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Proactive Incentive Strategies for Quality Improvement in a Three-Stage Supply Chain

Seung Ho Yoo
Sunmoon University
Email: shy1228@sunmoon.ac.kr

DaeSoo Kim
Korea University Business School
Email: kimd@korea.ac.kr

Thomas Y. Choi
W. P. Carey School of Business, Arizona State University
Email: thomas.choi@asu.edu

ABSTRACT

This study investigates proactive quality incentive strategies in a three-stage supply chain, consisting of a final assembler, a first-tier supplier (S1) and a second-tier supplier (S2). Five models are introduced by considering different incentive-offering paths among players. We then investigate their distinct characteristics and compare overall performances. A parallel incentive strategy taking a centralized control over S1 and S2 can best enhance the quality, market and profit performances. However, it needs to be carefully adopted since it can deteriorate the final assembler's profit. We provide a guideline for a supply chain to choose the best incentive strategy.

KEYWORDS: Quality improvement, Incentive strategy, Three-stage supply chain, Second-tier supplier, and Principal-agent paradigm

INTRODUCTION

Nowadays, it is commonly observed that a final assembler, such as GM and Toyota, runs its business in a multi-tiered supply chain system, delegating the production of a main component (or a main module) to its direct partner, a first-tier supplier, which also subcontracts the production of a subcomponent (or a sub module) to lower-tier suppliers (second- and/or third-tier suppliers) in the upstream supply chain. In this contemporary manufacturing environment, many firms' performances are significantly affected by the quality performances of lower-tier suppliers. This is more true if we consider a recent outsourcing trend in which many suppliers perform their own research and development (R&D), affecting the performance of a product and hence customer satisfaction and behaviors (Kaya & Özer, 2009). However, it is still not a common practice to proactively control lower tiers, having a direct tie with them. According to Slowick (2013) and Huang et al (2015), approximately 93% of firms work only with their direct partners, delegating the role and responsibility to control lower tiers. It is virtually impossible for many final assemblers to have visibility and proactively control the quality level of lower-tier suppliers. In the next paragraph, we introduce a Boeing case, a typical example of a multi-tiered supply chain situation, suffering from quality problems at lower tiers and reactively responding to them.

On 16 January 2013, the Federal Aviation Administration (FAA) grounded all Boeing 787 Dreamliners worldwide after a Dreamliner caught fire in Boston (D'amato, 2014). The fire was due to electrical failures, especially the internal short circuiting and thermal management problems in the lithium-ion batteries playing a key role in on-board power (D'amato, 2014). Before the grounding, there also had been several other electrical failures worldwide. The series of failures and subsequent grounding seriously tarnished the reputation of both Boeing and airlines, and there were also huge financial losses involved (Williard et al, 2013). Moreover, the situation went worse when the investigation released on March 15 through the National Transportation Safety Board (NTSB). Both the FAA and Boeing failed to identify the root causes of the electrical failures (Williard et al, 2013). The only thing clear was that the fire leading to the grounding was contributed directly by the lithium-ion battery manufactured by a second-tier supplier, GS Yuasa, a Japanese battery cell manufacturer, which was subcontracted by Boeing's first-tier supplier, Thales, a French aerospace technology firm, responsible for the electrical power conversion system (Williard et al, 2013; D'amato, 2014).

In order to drastically reduce the development cost and time for the Dreamliners, Boeing utilized an outsourcing structure similar to an automotive supply chain such as of GM and Toyota, contracting with approximately 50 first-tier suppliers and delegating them complete control of design and production of their pieces (Tang & Zimmerman, 2009). The first-tier suppliers were also fully responsible for controlling their own subcontractors (Tang & Zimmerman, 2009). While outsourcing 70% of the development and production activities, it was virtually impossible for Boeing to have visibility and fully understand the entire processes, especially of the lower tier suppliers (Tang & Zimmerman, 2009). In this tiered system, GS Yuasa produced and tested its battery different from the final design certified for use (Ostrower & Pasztor, 2014). Moreover, Thales' oversight of GS Yuasa did not assure that the manufacturing process of the battery was consistent with industry practices, while Boeing also did not audit GS Yuasa but allowed Thales to perform its own (D'amato, 2014). As a result of a thorough investigation, the NTSB called on Boeing to enhance oversight of its suppliers and entire supply chain (Ostrower & Pasztor, 2014), and Boeing stated that it made progress on enhancing reliability of the battery system by tightening up supplier oversight (Gates, 2015). However, these efforts were too belated and reactive to resolve the problems within a reasonable time period.

Actually, Boeing might have enough chances and time to proactively prevent those problems. As Tang and Zimmerman (2009) pointed out, it could have already recognized not only the limitation of reactive actions but also the importance of proactive control over the lower-tier suppliers when it faced a series of serious delay problems in delivering the Dreamliners to customers in 2008. Not only the incidents due to the lack of proactive control over lower-tier suppliers but also subsequent reactive actions of firms are not of Boeing only but common in practice, especially when a firm operates its business based on a multi-tiered system such as in the automotive industry. For example, Ford recalled SUVs to resolve a fuel system problem that could cause a fire in 2012, incurred by a second-tier supplier using an unapproved manual process to assemble relevant parts (Reuters, 2012). Aston Martin discovered in 2014 that the accelerator pedal arms from a second-tier supplier used counterfeit plastic material, affecting 75 percent of vehicles built between November 2007 and May 2012 (Klayman, 2014). In 2015, Fiat Chrysler recalled 86,000 pickup trucks due to the problems in rear axles from a second-tier supplier, which did not heat-treat those parts properly (Shepardson, 2015). Also in 2015, Toyota needed to find another second-tier supplier after it recalled 12 million vehicles for defective airbag inflators (Shiraki, 2015).

Considering the above, this may be the right time to discover the benefits of proactive control over suppliers in a multi-tiered supply chain system and reveal which type of proactive strategy can better enhance the quality and overall performances of a supply chain. In this study, we consider a three-echelon supply chain, consisting of a final assembler (A), a first-tier supplier (S1) and a second-tier supplier (S2), different from a common practice concentrating only on a dyadic relationship between a buyer and a single supplier. Then, five supply chain models with different incentive strategies are introduced which intend to proactively control the quality performances of suppliers by facilitating their investment in quality, especially considering the second-tier supplier. Note that we do not consider penalty contract schemes which represent reactive actions to correct the quality failures already occurred. The provision of incentives is reasonable in the recent outsourcing trend, in which many subcontractors invest in their own R&D capability and also provide product designs, affecting the performance of a product and subsequently customer satisfaction and demand (Kaya & Özer, 2009). This is different from the traditional role of a supplier which focuses only on meeting the specification the final assembler already determined in order to avoid penalties incurred due to the delivery of defective items. By considering possible incentive-offering paths among three players, combining the individual paths from A to S1, from S1 to S2 and/or from A to S2, we will show various incentive strategies which the final assembler can adopt in a multi-tiered supply chain. Then, we will first answer the following question: What is the condition under which a final assembler can proactively control suppliers by offering an incentive not only to a first-tier supplier but also to a second-tier supplier? Many firms are already aware of the importance the proactive management of lower tiers, but it is still not a common practice. In this study, we introduce proactive incentive strategies and offer a guideline clarifying the conditions under which a final assembler can adopt them. Then, through the comparison of supply chain models, we will answer the next question: Which proactive incentive strategy enhances the overall performances best in a multi-tiered supply chain? There can exist various proactive strategies to control suppliers, and they then will differently affect the overall performances of a supply chain. Especially, it is important to identify which strategy can guarantee the best performance not only to entire supply chain but also to each player. This is since there will be no motivation for the final assembler to adopt an incentive strategy if it helps enhance the profit of the entire supply chain but not its own. Therefore, we will reveal which proactive incentive strategy yields a superior performance in terms of not only the quality performance but also the market and profit performances of the entire supply chain and each player.

LITERATURE REVIEW

Two streams of research are directly relevant to the present study: (1) quality management in a supply chain, (2) supply chain management studies considering the multi-tiered system, beyond a dyadic relationship between a buyer and a supplier.

There have been a number of previous studies relevant to a quality management problem in a supply chain, such as Reyniers and Tapiero (1995), Baiman et al (2000; 2001), Lim (2001), Balachandran and Radhakrishnan (2005), Hwang et al (2006), Zhu et al (2007), Chao et al (2009), Hsieh and Liu (2010), Volodymyr and Christopher (2012). Majority of those studies investigated how a penalty contract based on the information from incoming inspection or/and external failures can control quality problems and minimize total cost. The reason why they adopted a penalty contract as the main option to control a supplier is since they focused on the traditional role of a supplier mainly responsible for the production process, determining the level of conformance quality to design specification the buyer already determined. Therefore, the number of defective items delivered to the buyer or customers is the main concern of those

studies, and the penalty contract is a reactive but very appropriate option to control quality failures already occurred.

However, as customer needs become more sophisticated and the competition between supply chains intensifies nowadays, dependency on suppliers which possess expertise in product design becomes higher in practice since it is inefficient and virtually impossible for a final assembler, such as Boeing and Toyota, to command all the relevant capabilities and technologies necessary (Yoo et al, 2015). Therefore, a recent outsourcing trend does not allow suppliers only to focus on conformance quality in production but also requests them to help enhance design quality of a product. Kaya and Özer (2009) and Xie et al (2011) pointed out this trend and investigated product quality mainly determined by a supplier. They focused on the non-contractible aspect of product quality by adopting a buying firm's contract offer based on the wholesale price, even though they considered a situation where not only a buying firm but also consumers can observe quality and their behaviors are also affected. Chen and Deng (2013) also considered a similar situation where customer demand and subsequently buyer's revenue is affected by a supplier's investment and resulting quality. They focused on investigating the effect of the buyer's supplier certification and relevant contract offer, especially under supplier's informational advantage in its quality. In the present study, we focus on the quality aspect which is observable and measurable to both final assembler and customers and their behaviors are also affected similarly to the above studies. Therefore, it is reasonable that we suppose the quality of a supplier is contractible, also considering recent supply chain practices where a final assembler strives to gain clear and complete visibility down through a multi-tiered supply chain. Then, we will reveal how a final assembler can proactively control suppliers' quality and enhance overall performances in a supply chain by facilitating suppliers' quality investment through an incentive offer.

Another research stream directly relevant to our study is supply chain studies dealing with a three-echelon supply chain. They are different from traditional papers focusing on a dyadic relationship between a buyer and a supplier, but they reflect recent issues in a contemporary business environment in which a firm strives to efficiently and effectively manage a multi-tiered supply chain system, similarly to the present one. In this stream, differently from our study, the research interest of a majority of studies has been a joint inventory decision in a three-echelon supply chain, typically in a supplier-manufacturer-retailer supply chain, while also integrating various recent issues, such as coordination through a quantity discount contract (Munson & Rosenblatt, 2001), pricing decision (Corbett & Karmarkar, 2001, Carr & Karmarkar, 2005), closed-loop supply chain design involving used item collection (Savaskan et al, 2004; Savaskan & Van Wassenhove, 2006), multiple suppliers and buyers (Jaber & Goyal, 2008), flexible return policies under demand uncertainty (Ding & Chen, 2008), allocation of cost savings from sharing demand information (Leng & Parlar, 2009), learning-based continuous improvement (Jaber et al, 2010), distribution of imperfect quality items (Sana, 2011), and a facility location problem (Tancrez et al, 2012).

We can recently find several studies dealing with supply chain issues involving the first- and second-tier suppliers similarly to our study. Kayış et al (2013) investigated a manufacturer's problem whether to delegate component procurement to a first-tier supplier or directly control it under information asymmetry about the suppliers' production costs. Huang et al (2015) investigated how a manufacturer can control the second-tier supplier which potentially violates social and environmental standards through either the manufacturer's direct control or delegation to a first-tier supplier. Ang et al (2015) and Bimpikis et al (2015) also similarly studied

a manufacturer's sourcing problem involving first- and second-tier suppliers, while focusing on exploring disruption risk from natural disasters.

However, despite their growing importance, a joint quality management problem in a multi-tiered system has not been studied extensively by academics. There exist only a few relevant studies, such as Dong et al (2013) and Wan et al (2014) which investigated a quality management issue involving both first- and second-tier suppliers. However, the focus of those studies mainly lies in reactively controlling quality failures already occurred through a penalty contract based on the information from incoming inspection and external failures similar to most previous quality management studies dealing with a dyadic relationship between a buyer and a supplier. Our study will introduce various incentive strategies of a final assembler to proactively control quality investment at both first- and second-tier suppliers by considering possible incentive-offering paths among three players. We aim to contribute to the literature by clearly revealing the condition under which the final assembler can adopt each strategy and proactively control suppliers. Moreover, the comparison of proactive incentive strategies will provide an important guideline to practicing managers by clarifying with which strategy the final assembler can enhance overall performances best, including quality, customer demand and profits of entire supply chain and each player.

BASIC FORMULATION

We consider a three-echelon supply chain, consisting of a final assembler, a first-tier supplier (S1) and a second-tier supplier (S2), which is common in the contemporary manufacturing environment. S1 and S2 also have a buyer-supplier relationship like the final assembler and S1. S1 purchases the subcomponent from S2 and supplies the main component to the final assembler after assembling the main and sub components. The supply chain deals with a product such as a vehicle, an electronic device or clothes, so customers' buying intention is mainly affected by the quality and price of a product. The demand is simply defined as follows.

$$D = \alpha - \beta p + \gamma q_1 + \delta q_2, \quad (1)$$

where α is the demand potential, and β , γ and δ are respective coefficients. The sales price of the product p negatively affects D as in many previous studies. To better describe the relationship between product quality and demand, we need the following assumption.

Assumption 1. *The product has a separable architecture with respect to components.*

There can be separable and inseparable architectures in a product as Baiman et al (2001) similarly pointed out. For example, the acceleration performance of a vehicle results jointly from many relevant components, such as an engine, a transmission, a tire and so on. On the other hand, customers also can separately identify and appraise many quality aspects from the vehicle in practice, such as the sound of an audio system, the softness of a leather seat, the performance of a break system and the durability of tires. Among both aspects of product architectures, we focus on the separable architecture in that customers can distinguish the quality of components from the finished product. Therefore, the final assembler has a strong motivation to proactively control suppliers by devising an incentive mechanism which separately evaluates and compensates for the quality level of each supplier.

In Equation (1), the quality levels at S1 and S2, q_1 and q_2 , are separately assessed by customers but jointly enhance the demand requests D . We regard each quality level as a single

composite measure which combines measurable quality attributes affecting the performance of a product and customer satisfaction and behaviors, similarly as in Karmarkar and Pitbladdo (1997) and Banker et al (1998). For example, quality attributes can be aggregated based on the importance weight of each attribute q_i as in Shi et al (2001) and Kim and Chhajed (2002), i.e., q_1 or $q_2 = \sum w_i q_i$ where the sum of weight $\sum w_i = 1$.

The final assembler purchases the main component from S1 and sells the product assembled to customers. In this study, we suppose that the supply of the product or component is based on the wholesale price contract, which is most basic but one of the most popular contract forms in practice due to its simplicity. Note that we do not focus on the supply contract design but the incentive strategy to enhance quality. The final assembler considers an incentive mechanism to enhance the overall quality of the final product which is jointly determined by quality investment at both S1 and S2. Therefore, the final assembler's profit Π_A is defined as follows.

$$\Pi_A = pD - cD - w_1D - T_{A1} - T_{A2} = \pi_A D - T_{A1} - T_{A2}, \quad (2)$$

where c is the unit assembly cost, w_1 is the unit wholesale price of the main component paid to S1 and π_A is the marginal profit of the final assembler, i.e., $\pi_A = p - c - w_1 > 0$. T_{A1} and T_{A2} are incentive payments for quality improvement from the final assembler to S1 and S2, respectively. In the next section, we will introduce five different incentive strategies and corresponding supply chain models by considering possible incentive-sharing paths among three players.

On the other hand, S1 supplies the main component to the final assembler by combining its main component and the subcomponent purchased from S2. Both S1 and S2 undertake their own R&D and hence incur the capital investment to enhance the quality levels of their own components. S1 can also consider an incentive mechanism like the final assembler in order to facilitate the quality investment of its direct supplier S2. This is since S1 knows that the quality enhancement at S2 will positively affect the supply of its main component to the final assembler. Therefore, the profits of S1 and S2, Π_1 and Π_2 , can be defined as follows.

$$\Pi_1 = w_1D - c_1D - w_2D - \lambda q_1^2 + T_{A1} - T_{12} = \pi_1 D - \lambda q_1^2 + T_{A1} - T_{12}, \text{ and} \quad (3)$$

$$\Pi_2 = w_2D - c_2D - \eta q_2^2 + T_{A2} + T_{12} = \pi_2 D - \eta q_2^2 + T_{A2} + T_{12}, \quad (4)$$

where c_1 and c_2 are unit costs of S1 and S2 for component production and w_2 is unit wholesale price of the subcomponent produced at S2. π_1 and π_2 are the marginal profits of S1 and S2, respectively, i.e., $\pi_1 = w_1 - c_1 - w_2 > 0$, and $\pi_2 = w_2 - c_2 > 0$. T_{12} is the quality incentive payment from S1 to S2, differently defined with respect to the supply chain model in the next section. λq_1^2 and ηq_2^2 are capital investments for quality improvement incurred at S1 and S2, respectively, where λ and η are parameters which represent the magnitude of investment. We utilize a quadratic form, increasing and convex in the level of quality, as in many previous studies related to quality investment, such as in Karmarkar and Pitbladdo (1997) and Banker et al (1998).

The main objective of this study is to compare proactive incentive strategies in a three-echelon supply chain, which will subsequently induce different results of quality innovation and overall performances. Therefore, we need to eliminate the effects of other factors, which in turn can distort the comparison result, and hence we add the following assumption.

Assumption 2. *The prices of the final product and components are fixed.*

Assumption 2 indicates a market situation in which a player does not have total control over the

prices of items and thus there are no significant price differences between market players. Given this assumption which regards the prices of final product and components, p , w_1 and w_2 , as parameters, we will concentrate on revealing the superiority of proactive incentive mechanisms.

In the next section, we introduce five supply chain models with different incentive strategies.

SUPPLY CHAIN MODELS

We consider a three-echelon supply chain, consisting of a final assembler, a first-tier supplier (S1) and a second-tier supplier (S2). Among various types of relationships and power dynamics among players in practice, we focus on a supply chain situation where a buying firm has greater bargaining power, such as in a typical manufacturing supply chain, such as Boeing, GM, Samsung, etc. Therefore, the final assembler is the focal company in the supply chain, leading joint quality innovation by proactively devising incentive strategies for suppliers, while S1 also has power over S2.

We introduce five incentive strategies for a three-echelon supply chain, considering possible incentive-offering paths among three players. They are (1) Case N: a basic case, no incentives (N) for quality improvement, (2) Case S: adopting a sequential incentive mechanism (S) from the final assembler to S1 and then from S1 to S2, (3) Case SI: a sequential incentive mechanism (S) with an additional indirect incentive (I) from the assembler to S1 for subcomponent quality of S2, (4) Case P: a parallel incentive scheme (P) from the assembler to both S1 and S2, forming a triadic relationship between players, and (5) Case PS: combining parallel (P) and sequential (S) incentive mechanisms.

Case N: A Basic Case, No Incentives

The general form of a proactive joint quality management problem with three players can be generalized as follows, based on the principal-agent paradigm.

Problems N, S, SI and PS:

$$\text{Maximize } \Pi_A(T_{A1}, T_{A2}) \quad (5)$$

$$\text{subject to } \Pi_1(q_1, T_{12} | T_{A1}, T_{A2}) > 0 \quad (6)$$

$$\text{Maximize } \Pi_1(q_1, T_{12} | T_{A1}, T_{A2}) \quad (7)$$

$$\text{subject to } \Pi_2(q_2 | q_1, T_{A1}, T_{A2}, T_{12}) > 0 \quad (8)$$

$$\text{Maximize } \Pi_2(q_2 | q_1, T_{A1}, T_{A2}, T_{12}) \quad (9)$$

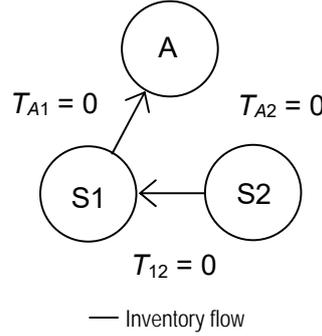
In this three-stage decision problem, the final assembler maximizes its own profit in (5) by determining the quality incentives for S1 and S2, T_{A1} and T_{A2} , but it needs to satisfy S1's constraints in (6) and (7). S1 participates in this joint innovation activity when a positive profit is guaranteed in the individual rationality constraint (6). In the incentive compatibility constraint (7), S1 maximizes its own profit, given the final assembler's decision on T_{A1} and T_{A2} , by determining its best response q_1 and T_{12} , the quality level of the main component and the quality incentive from S1 to S2. S1 also needs to satisfy the constraints of S2 in (8) and (9). S1 also needs to guarantee S2's positive profit in (8), and S2 maximizes its own profit in (9) by determining the quality of subcomponent q_2 , given the decisions of the final assembler and S1. We will obtain the solutions of supply chain models based on the above problem framework.

We starts from Case N, the very basic model only with inventory transactions among players as

illustrated in Figure 1. There are no incentives for quality improvement among players as in a typical transactional relationship, shown in Equation (10). Therefore, it can be regarded as a reactive strategy, with which the final assembler would correspond to a quality problem after it occurs, not proactively preventing it.

$$T_{A1} = T_{A2} = T_{12} = 0. \quad (10)$$

Figure 1: Case N (A: final assembler, S1: first-tier supplier, S2: second-tier supplier)



Based on Equation (10) without incentives and Assumption 2 with given p , w_1 and w_2 , the final assembler has nothing to control. Therefore, the three-stage decision structure in (5) through (9) reduces to two stages by ignoring (5) and (6). After applying Equation (10) into Equations (2) through (4) and based on the decision structure above, now two-stage, we can obtain the optimal solution by the backward induction like a typical Stackelberg game. We first obtain the best response of S2, q_2^{N*} , from the first-order necessary condition (FONC) of (9) and then the response of S1, q_1^{N*} , from FONC of (7).

$$q_1^{N*} = \frac{\gamma\pi_1}{2\lambda}, \text{ and } q_2^{N*} = \frac{\delta\pi_2}{2\eta}.$$

where $\pi_1 = w_1 - c_1 - w_2 > 0$ and $\pi_2 = w_2 - c_2 > 0$ in Equations (3) and (4).

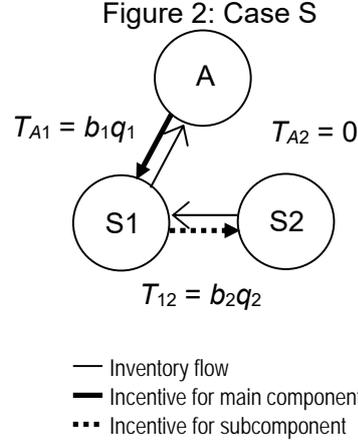
Applying q_1^{N*} and q_2^{N*} above into Equations (1) through (4), we can simply obtain the optimal demand and profits of all players and entire supply chain, i.e., the supply chain profit $\Pi = \Pi_A + \Pi_1 + \Pi_2$. All solutions in this study guarantee the concavity of profit functions by satisfying the second-order sufficient conditions. The solutions of Case N are summarized in Tables 1-3 in Section 4.5.

Case S: A Sequential Incentive Mechanism

Differently from the reactive Case N without quality incentives, we consider a sequential incentive scheme in Case S. This is a common benefit-sharing strategy in practice, in that a buying firm collaborates and shares its collaborative benefit only with its direct supplier. Therefore, as illustrated in Figure 2, the final assembler offers S1 an incentive to proactively control the quality of the main component, and then S1 also offers S2 an incentive for subcomponent quality. The incentives among players are defined as follows.

$$T_{A1} = b_1q_1, T_{A2} = 0, \text{ and } T_{12} = b_2q_2, \quad (11)$$

where b_1 and b_2 are the marginal incentives of resulting quality, paid from the final assembler to S1 and from S1 to S2, respectively.



After applying the incentives defined in Equation (11) into the general three-stage optimization problem framework in (5) through (9), we can obtain the solutions by the backward induction. We first obtain the best response of S2 from FONC of (9) as a function of b_2 .

$$q_2^S(b_2) = \frac{\delta\pi_2 + b_2}{2\eta}.$$

Then, after applying the above $q_2^S(b_2)$ into (7), we can obtain S1's best response by simultaneously solving FONCs of (7).

$$q_1^S(b_1) = \frac{\gamma\pi_1 + b}{2\lambda}, \text{ and } b_2^{S*} = \frac{\delta(\pi_1 - \pi_2)}{2}.$$

Next, we obtain the assembler's decision from FONC of (5) after applying the above into (5).

$$b_1^{S*} = \frac{\gamma(\pi_A - \pi_1)}{2},$$

where $\pi_A = p - c - w_1 > 0$ in Equation (2).

Applying b_1^{S*} and b_2^{S*} into $q_1^S(b_1)$ and $q_2^S(b_2)$, we obtain the closed-form solutions of q_1^{S*} and q_2^{S*} . The optimal demand and profits are also easily obtained if we apply b_1^{S*} , b_2^{S*} , q_1^{S*} and q_2^{S*} into Equations (1) through (4). We summarize the solutions of Case S in Tables 1-3 in Section 4.5.

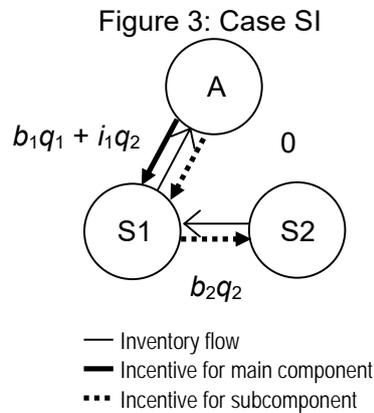
Case SI: A Sequential Incentive Mechanism with an Additional Indirect Incentive for Subcomponent

Collaboration between players in a supply chain is critical to sustain competitive advantage. However, it has been usually between a buying firm and its direct supplier as we describe in Case S. It is still not a common practice that a buying firm has a direct control over its lower-tier

suppliers. It is not easy for a buying firm to have enough capability to directly command all suppliers in a multi-tiered supply chain, and it is sometimes restricted by an antitrust law in some countries since it can hinder fair competition between suppliers in lower tiers. However, a final assembler still needs to find a proactive way to control a lower-tier supplier since its quality capability often has a significant impact on the performance of the overall supply chain. Therefore, in Case SI, we introduce an indirect (I) incentive scheme for subcomponent quality in addition to the sequential incentive scheme in Case S. It is from the final assembler to S1 so as to improve S1's incentive control over S2 and subsequently better manage S2's quality investment through S1, as illustrated in Figure 3. The incentives can be defined as follows.

$$T_{A1} = b_1q_1 + i_1q_2, T_{A2} = 0, \text{ and } T_{12} = b_2q_2, \tag{12}$$

where i_1 is the marginal indirect incentive for subcomponent quality paid from the final assembler to S1, while direct sequential incentives b_1 and b_2 are the same as in Case S.



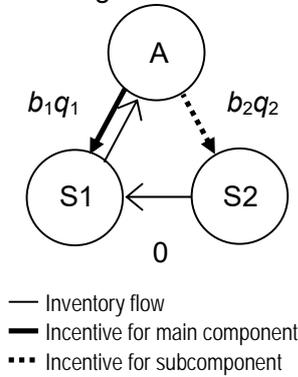
After applying Equation (12) into the general problem defined in (5) through (9) in Section 4.1 and by following the backward induction approach the same as Case S, we obtain the closed-form optimal solutions of Case SI. They are summarized in Tables 1 through 3.

Case P: A Parallel Incentive Mechanism

It has been a common practice that a buying firm concentrates only on controlling its direct supplier as we already stated in Cases S and SI. However, nowadays we can observe contemporary firms which understand the interrelations among players in a multi-tiered supply network as Yan et al (2015) pointed out, such as Honda, Toyota and LG Electronics (LGE). They have tried to establish direct contractual relationships with a lower-tier supplier so as to proactively take better control over quality, especially if S2 potentially exerts a critical impact on the performances of the final assembler and entire supply chain (Yan et al, 2015). In Case P, we adopt this contemporary situation in which the final assembler takes the centralized control over both S1 and S2. The final assembler establishes a direct relationship with S2, bypassing S1, similarly as in the relationship between LGE and Taiwan Semiconductor Manufacturing Company (TSMC), bypassing the first-tier supplier, Qualcomm (Choi & Linton, 2011). Therefore, the sequential relationship between three players changes to a triadic relationship as shown in Figure 4. In this parallel incentive path from the final assembler to both S1 and S2, the incentives among players can be defined as follows.

$$T_{A1} = b_1q_1, T_{A2} = b_2q_2, \text{ and } T_{12} = 0. \tag{13}$$

Figure 4: Case P



Considering the assembler’s centralized control over both S1 and S2 bypassing S1, the three-stage problem structure in (5) through (9) also needs to change to two stages with multiple (two) agents (or followers) like below.

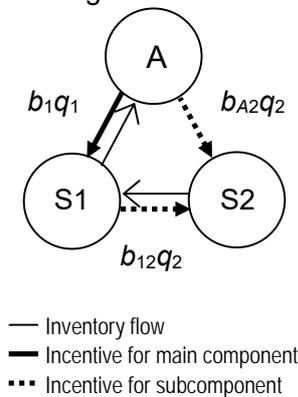
Problem P:

$$\begin{aligned} &\text{Maximize} && \Pi_A(b_1, b_2) \\ &\text{subject to} && \Pi_1(q_1 | b_1, b_2) > 0 \\ & && \text{Maximize} && \Pi_1(q_1 | b_1, b_2) \\ & && \Pi_2(q_2 | b_1, b_2) > 0 \\ & && \text{Maximize} && \Pi_2(q_2 | b_1, b_2) \end{aligned}$$

By following the backward induction similar to former cases but with two agents, we first obtain the best responses of S1 and S2, q_1 and q_2 , separately as functions of b_1 and/or b_2 . Then, after applying both q_1 and q_2 to the assembler’s profit Π_A , we can obtain the final assembler’s decision from FONCs of Π_A . The solutions of Case P are summarized in Tables 1-3 in the next section.

Case PS: Combining Both Parallel and Sequential Incentives

Figure 5: Case PS



In Case P, we consider a triadic relationship between players involving a parallel incentive path

from the assembler to both S1 and S2, while not considering S1's quality incentive for S2. In Case PS, we include all possible incentive paths among players as shown in Figure 5 by combining parallel and sequential incentive schemes in Cases P and S. Therefore, the incentives can be defined in the triadic relationship of Case PS as follows.

$$T_{A1} = b_1 q_1, T_{A2} = b_{A2} q_2, \text{ and } T_{12} = b_{12} q_2, \quad (14)$$

where b_{A2} is the quality incentive for subcomponent quality from the assembler to S2 and b_{12} is the incentive from S1 to S2, while S2's total quality incentive is $b_2 = b_{A2} + b_{12}$.

Case PS forms a triadic relationship like Case P, but Case PS maintains the three-stage decision problem described in (5) through (9), accompanying the triple marginalization problem, since it additionally includes the sequential incentive scheme. Applying the incentives in Equation (14), we obtain the closed-form solutions of Case PS, summarized in Tables 1 through 3.

Case	Incentive		
	b_1^*	b_2^*	i_1^*
N	0	0	N/A
S	$\frac{\gamma(\pi_A - \pi_1)}{2}$	$\frac{\delta(\pi_1 - \pi_2)}{2}$	N/A
SI	$\frac{\gamma(\pi_A - \pi_1)}{2}$	$\frac{\delta(\pi_1 - \pi_2)}{2} + \frac{\delta(\pi_A - (\pi_1 + \pi_2))}{4}$	$\frac{\delta(\pi_A - (\pi_1 + \pi_2))}{2}$
P	$\frac{\gamma(\pi_A - \pi_1)}{2}$	$\frac{\delta(\pi_A - \pi_2)}{2}$	N/A
PS	$\frac{\gamma(\pi_A - \pi_1)}{2}$	$\frac{\delta(\pi_1 - \pi_2)}{2} + \frac{\delta(\pi_A - (\pi_1 + \pi_2))}{4}$	N/A

* $\pi_A = p - c - w_1 > 0$, $\pi_1 = w_1 - c_1 - w_2 > 0$, $\pi_2 = w_2 - c_2 > 0$

* In Case PS, $b_2^{PS*} = b_{A2}^{PS*} + b_{12}^{PS*}$, where $b_{A2}^{PS*} = \delta(\pi_A - (\pi_1 + \pi_2))/2$, and $b_{12}^{PS*} = \delta(\pi_1 - \pi_2)/2 - \delta(\pi_A - (\pi_1 + \pi_2))/4$

Case	Quality		Consumer response
	q_1^*	q_2^*	D^*
N	$\frac{\gamma\pi_1}{2\lambda}$	$\frac{\delta\pi_2}{2\eta}$	$D_0 + \frac{\gamma^2\pi_1}{2\lambda} + \frac{\delta^2\pi_2}{2\eta}$
S	$\frac{\gamma(\pi_A + \pi_1)}{4\lambda}$	$\frac{\delta(\pi_1 + \pi_2)}{4\eta}$	$D_0 + \frac{\gamma^2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2(\pi_1 + \pi_2)}{4\eta}$
SI	$\frac{\gamma(\pi_A + \pi_1)}{4\lambda}$	$\frac{\delta\pi}{8\eta}$	$D_0 + \frac{\gamma^2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2\pi}{8\eta}$
P	$\frac{\gamma(\pi_A + \pi_1)}{4\lambda}$	$\frac{\delta(\pi_A + \pi_2)}{4\eta}$	$D_0 + \frac{\gamma^2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2(\pi_A + \pi_2)}{4\eta}$
PS	$\frac{\gamma(\pi_A + \pi_1)}{4\lambda}$	$\frac{\delta\pi}{8\eta}$	$D_0 + \frac{\gamma^2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2\pi}{8\eta}$

* $D_0 = \alpha - \beta p$, $\pi_A = p - c - w_1 > 0$, $\pi_1 = w_1 - c_1 - w_2 > 0$, $\pi_2 = w_2 - c_2 > 0$, $\pi = \pi_A + \pi_1 + \pi_2 = p - c - c_1 - c_2 > 0$

Table 3: Solution summary: Profits				
Case	Final assembler	S1	S2	Supply chain
	Π_A^*	Π_1^*	Π_2^*	Π^*
N	$D_0\pi_A + \frac{\gamma^2\pi_A\pi_1}{2\lambda} + \frac{\delta^2\pi_A\pi_2}{2\eta}$	$D_0\pi_1 + \frac{\gamma^2\pi_1^2}{4\lambda} + \frac{\delta^2\pi_1\pi_2}{2\eta}$	$D_0\pi_2 + \frac{\gamma^2\pi_1\pi_2}{2\lambda} + \frac{\delta^2\pi_2^2}{4\eta}$	$D_0\pi + \frac{\gamma^2\pi_1(\pi + (\pi_A + \pi_2))}{4\lambda} + \frac{\delta^2\pi_2(\pi + (\pi_A + \pi_1))}{4\eta}$
S	$D_0\pi_A + \frac{\gamma^2(\pi_A + \pi_1)^2}{8\lambda} + \frac{\delta^2(\pi_1 + \pi_2)\pi_A}{4\eta}$	$D_0\pi_1 + \frac{\gamma^2(\pi_A + \pi_1)^2}{16\lambda} + \frac{\delta^2(\pi_1 + \pi_2)^2}{8\eta}$	$D_0\pi_2 + \frac{\gamma^2\pi_2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2(\pi_1 + \pi_2)^2}{16\eta}$	$D_0\pi + \frac{\gamma^2(\pi_A + \pi_1)(3\pi + \pi_2)}{16\lambda} + \frac{\delta^2(\pi_1 + \pi_2)(3\pi + \pi_A)}{16\eta}$
SI	$D_0\pi_A + \frac{\gamma^2(\pi_A + \pi_1)^2}{8\lambda} + \frac{\delta^2\pi^2}{16\eta}$	$D_0\pi_1 + \frac{\gamma^2(\pi_A + \pi_1)^2}{16\lambda} + \frac{\delta^2\pi^2}{32\eta}$	$D_0\pi_2 + \frac{\gamma^2\pi_2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2\pi^2}{64\eta}$	$D_0\pi + \frac{\gamma^2(\pi_A + \pi_1)(3\pi + \pi_2)}{16\lambda} + \frac{7\delta^2\pi^2}{64\eta}$
P	$D_0\pi_A + \frac{\gamma^2(\pi_A + \pi_1)^2}{8\lambda} + \frac{\delta^2(\pi_A + \pi_2)^2}{8\eta}$	$D_0\pi_1 + \frac{\gamma^2(\pi_A + \pi_1)^2}{16\lambda} + \frac{\delta^2\pi_1(\pi_A + \pi_2)}{4\eta}$	$D_0\pi_2 + \frac{\gamma^2(\pi_A + \pi_1)\pi_2}{4\lambda} + \frac{\delta^2(\pi_A + \pi_2)^2}{16\eta}$	$D_0\pi + \frac{\gamma^2(\pi_A + \pi_1)(3\pi + \pi_2)}{16\lambda} + \frac{\delta^2(\pi_A + \pi_2)(3\pi + \pi_1)}{16\eta}$
PS	$D_0\pi_A + \frac{\gamma^2(\pi_A + \pi_1)^2}{8\lambda} + \frac{\delta^2\pi^2}{16\eta}$	$D_0\pi_1 + \frac{\gamma^2(\pi_A + \pi_1)^2}{16\lambda} + \frac{\delta^2\pi^2}{32\eta}$	$D_0\pi_2 + \frac{\gamma^2\pi_2(\pi_A + \pi_1)}{4\lambda} + \frac{\delta^2\pi^2}{64\eta}$	$D_0\pi + \frac{\gamma^2(\pi_A + \pi_1)(3\pi + \pi_2)}{16\lambda} + \frac{7\delta^2\pi^2}{64\eta}$

* $D_0 = \alpha - \beta p$, $\pi_A = p - c - w_1 > 0$, $\pi_1 = w_1 - c_1 - w_2 > 0$, $\pi_2 = w_2 - c_2 > 0$, $\pi = \pi_A + \pi_1 + \pi_2 = p - c - c_1 - c_2 > 0$

COMPARISON OF INCENTIVE STRATEGIES

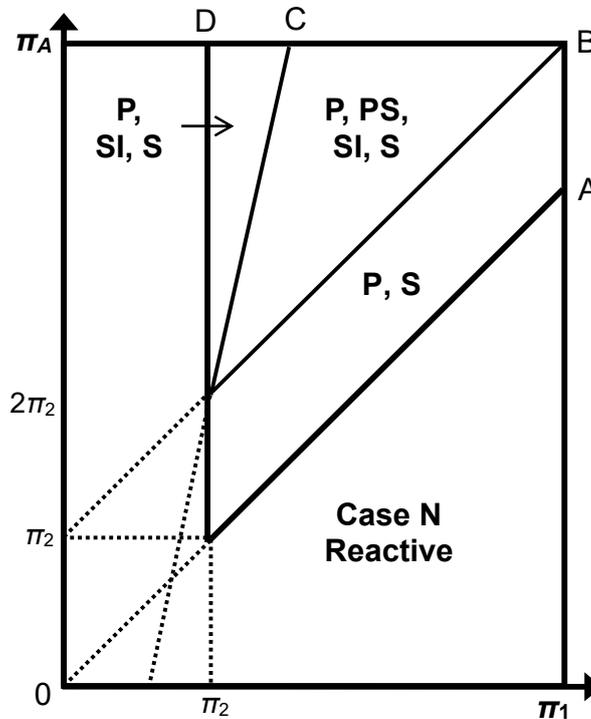
In this section, we compare incentive strategies in a three-echelon supply chain and reveal their different characteristics. First, we find the conditions under which the final assembler can adopt the proactive incentive strategies by investigating the results in Table 1.

Proposition 1. *Conditions under which each incentive can exist are as follows.*

- (1) b_1^* can exist in all cases when $\pi_A > \pi_1$.
- (2) b_2^* exists when $\pi_1 > \pi_2$ in Case S, $\pi_A > \pi_2$ in Case P and $\pi_1 + \pi_2 < \pi_A < 3\pi_1 - \pi_2$ in Case PS. Both b_2^* and i_1^* exist in Case SI when $\pi_1 > \pi_2$ and $\pi_A > \pi_1 + \pi_2$.

Proof. To have $b_1^* > 0$, $b_2^* > 0$, and/or $i_1^* > 0$ in each case from Table 1, we directly obtain the conditions in Proposition 1. □

Figure 6: Conditions under which each incentive strategy exists (A: $\pi_A = \pi_1$, B: $\pi_A = \pi_1 + \pi_2$, C: $\pi_A = 3\pi_1 - \pi_2$, D: $\pi_1 = \pi_2$)



We first need to note that the reason why each player intends to adopt a quality incentive is in order to proactively protect its own business interest and profitability. Observe in Table 1 that each player reflects its own profitability when offering the incentive, i.e., $b_1^* = f(\pi_A)$ in all cases, while $b_2^{S^*} = f(\pi_1)$, $b_2^{SI^*} = f(\pi_1, \pi_2)$, $b_2^{P^*} = f(\pi_A)$ and $b_2^{PS^*} = f(\pi_1, \pi_2)$ (see together the incentive-offering paths in Figures 1-5). Therefore, it is straightforward that quality incentives depend on the relative profitability of players, and only a player sufficiently better off than the other has a motivation to proactively control suppliers by offering incentives. That is, as shown in Propositions 1(1) and 1(2), $\pi_A > \pi_1$ to have $b_1^* > 0$, and at least $\pi_1 > \pi_2$ to have $b_2^* > 0$ and/or $i_1^* > 0$, where the marginal profits of the final assembler, S1, S2 and supply chain are $\pi_A = p - c - w_1 > 0$, $\pi_1 = w_1 - c_1 - w_2 > 0$, $\pi_2 = w_2 - c_2 > 0$ and $\pi = \pi_A + \pi_1 + \pi_2 = p - c - c_1 - c_2 > 0$,

respectively, as defined in Equations (2) through (5). If we combine the criteria to have both $b_1^* > 0$ and $b_2^* > 0$ (and also $i_1^* > 0$), the condition areas can be graphically illustrated as in Figure 6, under which the final assembler can proactively utilize each incentive strategy. As shown in Figure 6, each incentive strategy cannot always be adopted. If a buying firm (the final assembler or S1) is not better off than a supplier firm (S1 or S2), i.e., $\pi_A < \pi_1$ or $\pi_1 < \pi_2$, it is a rational decision to reactively respond to quality failures while maintaining only a transactional relationship with suppliers (Case N). Next, we compare the amount of each incentive, which in turn affects the overall performances in a multi-tiered supply chain.

Proposition 2. *Comparing the incentives for S1 and S2 in incentive models, respectively, they are related as:*

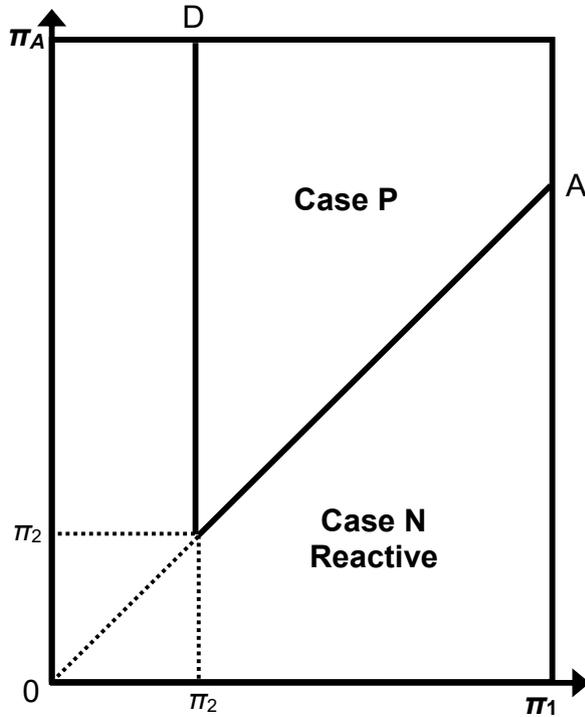
- (1) $b_1^{S^*} = b_1^{SI^*} = b_1^{P^*} = b_1^{PS^*} > 0$ if $\pi_A > \pi_1$. Otherwise, they do not exist.
- (2) $b_2^{P^*} > b_2^{S^*}$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_1 > \pi_2$,
 $b_2^{P^*} > b_2^{PS^*} = b_2^{SI^*} > b_2^{S^*}$ if $\pi_1 + \pi_2 < \pi_A < 3\pi_1 - \pi_2$, and
 $b_2^{P^*} > b_2^{SI^*} > b_2^{S^*}$ without Case PS if $\pi_A > 3\pi_1 - \pi_2$ and $\pi_1 > \pi_2$.
- (3) Comparing Cases SI and S, $b_2^{SI^*} - b_2^{S^*} = i_1^{SI^*}/2$.

Proof. By directly comparing b_1^* or b_2^* of all incentive models in Table 1, respectively, and considering the conditions to have both b_1^* and $b_2^* > 0$ in Proposition 1, we obtain the results in Proposition 2. □

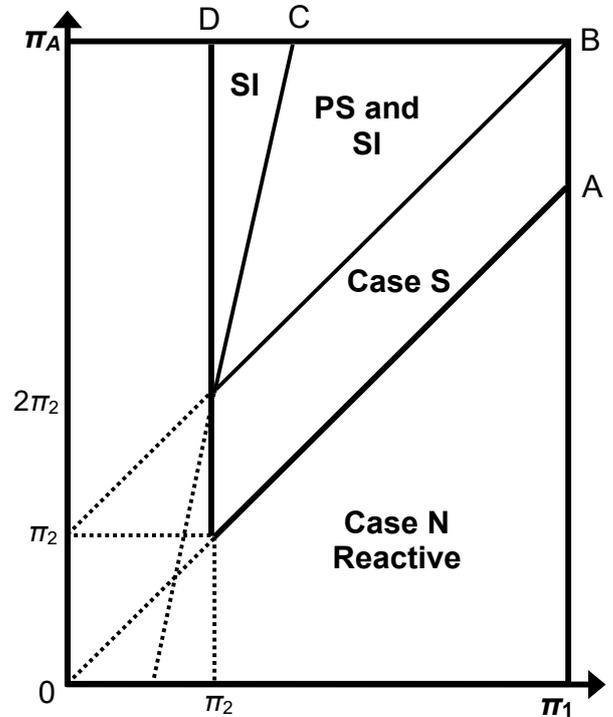
In the dyadic relationship between the final assembler and S1, the quality incentive for the main component is identical in all cases. There is only a decision whether offering an incentive or not as shown in Proposition 2(1). However, if we expand our view to proactively have a direct control over the lower tier, we can observe that there can be various relationships in the quality incentives for S2 as shown in Proposition 2(2). The results are graphically illustrated in Figure 7. As illustrated in Figure 7(a), when the final assembler forms a triadic relationship in Case P, the largest quality incentive can be offered to S2. This is since the final assembler takes the centralized control over both S1 and S2, and hence the supply chain becomes most efficient by mitigating the multiple marginalization issues (see the two-stage decision structure of Case P shown in Section 4.4). We can also observe that Case P is less restricted in offering the incentive for S2 and hence easier to be adopted than other sequential incentive schemes as we see in Proposition 2(2) and also Figures 6, 7(a) and 7(b). While Case P always offers the largest incentive for S2, we also illustrate the comparison result of sequential incentive schemes without Case P in Figure 7(b) since Case P, directly controlling S2, cannot be considered due to a certain regulation in some practices. We can also interestingly observe that the incentives for S1 and S2 are exactly the same in Cases SI and PS despite their different incentive mechanisms as illustrated in Figures 3 and 5, while Case SI is less restricted to be adopted than Case PS as shown in Figure 7(b). We can also observe that an inefficiency problem occurs in Case SI as pointed out in Proposition 2(3). Note that S1 passes S2 only the half of the final assembler's indirect incentive for subcomponent quality, while it internalizes the other half, i.e., comparing two results with and without indirect incentives of Cases SI and S, $b_2^{SI^*} - b_2^{S^*} = i_1^{SI^*}/2$. Overall, various incentive results, especially for the lower-tier S2, then will differently affect the overall performances. Next, Proposition 3 summarizes the comparison results of quality performances in five supply chain models.

Figure 7: Graphical representation of the case dominating others, in Propositions 2(2), 3(2), 4 and 5(2) (A: $\pi_A = \pi_1$, B: $\pi_A = \pi_1 + \pi_2$, C: $\pi_A = 3\pi_1 - \pi_2$, D: $\pi_1 = \pi_2$)

(a) Including Case P, always dominating



(b) Without Case P



Proposition 3. The levels of quality at S1 and S2 are related as:

- (1) $q_1^{P^*} = q_1^{PS^*} = q_1^{SI^*} = q_1^{S^*} > q_1^{N^*}$ if $\pi_A > \pi_1$.
- (2) $q_2^{P^*} > q_2^{S^*} > q_2^{N^*}$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_1 > \pi_2$,
 $q_2^{P^*} > q_2^{PS^*} = q_2^{SI^*} > q_2^{S^*} > q_2^{N^*}$ if $\pi_1 + \pi_2 < \pi_A < 3\pi_1 - \pi_2$, and
 $q_2^{P^*} > q_2^{SI^*} > q_2^{S^*} > q_2^{N^*}$ without Case PS if $\pi_A > 3\pi_1 - \pi_2$ and $\pi_1 > \pi_2$.

Proof. By directly comparing q_1^* or q_2^* of all cases in Table 2 and considering the conditions to have both b_1^* and $b_2^* > 0$ in Proposition 1, we obtain the results in Proposition 3. \square

We can observe in Propositions 3(1) and 3(2) that all proactive incentive strategies enhance the quality performances at both S1 and S2 than the reactive Case N if they can be adopted, i.e., $q_1^* > q_1^{N^*}$ and $q_2^* > q_2^{N^*}$ for Cases S, SI, P and PS. Because of the same incentive offerings to S1 as shown in Proposition 2(1), the quality levels of the main component at S1 are also induced identical regardless of the incentive strategies as in Proposition 3(1). The quality performances of S2 are also directly determined by the incentives for S2 as shown in Proposition 3(2). Therefore, the case which dominates others can be illustrated the same as Figure 7. As we can see in Proposition 3(2), note that a superior quality result is promised when the final assembler expands its sight and proactively controls the lower-tier supplier S2 as in Case P, PS or SI, i.e., $q_2^{P^*}$, $q_2^{PS^*}$ or $q_2^{SI^*} > q_2^{S^*}$. We cannot expect a higher quality performance when the supply chain player collaborates only with its direct partner as in Case S. Case P always dominates other incentive strategies by proactively forming a triadic relationship and directly controlling both S1 and S2 with the largest incentives as shown in Proposition 3(2) and

Figure 7(a). On the other hand, the indirect incentive in Case SI enhances the quality performance of S2 comparing to Case S, but one needs to remind again that the indirect control accompanies the inefficiency problem as also pointed out in Proposition 2(3). In Case PS, the final assembler directly controls both S1 and S2 like Case P, but a practicing manager needs to note that additionally combining the sequential incentive scheme can rather deteriorate the performance by inducing the marginalization problem.

Proposition 4. Comparing the demand D^* and supply chain profit Π^* , they are related as follows.

Case $P > S > N$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_1 > \pi_2$,

Case $P > PS = SI > S > N$ if $\pi_1 + \pi_2 < \pi_A < 3\pi_1 - \pi_2$, and

Case $P > SI > S > N$ without Case PS if $\pi_A > 3\pi_1 - \pi_2$ and $\pi_1 > \pi_2$.

Proof. By directly comparing D^* or Π^* of all cases in Tables 2 and 3 and considering the conditions in Proposition 1 together, we obtain the results of Proposition 4. \square

Because the quality level at S1 is induced the same as shown in Proposition 3(1), the market performance D^* is directly affected by the quality level at S2 shown in Proposition 3(2), and the profit performance of the entire supply chain Π^* is also determined the same. Therefore, Figure 7 can also represent the results of Proposition 4. Case P also guarantees superior market and profit performances of the overall supply chain, while all proactive incentive strategies guarantee the performance enhancement comparing to the reactive strategy (Case N) if they can be adopted. Next, Proposition 5 compares the profit performance of each player.

Proposition 5. Comparing the profit of each player, we obtain the following properties.

(1) For the final assembler's profit Π_A^* , we obtain the following results.

$\Pi_A^{S^*} > \Pi_A^{P^*} > \Pi_A^{N^*}$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_1 > (\pi_A^2 + \pi_2^2)/(2\pi_A)$,
 $\Pi_A^{P^*} > \Pi_A^{S^*} > \Pi_A^{N^*}$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_2 < \pi_1 < (\pi_A^2 + \pi_2^2)/(2\pi_A)$,

$\Pi_A^{PS^*} = \Pi_A^{SI^*} > \Pi_A^{S^*} > \Pi_A^{P^*} > \Pi_A^{N^*}$ if $\pi_A > \pi_1 + \pi_2$ and $\pi_1 > (\pi_A^2 + \pi_2^2)/(2\pi_A)$,

$\Pi_A^{PS^*} = \Pi_A^{SI^*} > \Pi_A^{P^*} > \Pi_A^{S^*} > \Pi_A^{N^*}$ if $\pi_A < (\sqrt{2}+1)\pi_1 - \pi_2$ and $\pi_1 < (\pi_A^2 + \pi_2^2)/(2\pi_A)$,

$\Pi_A^{P^*} > \Pi_A^{PS^*} = \Pi_A^{SI^*} > \Pi_A^{S^*} > \Pi_A^{N^*}$ if $\max[\pi_1 + \pi_2, (\sqrt{2}+1)\pi_1 - \pi_2] < \pi_A < 3\pi_1 - \pi_2$, and

$\Pi_A^{P^*} > \Pi_A^{SI^*} > \Pi_A^{S^*} > \Pi_A^{N^*}$ without Case PS if $\pi_A > 3\pi_1 - \pi_2$ and $\pi_1 > \pi_2$.

(2) In terms of the profits of S1 and S2, Π_1^* and Π_2^* , we obtain the following relationships.

Case $P > S > N$ without Cases SI and PS if $\pi_1 < \pi_A < \pi_1 + \pi_2$ and $\pi_1 > \pi_2$,

Case $P > PS = SI > S > N$ if $\pi_1 + \pi_2 < \pi_A < 3\pi_1 - \pi_2$, and

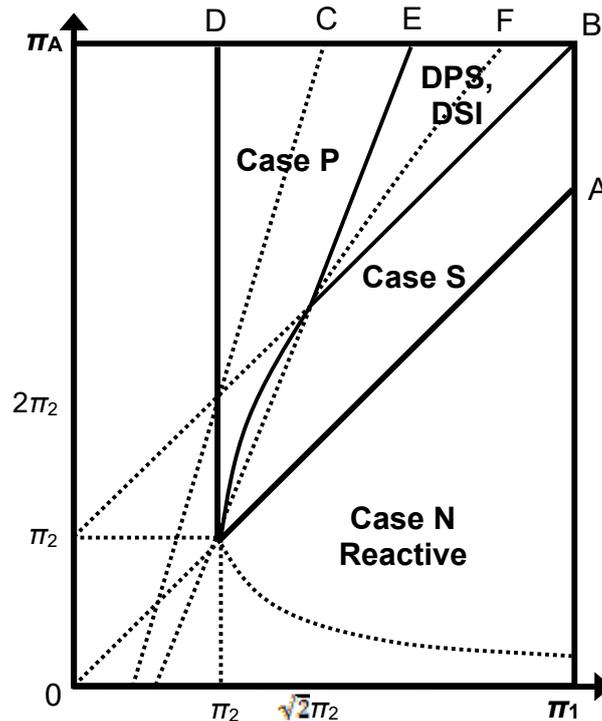
Case $P > SI > S > N$ without Case PS if $\pi_A > 3\pi_1 - \pi_2$ and $\pi_1 > \pi_2$.

Proof. By directly comparing Π_A^* , Π_1^* or Π_2^* of all cases in Table 3, respectively, and considering the conditions in Proposition 1 together, we obtain the comparison results of Proposition 5. \square

Proposition 5(2) indicates that both S1 and S2 are also better off when they are in the triadic relationship under the final assembler's central control in Case P, the same as the result of the entire supply chain in Proposition 4. However, the assembler's profit performance is quite different as shown in Proposition 5(1). The mitigation of multiple marginalization issues in Case P does not always help the final assembler to achieve the superior profit performance as also graphically illustrated in Figure 8. This does mean that Case P cannot always be regarded as a superior alternative even though it not only yields superior quality and market performances but also guarantees the best profit results to S1, S2 and the entire supply chain. The proactive and direct control over all suppliers makes the overall supply chain efficient but imposes a burden to

the final assembler by incurring not only additional control issues involving the lower-tier suppliers but also cost issues due to excessive incentive offerings. As the focal company in the supply chain, the final assembler may make a decision to enhance the overall performances of the supply chain and its partners, not considering its own profit but accepting all the burdens. However, it is more rational that the final assembler with the bargaining power does not have any intention to accept its loss. In this situation, the choice of the proactive incentive strategy in the multi-tiered supply chain will follow the results in Proposition 5(1), graphically illustrated in Figure 8, maximizing the final assembler’s profitability, rather than the result in Figure 7(a). In order to directly control supply chain partners and mitigate marginalization issues by proactively expanding its view to the lower tier and forming a triadic relationship, the final assembler needs to be sufficiently profitable enough, especially comparing to its direct partner S1 which also has the intention to have the control over the lower-tier supplier S2. That is, π_A needs to be sufficiently larger than π_1 to be in the condition area illustrated in Figure 8 under which Case P guarantees a superior profit to the final assembler. Then, the proactive control over suppliers, especially having a direct tie with the lower tier as in Case P, can be advantageous not only to the entire supply chain but also to the final assembler.

Figure 8: The condition of Π_A^* in each case dominating other cases (A: $\pi_A = \pi_1$, B: $\pi_A = \pi_1 + \pi_2$, C: $\pi_A = 3\pi_1 - \pi_2$, D: $\pi_1 = \pi_2$, E: $\pi_A = (\sqrt{2}+1)\pi_1 - \pi_2$, F: $\pi_1 = (\pi_A^2 + \pi_2^2)/(2\pi_A)$)



NUMERICAL EXAMPLE

Case FI: Full Integration as a Benchmark

For the numerical example, we add a fully-integrated supply chain model (Case FI) as a benchmark for the former practical cases, decentralized. Case FI can be considered an ideal

first-best situation, in which the final assembler can monitor and control all players' actions without incurring cost. By integrating overall processes, the final assembler's profit Π_A^{FI} is the same as the supply chain's profit Π^{FI} , where the superscript *FI* denotes Case FI.

$$\Pi_A^{FI} = \Pi^{FI} = \Pi_A + \Pi_1 + \Pi_2 = (p - c - c_1 - c_2)D - \lambda q_1^2 - \eta q_2^2 = \pi D - \lambda q_1^2 - \eta q_2^2, \quad (15)$$

where D , Π_A , Π_1 and Π_2 are in Equations (1) through (4). π is the entire supply chain's marginal profit, i.e., $\pi = \pi_A + \pi_1 + \pi_2 = p - c - c_1 - c_2 > 0$.

By simultaneously solving FONCs of the problem (15), we obtain

$$q_1^{FI*} = \frac{\gamma\pi}{2\lambda}, \text{ and } q_2^{FI*} = \frac{\delta\pi}{2\eta}.$$

By applying the above into Equations (1) and (15),

$$D^{FI*} = D_0 + \frac{\gamma^2\pi}{2\lambda} + \frac{\delta^2\pi}{2\eta}, \text{ and } \Pi_A^{FI*} = \Pi^{FI*} = D_0\pi + \frac{\gamma^2\pi^2}{4\lambda} + \frac{\delta^2\pi^2}{4\eta}.$$

The solution of Case FI will be used as the benchmark for practical decentralization cases.

Numerical Example

We introduce a numerical example not only to verify the results of propositions in a practical parameter setting but also to discover important implications more. We set the parameters as follows: $D = \alpha - \beta p + \gamma q_1 + \delta q_2 = 2000 - 10p + 30q_1 + 30q_2$, $\lambda = \eta = 100$, $p = 115$, $w_1 = 60$, $w_2 = 20$, $c = 20$, $c_1 = 20$, $c_2 = 10$. By the parameter setting above, the marginal profits are $\pi_A = p - c - w_1 = 35$, $\pi_1 = w_1 - c_1 - w_2 = 20$, $\pi_2 = w_2 - c_2 = 10$ and $\pi = \pi_A + \pi_1 + \pi_2 = p - c - c_1 - c_2 = 65$. Therefore, we can have the internal solutions in all incentive models (we satisfy the condition area under which Cases P, PS, SI and S can exist in Figure 6). To analyze the profit performance of each incentive contract, we consider the measure introduced in Cachon (2003): the contract efficiency (Π/Π^{FI}), indicating how closely the supply chain profit of each proactive incentive contract approaches the ideal first-best optimum in Case FI. We also additionally consider the profit share of each player ($PS_j = \Pi_j/\Pi$). For the final assembler, the focal company in the supply chain, the incentive strategy is attractive if both efficiency and its profit share are high (Cachon, 2003). Table 4 summarizes the solutions.

From the results in Table 4, we can identify several managerial implications below.

- Any proactive incentive strategies provide a supply chain a chance to enhance overall performances as also shown in Propositions 3 through 5. Comparing to reactive no incentive scheme, a reactive strategy (Case N), we can observe that the quality levels at S1 and S2, the demand requests of customers and the profits of the final assembler, S1, S2 and supply chain are all enhanced in any incentive strategies.
- The quality and market performances and the profits of S1, S2 and the entire supply chain are always superior in Case P as also shown in Propositions 3, 4 and 5(2).
- However, we observe that the final assembler's profit is superior not in Case P but in Cases PS and SI, i.e., $\Pi_A^{PS*} = \Pi_A^{SI*} > \Pi_A^{S*} > \Pi_A^{P*} > \Pi_A^{N*}$. This is since the parameter set satisfies the conditions, $\pi_A (= 35) > \pi_1 + \pi_2 (= 30)$ and $\pi_1 (= 20) > (\pi_A^2 + \pi_2^2)/(2\pi_A) (= 18.93)$ in

Proposition 5(1).

Table 4: Summary of the numerical example (Contract Efficiency, $Eff^i = \Pi^i/\Pi^F$ where $i = \text{Case N, S, SI, P or PS}$; Profit share, $PS_j = \Pi_j/\Pi$ where $j = A$ (the final assembler), 1 (S1) or 2 (S2))							
		Benchmark	No Incentive	Incentive Strategies			
		Case FI	Case N	Case S	Case SI	Case P	Case PS
Incentive	b_1	N/A	0	225	225	225	225
	b_2	N/A	0	150	187.5	375	187.5
	i_1	N/A	0	0	75	0	0
Total	T_{A1}	N/A	0	928	1,111	928	928
	T_{12}	N/A	0	338	457	0	274
	T_{A2}	N/A	0	0	0	1,266	183
Quality	q_1	9.750	3.000	4.125	4.125	4.125	4.125
	q_2	9.750	1.500	2.250	2.438	3.375	2.438
Investment	λq_1^2	9,506	900	1,702	1,702	1,702	1,702
	ηq_2^2	9,506	225	506	594	1,139	594
Demand	D	1,435	985	1,041	1,047	1,075	1,047
Profit	Π_A	74,263	34,475	35,516	35,530	35,431	35,530
	Π_1	N/A	18,800	19,714	19,890	20,727	19,890
	Π_2	N/A	9,625	10,244	10,332	10,877	10,332
	Π	74,263	62,900	65,473	65,751	67,034	65,751
Efficiency	Eff	1.0000	0.8470	0.8816	0.8854	0.9027	0.8854
Profit Share	PS_A	1.0000	0.5481	0.5424	0.5404	0.5286	0.5404
	PS_1	N/A	0.2989	0.3011	0.3025	0.3092	0.3025
	PS_2	N/A	0.1530	0.1565	0.1571	0.1623	0.1571

- Proactive incentive strategies also allow a supply chain to become more efficient and approach the ideal profit level of the fully-coordinated Case FI, i.e., Eff^S, Eff^{SI}, Eff^P and $Eff^{PS} > Eff^N$, while Case P yields the best efficiency of 90.27%, improved by 5.57% from the result of the reactive Case N without any incentive.
- Profit shares of S1 and S2 are also enhanced through proactive incentive strategies, i.e., $PS_1 > PS_1^N$ and $PS_2 > PS_2^N$ in Cases S, SI, P and PS, while Case P guarantees the highest profit shares to both S1 and S2. However, we can observe that proactive strategies deteriorate the final assembler's profit share, i.e., $PS_A < PS_A^N$ in Cases S, SI, P and PS, even though the final assembler's profit itself increases.
- The reactive Case N guarantees the highest profit share to the final assembler. Therefore, it is impossible to initiate joint quality innovation through a proactive incentive strategy if the final assembler, the focal company in a supply chain, only considers its relative share among supply chain's overall profit. The final assembler needs to overcome a myopic view in order to enhance not only the overall performance of the entire supply chain but also its own.

Overall, it is very important in practice to proactively control suppliers that each supply chain

player, especially the focal company, needs to systematically understand the interaction between players in order to have a thorough understanding of performance dynamics in a supply chain.

CONCLUDING REMARKS

This study investigated proactive incentive strategies for quality improvement in a three-stage supply chain, consisting of a final assembler, a first-tier supplier (S1) and a second-tier supplier (S2). Five different supply chain models are introduced by considering different incentive-offering paths among three players. We then investigated their distinct characteristics and compared their overall performances, including quality, market and profit performances. Through investigation and comparison of those models, we found important implications. They can be summarized as follows.

First, only a buying firm sufficiently profitable comparing to a supplier firm can proactively control suppliers by offering incentives. The reason why each player adopts an incentive is in order to proactively protect its own business interest and profitability by controlling its supplier.

Second, when the final assembler forms a triadic relationship by adopting a parallel incentive strategy, offering incentives to both S1 and S2, the largest quality incentive can be offered to S2. This is since the final assembler takes the centralized control over both S1 and S2, and hence the supply chain becomes most efficient by mitigating the multiple marginalization issues.

Third, any proactive incentive strategies, whether parallel or sequential, always provide a supply chain a chance to enhance overall performances. Comparing to reactive no incentive scheme, the quality levels at S1 and S2, the demand requests of customers and the profits of the final assembler, S1, S2 and supply chain are all enhanced in any proactive incentive strategies.

Fourth, the performance of the parallel incentive strategy always dominates other sequential incentive strategies by proactively forming a triadic relationship and directly controlling both S1 and S2 with the largest incentives, in terms of not only quality and market performances but also profit performances at S1, S2 and entire supply chain.

Fifth, however, the parallel incentive strategy cannot always be regarded as a superior alternative in a supply chain. This is since it does not always guarantee the superior profit performance of the final assembler. The proactive and direct control over all suppliers makes the overall supply chain efficient but imposes a burden to the final assembler by incurring not only additional control issues involving the lower-tier suppliers but also cost issues due to excessive incentive offerings. To effectively adopt the parallel incentive strategy, the final assembler needs to be sufficiently profitable enough, especially comparing to its direct partner S1 which also has the intention to have the control over the lower-tier supplier S2.

Sixth, the reactive strategy without incentives guarantees the highest profit share to the final assembler. Therefore, it is impossible to initiate joint quality innovation through a proactive incentive strategy if the final assembler only considers its relative share among supply chain's overall profit. The final assembler needs to overcome a myopic view in order to enhance not only the overall performance of the entire supply chain but also its own. .

We aim to contribute to the body of knowledge and supply chain practices by revealing different characteristics of proactive incentive strategies for quality improvement in a three-stage supply

chain and by providing important implications.

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