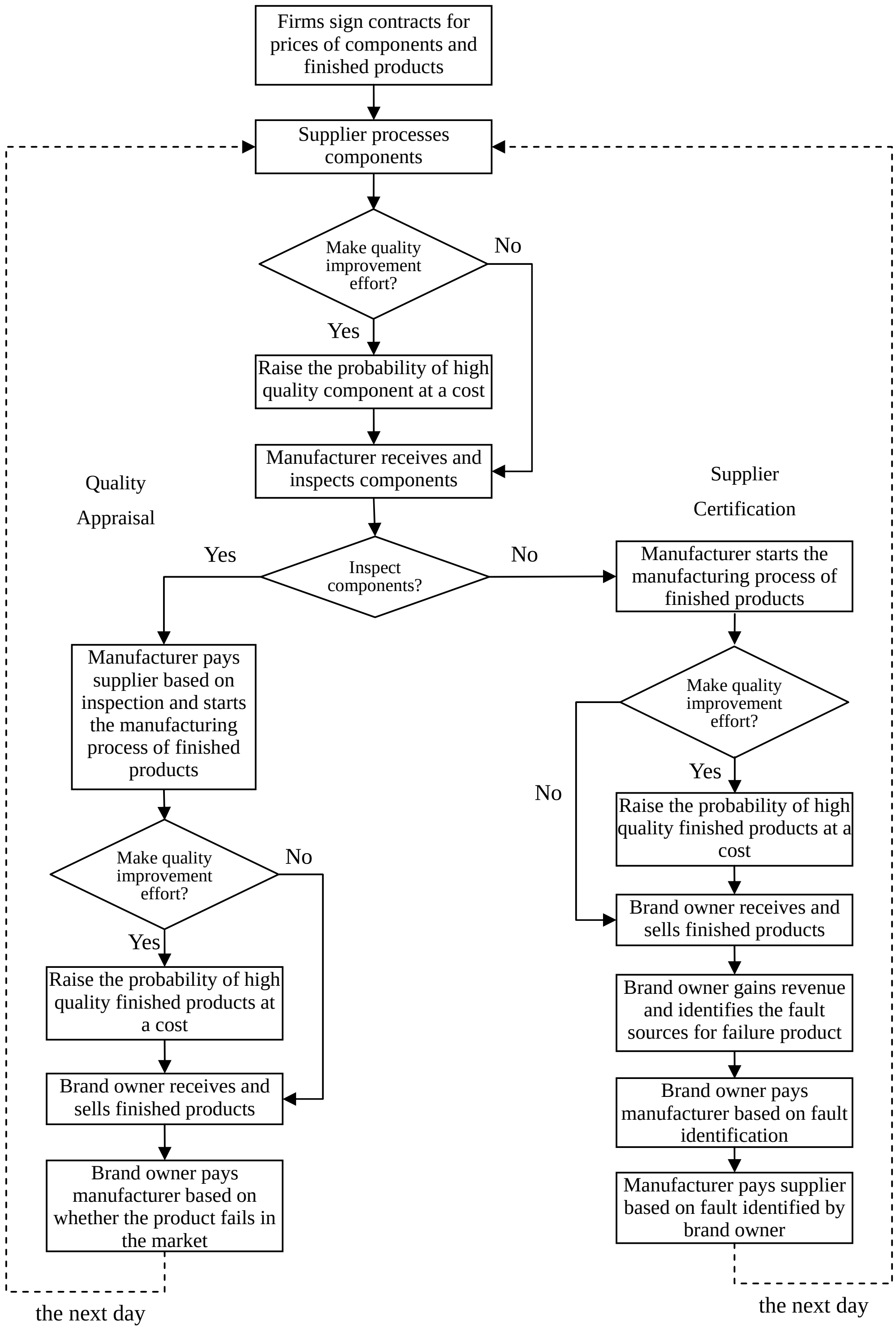
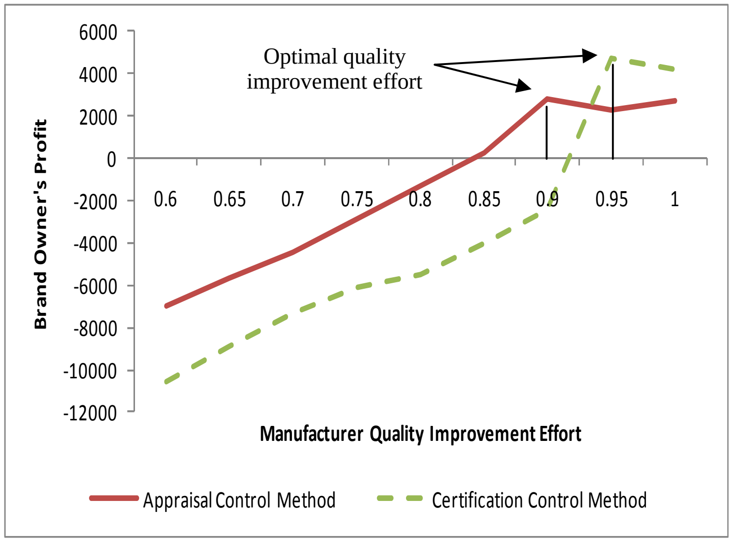
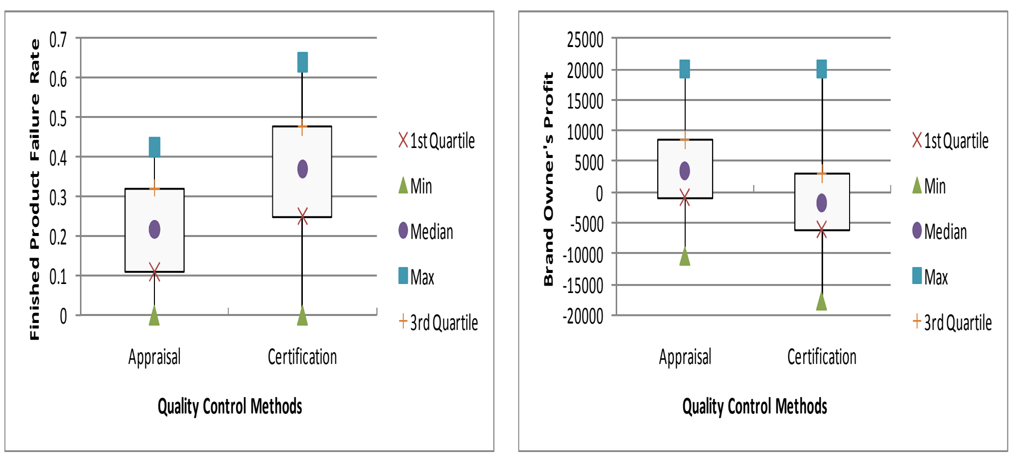


Figure 2. Quality decision-making process



Note: supplier's quality improvement effort fixed at 0.90.

Figure 3. Impact of manufacturer's quality improvement effort on brand owner profit



(a) Finished Product Failure Rate (b) Brand Owner Profit

Figure 4. Box-plots of brand owner profit under two quality control methods

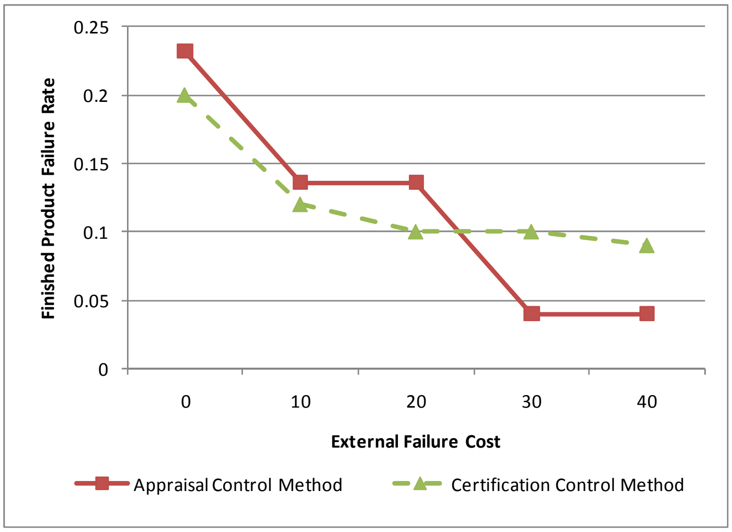


Figure 5. Influence of quality control methods on finished product failure rate with varying external failure cost

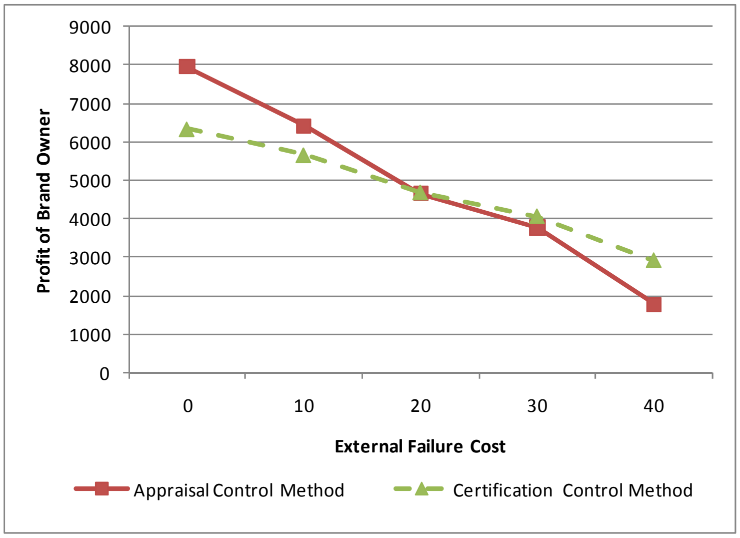


Figure 6. Influence of quality control methods on brand owner profit with varying external failure cost