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An Incentive Structure for the Management of Supplier Quality

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Abstract
As our recent study shows, quality is the foremost concern in regard to sourcing parts from suppliers. Most companies seek to ensure vendor quality through measures such as auditing their suppliers' manufacturing systems or the specification of penalties, which do not always guarantee perfect quality levels. This paper summarizes current industrial practices for achieving high supplier quality and presents a review of the literature pertaining to the subject. Subsequent to the discussion of the indications that may be drawn from the state of the art, a combined penalty and reward structure is proposed.

Keywords
Supply Chain Management, Quality Management, Repeated Games

1 INTRODUCTION
The environment of today's production enterprises is characterized by shortened product life cycles, a rapidly growing number of products and variants as well as fast technological advancement [1]. The resulting complexity in production has lead Original Equipment Manufacturers (OEMs) of various industries towards a continuous reduction of the amount of in-house value creation ([2], [3]). Today's suppliers and their vendors provide components, subassemblies or even entire products [4], which brings forth complex supply chains. Thus, the capabilities of suppliers significantly determine the success of the buyer.

The results of a recent survey of 48 companies from the aerospace, automotive, electronics and mechanical engineering industry (drawn from [5]) have shown that the ability of a potential supplier to deliver products in the specified quality is the most dominant priority when a vendor is chosen. Figure 1 summarizes this finding in terms of the percentage of respondents that specified one of five importance levels for each of six supplier selection priorities.

In this context quality is defined (in accordance with ISO 8402) as the fulfillment of "the totality of characteristics of an entity (product) that bear on its ability to satisfy stated and implied needs" of the customer [6]. The quality level of a supplier is characterized by the percentage of parts that meet the quality definition.

To achieve the desired supplier quality many companies have a supplier certification program in place in order to pre-assess a potential supplier's capabilities, especially when the duration of the contract between the parties is long (according to [7]). Empirical research has shown that this measure has considerable effect (> 30 % reduction in defects according to [7]), but does not lead to perfect vendor quality. The remaining quality fluctuations are meant to be offset through various, sometimes contractually specified, measures, such as inspection frequencies, which the supplier must carry out. Furthermore, suppliers must often incur the cost of defective parts and additionally pay a quality penalty when faulty parts are delivered. Nevertheless, as it will be discussed in section 2.2, perfect quality is seldom achieved in most industries.

In the view of this paper, a significant increase in supplier quality can sometimes be achieved through offering the supplier a financial incentive when perfect quality is delivered, rather than solely employing incoming inspection and penalties as a threat. In section 2, we present a basis for the derivation of such an incentive structure and provide an overview of the current practice in four industries as well as a review of supplier quality management literature. We also provide a discussion of the indications drawn from these approaches. In section 3, we derive an incentive model based on two different strategies for repeated games. We
summarize our findings and provide ideas for future research in section 4.

2 SUPPLIER QUALITY MANAGEMENT

2.1 Industrial Practice

To better understand current supplier quality management practices in industry, we interviewed four companies (one from aerospace, two from automotive, one from mechanical engineering) and reviewed ten vendor quality guidelines published by firms of the aerospace ([8], [9], [10]), automotive ([11], [12], [13], [14]) and electronics ([15], [16], [17]) industry. As a result of this analysis, six supplier quality management activity groups were identified.

The first group of quality management activity contains general measures for the supplier selection process such as the reduction of the supplier base and the definition of required quality management standards for the vendor (e.g. ISO 9001:2000 or buyer specific standards). These standards are assessed by the buyer during onsite process audits of the supplier’s overall manufacturing system. Some companies have organized their procurement employees in such a way that their staff is responsible for certain parts, rather than for a number of suppliers. With this organizational structure, these companies achieve close monitoring. One difference among the various industries is that airplane manufacturers emphasize that standards must not only be fulfilled by the vendor, but also be implemented at the supplier’s suppliers.

The second group of quality management activity focuses on changes in the product and the supplier’s production facility. All of the analyzed companies require an approval request by the supplier in case of a change in the product design, the production processes or tools. Some of these companies also require a notice when the testing and calibration method (mainly airplane industry), the maintenance program or the specified shipping and packaging procedures are modified. We encounter a limited number of firms, which provide their suppliers with extensive support in regard to product and process design prior to the product launch.

The third group of quality management activity focuses on measures that ensure product quality during the product life cycle. For example, suppliers are expected to conduct statistical process control (measured by the Process Capability or the Process Performance Indexes, respectively Cpk or Ppk), inspect parts and carry out 6-sigma initiatives. In this group, a distinct feature of the airplane industry is that parts are sometimes inspected through the buyer or a third party at the supplier’s premises and test reports must be delivered with the part before they are accepted.

The fourth group of quality activity addresses actual supplier quality through actions such as performance measurement reports (e.g. ppm) and supplier rankings. Upon the detection of quality problems, buyers issue corrective action requests, to which suppliers must respond in the form of action plans within a certain time window. Some companies (except aerospace industry) convey the quality cost to their suppliers and let them incur a penalty according to the reviewed supplier quality guidelines. A procurement manager from the automotive industry reported that suppliers are charged a flat rate of 1.1 times the part price, if defects are identified. This factor may increase significantly for vendors that have severe quality issues. However, penalties may not be enforced, especially when the buyer is dependent on a supplier with considerable market power, as discussions with four production managers have shown.

As a result of the interviews, we identify the fifth group of quality activities to be preventive measures that include incoming quality inspection or sampling and quality related safety stock. Some buyers record lot numbers to detect the root causes of deficiencies and to identify other potentially defective parts.

The last group of quality management measures comprises the prescription of continuous improvement activities to reduce the supplier’s failure rate and required internal quality cost. Yet, all of the interviewed companies emphasized that they are willing to pay a higher part price, if quality levels rise to their expectations.

2.2 Implications from Industrial Practice

Referring to the preceding sections, it may be assumed that the aerospace industry has the strictest quality management measures, which could stem from the high safety regulations required to ensure a reliable product. This conjecture may also be drawn from an aerospace industry report by CAPS RESEARCH [18], which states that the 17 analyzed companies have a mean supplier quality of 100 %. Airplane manufacturers require evidence of quality tests from their suppliers and some of the industries OEMs inspect the products quality conformance at the supplier’s site. Finally, this industry seems to take greater influence upon n-tier suppliers in terms of the enforcement of quality management standards.

Although empirical data to draw any conclusion is sparse, the quality levels realized by airplane manufacturers are not matched by other industries. For instance, the ACCENTURE study [19] concludes that the quality conformance rate averages 95.7 % over the retail, consumer and capital goods industries. A benchmarking study [20] with data obtained from the 2004 “Factory of the Year” award (hosted by AT Kearney) shows that the top quartile
of the participating German automotive suppliers spends an average 8.3% of their total cost for external failures (including warranty cost, cost due to insufficient parts and administrative spending). In comparison, external failure cost amounts to 11.8% in other industries (top quartile). Even though the proportion of warranty cost due to, for example, insufficient product design may be more significant, these numbers suggest that quality issues exist in industry. Another interesting fact is that the cost of quality (defect prevention, testing and cause elimination cost) is merely between 0.6 and 1.4% of the overall cost according to this survey, which implies that suppliers seek to minimize quality costs. Thus some sort of motivation needs to be provided by the buyer to ascertain high quality levels, which can either be a financial incentive, a penalty or, as in the aerospace industry, a rigid form of supplier control.

2.3 Literature

A good overview of the literature on the management of supplier quality has been provided by Tsay et al. [21], which we employ as an outline for this section. They group contributions to this field into three categories, namely economics, inventory management and game theoretic supply chain research. Relating to the first mentioned field, Tirole [22] offers an extensive overview on economic quality models. To differentiate products, he classifies search, experience and credence goods (as in [23], [24]). The first type encompasses such products, for which the quality can be ascertained before the purchase (e.g. clothing). In the case of experience goods the quality is learned subsequent to procurement. If the quality of a product can not be assessed at all, it is categorized as a credence product (e.g. toothpaste).

In the supply chain relationships we address in this paper, products belong to the group experience goods, because the quality of products and thus the expected quality are learned each time parts are actually delivered. This is the case even though the supplier’s manufacturing system may have been assessed or first parts have been inspected before the start of the relationship.

The economic models for experience goods discussed by Tirole focus on quality levels as one of the supplier’s management choices. They concentrate on optimal quality levels as a reaction to a given level of customer appreciation for quality to attain the best possible profit. Due to the fact that in the production industry a detailed definition of quality is provided to the supplier by the buyer, the level of quality is not a management choice but a requirement. This quality level may or may not be fulfilled by the vendor depending on the incentive structure of the arrangement. However, one of Tirole’s findings relevant to this paper is that warranties (or penalties) granted by the supplier can be interpreted by the buyer as a signal for high quality prior to supplier selection. Secondly, repeated purchases offer the consumer valuable information in regard to the expected quality. As the relationship between a buyer and a supplier is usually based on long term agreements, this knowledge can be used to redefine the boundary conditions of procurement over the duration of the relationship.

Another economic evaluation of the cost of production quality has been developed by Tagaras & Lee [25]. They consider a buyer who has the opportunity of increasing the quality of a procured part by paying a higher part price. The part is defective with the probability p and the buyer’s production process, for which the part is an input, fails with the probability of q. From the costs that arise when the input is defective (r1), when the buyer’s process fails (r2) or when both apply (r12), the buyer’s expected unit quality cost may be calculated as \[ \phi(p) = p(1-q)r_1 + q(1-p)r_2 + pqr_2. \] From the quality cost and the unit purchase cost \( C(p) \) (which is assumed to be either linear or quadratic) the total acquisition cost \( K(p) \) may be derived. An analysis thereof reveals that the buyer’s choice of supplier quality depends not only on the vendor’s price but also on the buyer’s own process capabilities. Under certain circumstances the buyer is thus better off when lower quality is procured.

The body of inventory management literature focusing on quality issues is broad. It mainly discusses optimal stock levels or order sizes when dealing with varying supplier quality. For instance, Starbird [26] develops a model that identifies conditions under which delivering zero defects is an optimal strategy for an expected cost minimizing supplier facing a buyer with a fixed sampling policy. These conditions are a function of the buyer’s sample (n) and acceptance size (c) and demand rate (\( \lambda \)), as well as the supplier’s delivery lot size (L), inventory holding (i), pass-through (\( i - \text{the cost of a lot returned by the buyer} \)) and set-up costs (K). The model yields different conditions, depending on the nature of the supplier’s quality cost function, which is assumed to be either linear, exponential or asymptotic. Further examples of such research include e.g. Alicke [27] or Huang [28], but it is not directly related to this article, as the objective of this paper is to prevent deficiencies of procured parts rather than coping with them.

The game theoretic literature relating to supplier quality management is sparse, but most relevant to the ideas we develop in the following sections. An interesting model has been developed by Reyniers & Tapiero [29]. They use a game theoretic formulation of the supply chain relationship to examine the impact of contract parameters on the supplier quality, the buyer’s inspection policy and the implications for the quality of the end product. In this model the supplier chooses one of two production methods as an expression of the level of
manufacturing technology, quality management capabilities, etc.), which differ in production cost \( T \) and defect probability \( p \), where higher production cost leads to higher quality levels. The buyer does not observe the supplier's choice, but may inspect incoming parts at cost \( m \) or integrate the part directly into the end product. If a defect is detected, the supplier incurs the repair cost \( C \) and an additional rebate \( Ax \). If a procured part is found defective at the final customer, a failure cost \( R \) arises of which a fraction \( a \) is paid by the supplier and \((1-a)\) is incurred by the buyer. The option of testing or not testing on the buyer side and the two levels of technology that may be chosen by the supplier result in a bi-matrix game, which may be solved for Nash equilibria. The game has an equilibrium in mixed strategies, which yields the following insights: (a) the probability that the buyer inspects is increasing in the relative production cost differential \( \Delta T / \Delta p \) (where \( \Delta T \) is the incremental cost of better technology and \( \Delta p \) is the incremental probability of a defective part using the inferior technology), (b) the probability of using inferior technology is increasing in the buyer's inspection cost \( m \), (c) the final quality of the supplier-buyer chain is a decreasing function of the proportion of the warranty cost borne by the supplier, a decreasing function of the buyer's inspection cost and an increasing function of the ratio \( \Delta T / \Delta p \). Furthermore, REYNERS & TAPIERO show through a cooperative quality game that the value of cooperation, which stems from the move from independent to joint decision-making and thus eliminates information asymmetry, is decreasing in \( Ax \) for both parties and decreasing in \( a \) for the buyer.

LIM [30] has developed a model with identical parameters as REYNERS & TAPIERO for considering the trade-off between inspection and warranty schemes under asymmetric information in regard to the supplier's technology type. By utilizing the revelation principle, LIM comes to the conclusion that the supplier's expected amount of compensation cost per defective unit (either as a price rebate or a warranty) is constant and independent of the technology type of the supplier. Furthermore, he finds pooling equilibria for situations in which the buyer has to share the cost of the compensation schemes. Thus there is a critical level of technology such that the buyer always conducts inspection, whereas she prefers a warranty scheme, if the quality level is superior to the critical value.

2.4 Implications from Research
The models developed by REYNERS & TAPIERO (main findings) and LIM assume that the level of technology (respectively knowledge about the supplier's manufacturing system) cannot be anticipated by the buyer, which is not the case in industrial practice, since process audits at the supplier are a common measure (see group 1). Thus the buyer can get some notion of the supplier's process capability and required quality measures (see group 2).

Furthermore, REYNERS & TAPIERO, LIM and STARBIRD focus on the incoming inspection respectively sampling policies and compensation schemes a buyer must adopt to obtain high quality levels from a supplier. The numbers cited in section 2.2 suggest that, especially under today's continuously decreasing profit margins, suppliers will sometimes take the risk of paying a penalty in order to save quality cost. Thus, our approach to mitigate the risk of low quality is to offer the supplier a higher part price when quality is delivered and the required quality measures are carried out. This is in line with the statements of the interviewed production managers (see group 4) and the assumptions of TAGARAS & LEE.

The parameters for modeling supplier management employed by REYNERS & TAPIERO and LIM seem sufficient in terms of industrial practice. However, none of the cited authors have incorporated the repeated nature of the supplier - buyer relationship, pointed out by TIROLE, into their models. In our view, conditioning the actions of the involved parties on the behavior of their counterparts is an important aspect for the design of a supplier quality management model.

3 AN INCENTIVE STRUCTURE FOR SUPPLIER QUALITY MANAGEMENT
To capture the repetitive nature of the procurement process, we utilize the theory of repeated games (refer to [31], [32]) for the derivation of an incentive structure in this paper.

3.1 Repeated Games and Quality Management
A repeated game consists of a finite or infinite series of stages games \( G \), which involve a player set \( I = \{1, ..., n\} \). Hence, there are two players in the supplier - buyer relationship and every delivery of parts represents a stage game.

In each stage, every players' actions are a choice from her action space \( A_i \). The space of possible action profiles is thus \( A = X_1 \times A_2 \). For each player the set of actions available to her in any period of the game is the same regardless of which period it is and irrespective of which actions have taken place in the past. Following the discussion in section 2.4, the supplier's actions are to deliver imperfect \( (q) \) or perfect quality \( (q_{wd}) \), while the buyer can pay a price that includes a quality premium \( (w^+) \) or just the common market price \( (w) \) combined with a penalty structure (see group 4).

Each player has a von Neumann-Morgenstern utility function defined over the outcomes of \( G \) and every players ultimate payoff is an additively separable function of her discounted per-period payoffs, if the \( G \) is played several times. The payoffs to the players from the stage game in any period depend only on
the action profile played in that period and therefore the quality level of the supplier and the part price paid by the buyer.

In repeated games the typical “standard signaling” assumption is made. This means that the play which occurred in each repetition of the stage game is revealed to all players before the next stage game. Combined with perfect recall this allows subsequent choices to be conditioned on the past actions of other players. These properties of repeated games fit particularly well to the nature of the quality management process, because the buyer learns the quality level of the supplier each time parts are delivered. She records this knowledge in the form of performance reports and can decide upon quality management actions based on these metrics (see group 4).

The first period of the game is labeled \( t = 0 \), whereas the final period, if one exists, is period \( T \). Thus the repeated game comprises a total of \( T+1 \) periods. Since a supplier will usually seek to deliver parts to a buyer longer than a single product life cycle, it is reasonable to assume that the game is played for an infinite number of stages \( (n) \), as the supplier does not know when the game will end.

An action which player \( i \) executes in period \( t \) is referred to as \( \alpha_i^t \). The action profile played in period \( t \) then is the \( n \)-tuple of the individuals’ stage game actions \( \alpha^t = (\alpha_1^t, ..., \alpha_n^t) \). As the players are allowed to condition their stage game action choices in later periods upon actions taken earlier by other players, they base their decisions on the history of the game. The history at time \( t \) is defined as \( h^t = (\alpha_1^1, \alpha_1^2, ..., \alpha_1^t) \) and the specification of \( h^t \) thus includes within it a definition of all previous histories. For instance, the history \( h^1 \) is a concatenation of \( h^t \) with the action profile \( \alpha_1^1 \). The set of all possible histories is thus the \( n \)-fold Cartesian product of the space of stage game action profiles \( \alpha \).

As mentioned above, player \( i \)’s period-\( t \) stage game strategy \( s^t_i \) is a function of this history, where \( \alpha_i^t = s^t_i(h^t) \) is the action profile she would play in period \( t \) if the previous play had followed \( h^t \). A player’s stage game action in any period and after any history must be drawn from her action space for that period, but because the game is stationary her stage game action space \( \alpha_i \) does not change with time, which may be expressed as \( \forall t \in I \forall h^t \in \alpha \), \( s^t_i(h^t) \in \alpha_i \). The period-\( t \) stage game strategy profile is thus described as \( s^t = (s^t_1, ..., s^t_n) \). Using the stage game strategies as building blocks, player \( i \)’s strategy for the repeated game is expressed as \( s^t = (s_1^t, ..., s_n^t) \). When the repeated game strategy profile \( s^t \) is played the payoff to player \( i \) is defined as

\[
u_i(s^t) = \sum d^t g_i(s^t(h^t)) \tag{1}\]

where \( d^t \) is the common discount factor, which may be interpreted as an expression of time preference, and \( g_i \) is the stage game payoff resulting from the strategy profile. A repeated game strategy profile is a Nash equilibrium for all players when

\[
\bar{s}_i \in \arg \max g_i(s, \bar{s}_-) \tag{2}
\]

A subgame-perfect equilibrium strategy profile is one such that the restriction of \( \bar{s} \) to any subgame is a Nash equilibrium strategy profile in that subgame.

### 3.2 Incentives based on a Grimm Trigger Strategy

To derive conditions under which a supplier will deliver perfect quality, we employ a Grimm Trigger strategy (for a model on the efficiency of employment see [33]). This strategy prescribes cooperating in the initial period and then cooperating as long as both players have cooperated in previous periods. Following the actions of the supplier and the buyer, defined in the preceding section, the Grimm Trigger strategy for the infinitely repeated game between the buyer and the supplier can be expressed as follows:

\[
s^t_i(h^t) = \begin{cases} 
\alpha^t & (w^*, q_{100}) \\
\alpha^t & (w^*, q_{100}) \\
(\alpha^t, q) & \text{otherwise} 
\end{cases} \tag{3}
\]

This means that the buyer will pay the supplier a part price of \( w^* \), which includes a quality premium, in the first period of the relationship and continue to do so, provided that perfect quality is delivered. If the supplier does not provide high quality, the buyer will pay the market price \( w \) and charge a penalty \( r \) (indicated by \( w' \)) for the remainder of \( G \). The supplier will comply with the arrangement, provided that the buyer will pay \( w^* \) when high quality is delivered. The sequence of events for the design of such an agreement is as follows: (1.) The buyer (with perfect production processes) selects a supplier that is capable of producing the desired parts and inspects the supplier’s manufacturing system (which is realistic as mentioned in 2.1 – group 1). In doing this, the buyer acquires knowledge in regard to the process capability and the quality cost of the supplier. The first can be measured by the probability \( (p) \) that a shipment of parts will include only good parts, which must be derived from historical data such as internal quality reports, process capability histograms or previous experience. Based on this knowledge and the definition of required quality measures (as described in section 2.1 – groups 2 and 3), the cost of quality per part \( (q_i) \) may be assessed by the buyer. (2.) The supplier and the buyer then agree on a per part
penalty \( r \) (includes cost for rejected materials and penalties charged by the buyer or the end customer) that is incurred by the supplier, if bad parts are delivered. This, according to section 2.1 (group 4), is common practice for suppliers that have limited market power and also in line with the findings of Tirole. (3.) With this knowledge the buyer calculates a part price, which the supplier accepts. (4.) If the supplier does not deliver perfect quality, the buyer switches back to a combination of the market price and a quality penalty until the relationship between the parties ends.

To derive the required price, we consider the present value of the supplier’s payoffs. As mentioned above, if the supplier provides high quality parts in the initial period of the product life cycle, she receives a part price of \( w^* \). The buyer continues to pay this price, if parts are free of defects. Thus for the cooperative game between the supplier and the buyer, the present value of the supplier’s payoff according to (1) amounts to

\[
P_c = w^* - q - c + \delta w^* q - c + \delta^2 w^* q - c + \ldots + \delta^{m+1} w^* q - c
\]

where \( \delta \) is the discount factor, which equals \( 1/(1 + ir) \), \( ir \) is the interest rate and \( c \) (\( w - c - q > 0 \)) is the per part production cost (material and machine cost, etc.).

If the supplier decides not to provide high quality, but to deliver the parts without applying quality enhancing measures subsequent to production, she will receive a payoff of \( w^* \) in the first period (as the game assumes simultaneous moves in each stage) and \( w^* \) with the probability of \( p \) in the following periods. In this case faulty parts are supplied with the probability of \( (1-p) \) and thus the buyer will pay the market price \( w \) and the supplier will incur an expected penalty cost \( E(r) \) from thereon. The present value of the supplier’s payoff then results in

\[
P_c = w^* - q - c + p \delta w^* q - c + (1-p) \delta w^* q - E(r) + \delta^2 (w^* q - c) + \ldots + p \delta^2 w^* q - c + (1-p) \delta^2 (w^* q - E(r)) + \ldots
\]

(5)

To induce perfect supplier quality, \( P_c \) must be set greater or at least equal to \( P_c \). Through applying geometric progression and rearranging the parameters of the resulting inequality, the following result can be obtained for \( w^* \):

\[
w^* \geq w - E(r) + \left( \frac{(1-\delta)}{\delta(1-p)} \right) q.
\]

(6)

For an interpretation of this result we differentiate five cases. If the expected penalty cost \( E(r) \) equals the quality cost \( q \), then the buyer must pay a quality premium of \( \frac{(1-\delta)}{\delta(1-p)q} \).

(1). In relationships where the cost of quality exceeds the expected penalty, the part price \( w^* \) will include the premium as well as a fraction of \( q \), (2). In cases where the expected penalty is greater than the quality cost, but smaller than the sum of \( q \), and the value of the premium, a partial premium must be included in the part price (3). Should \( E(r) \) be greater than this amount, it is sufficient for the buyer to pay the market price (4). This is because in this case (6) yields values lower than \( w \), which implies that under such an arrangement a quality premium is already included in the market price (as for instance in the case of the automobile manufacturer cited in section 2.1 that charges a penalty of 1.1 times the part price). If a penalty can not be enforced, for instance when a supplier has considerable market power, then the buyer must pay the full cost of quality and the quality premium in order to attain perfect quality levels (5).

\[\text{Figure 2. Incentive structure portfolio}\]

These five cases are summarized in the incentive structure portfolio depicted in Figure 2. However, for (6) to be a Nash equilibrium (as required by (2)) of the repeated game, the difference between \( w^* \) and \( w \) must be smaller than the savings that the buyer gains from paying the quality premium and thus receiving perfect quality. This means that the following inequality must hold:

\[
v - w^* \geq v - w - q + E(r)
\]

(7)

In this relation \( v \) is the value of the purchased product to the buyer and \( q \) is the per part quality cost that arises for the buyer when defects occur. As mentioned in section 2.1 the latter may include the
cost of incoming inspection, safety stock (group 5) or quality related production disruptions.

For the strategies specified to be a subgame-perfect equilibrium \( \psi(\psi') \) must be a Nash equilibrium strategy profile in every subgame. To evaluate this, we assess subgames with histories beginning after stage games where \( \psi^* \) has been paid by the buyer and perfect quality has been supplied and such where at least once \( \psi \) has been the part price and imperfect quality has been delivered. As discussed above, subgames of the first kind represent a Nash equilibrium of the stage game if (6) and (7) hold. Latter subgames will only occur in cases where the expected penalty cost is smaller or equal to the quality cost. Under these circumstances, it is a best response for the buyer to pay the part price for the duration of the relationship (as for instance when procuring for a supplier with great market power). Assuming that there is no other buyer that will demand at least equal volumes and pay a higher part price, the described conditions are also optimal for the supplier. Thus the Grimm Trigger strategy represents a subgame-perfect equilibrium.

3.3 Numerical Example for the Grimm Trigger Strategy

To provide some intuition of the behavior of the part price \( \psi^* \), we plot the results of a numerical example with a market price \( (w) \) of 50 (monetary units), a per part quality cost \( (q) \) of 10 and an expected penalty cost of \( (E(r)) \) of 11 in Figure 3. As it can be inferred from the resulting surface, the part price \( \psi^* \) increases nonlinearly with the quality level of the supplier \( (p) \), nonlinearly increases with decreasing discount factors \( (\delta) \) and, as it can be easily seen from (6), linearly increases with the cost of quality \( (q) \) for fixed \( E(r) \).

![Figure 3. Numerical example](image)

If we assume that a discount factor \( (\delta) \) between 0.9 and 0.95 is reasonable, which results from an interest rate or weighted average cost of capital between 5 and 10%, the part price the buyer must pay to receive perfect quality only exceeds the market price somewhat for suppliers that have quality level of close to 1 in this example. The difference between \( \psi^* \) and \( \psi \) then represents a partial quality premium as indicated in Figure 2 (III).

3.4 Incentive Structure based on the Limited Retaliation Strategy

As an alternative to Grimm Trigger strategies we can also employ a more forgiving concept. Limited Retaliation strategies prescribe cooperation in the first period and \( k \) periods of punishment for every defection of any payer, followed by reverting to cooperation, no matter what has occurred during the punishment phase. In terms of quality management this implies that the buyer will pay a part price of \( \psi^* \) to the supplier as long as perfect quality is provided, pay only \( \psi \) for \( k \) periods and charge the penalty if the supplier delivers bad quality and then continue to incur \( \psi^* \) as long as the game is cooperative. In summary this strategy can be stated as follows:

\[
\begin{align*}
\psi^* &= \psi^* q_{100}^* \\
\psi &= \psi^* q_{10}^* \text{ if } \delta^* = \psi^* q_{100}^* \\
\psi &= \psi^* q_{100}^* \text{ if } \tau = k \\
\psi &= \psi^* q_{10}^* \text{ if } \tau = k \\
\psi &= \psi^* q_{10}^* \text{ if } \tau = \psi^* q_{10}^* \\
\psi &= \psi^* q_{10}^* \text{ if } \tau = \psi^* q_{10}^* \\
\psi^* &= \psi^* q_{10}^* \text{ if } \tau = \psi^* q_{10}^*
\end{align*}
\]

To establish this strategy as a Nash equilibrium of the repeated game, we must ascertain that a one-shot deviation (see [31]) is not profitable for the supplier and (7) must hold. As in the preceding section, if the supplier decides to omit quality enhancing measures, she will receive a part price of \( \psi^* \) with the probability \( p \). If defects are detected by the buyer with the probability \( (1-p) \), the supplier receives the market price \( \psi \) and incurs a penalty of \( E(r) \) for \( k \) periods followed by an infinite stream of \( \psi^* \). Thus the present value of the supplier’s payoff for a single deviation will amount to

\[
\begin{align*}
\rho_{\psi^*} &= w^{\psi^* - c} + \rho_{\psi}(w^{\psi^* - c}) + \\
(1-p) \left( \frac{\delta^*}{1-\delta^*} (w-c-E(r)) + \delta^*(w^{\psi^* - q}) \right) + \\
\rho_{\psi^*} \delta^*(w^{\psi^* - c}) + \\
\rho_{\psi^*} (1-p) \left( \frac{\delta^*}{1-\delta^*} (w-c-E(r)) + \delta^*(w^{\psi^* - q}) \right) + \\
\rho_{\psi^*} \delta^*(w^{\psi^* - c}) + \\
\rho_{\psi^*} (1-p) \left( \frac{\delta^*}{1-\delta^*} (w-c-E(r)) + \delta^*(w^{\psi^* - q}) \right)
\end{align*}
\]

By requiring \( P \) to be greater or at least equal to \( P_{\psi^*} \), applying geometric progression and rearranging the terms the resulting \( \psi^* \) can then be expressed as.
\[ w \in w - E(v) = \left( 1 - \frac{(1 - \delta)}{\delta - p \delta - \delta^2 + p \delta^3} \right) y. \] (10)

which equals (5) for infinite \( k \). It can easily be seen that (10) yields results that are greater than those obtained from (5) for small \( k \). However, for the example considered in section 3.3, values within the same range can be achieved by setting \( k \) to 30. The Limited Retaliation strategy is a subgame-perfect equilibrium of the repeated game, if the conditions discussed in the preceding section are true.

Nevertheless, since the games are designed in such a way that it will not be profitable for the supplier to consciously deliver imperfect quality, it should be sufficient to employ a Grimm Trigger strategy for the management of supplier quality. Due to the fact that delivery quality will never be completely perfect (this is for instance the case for one of the interviewed automobile suppliers, which strives towards perfect quality, but still has a two-digit ppm-rate), it may be more efficient to require a quality level that is close to 100% under the Grimm Trigger agreement than to accept the more costly punishment phase.

4 SUMMARY AND FUTURE RESEARCH

A recent study has shown that supplier quality is the foremost concern when parts are procured. In this paper we have provided a summary of industrial practice in regard to supplier quality management and have presented a review of the literature on the topic. Based on this discussion we have derived an incentive structure for achieving high supplier quality through employing the concept of infinitely repeated games.

By applying Grimm Trigger strategies, we have established a portfolio for the price a buyer must pay part per part. The scheme shows that if the supplier is willing to accept a high quality penalty, it is sufficient for the buyer to pay the market price. However, if the supplier can not be punished for delivering inferior quality, it may be necessary to include the cost of quality as well as a quality premium in the part price to obtain high quality levels.

We assume that nowadays most companies either charge their suppliers per part penalties that may even exceed the part price or accept the supplier quality level in situations where the supplier's market power is significant. As the interviewed companies are willing to pay a higher part price for good quality, the derived insights may be especially helpful in the latter case or in situations where only minor penalties can be enforced due to decreased profit margins. Similar results can be obtained with strategies more forgiving than Grimm Trigger strategies, as we have shown through concept of Limited Retaliation. However, due to the nature of the design of the game, it should be sufficient to employ the less forgiving strategy. Nevertheless, the definition of perfect quality could be relaxed to a defect rate of close to 100%, due to the fact that even when quality management measures carried out by the supplier conform to the buyer's expectations, defects can always occur.

As the savings the buyers can achieve through enhanced quality are crucial to the ideas we develop in this paper, an empirical investigation of the impact of better quality on the buyer's cost structure would greatly contribute to the findings of this article (see (7)).

5 REFERENCES


6 BIOGRAPHY

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