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ORIGINAL RESEARCH

How to facilitate supplier-supplier collaboration: The impact of a manufacturer's order allocation policy and subsidy offering

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Abstract
In response to rapidly changing market conditions, manufacturers are increasingly trying to induce collaborative interactions between suppliers to facilitate the sharing of problem-solving ideas, technical advice, and managerial know-how. However, even if supplier-supplier collaboration is an effective way to enhance operational performance, it could be challenging if the suppliers compete to win the same order from the manufacturer. By employing a game-theoretical model, this study explores how a manufacturer can leverage the order allocation policy to facilitate collaboration between two competing suppliers. The results show that the timing of the order allocation policy announcement is critical. If the policy is announced after observing the behavior of the suppliers, the manufacturer cannot induce the desired outcome. However, the announcement that precedes the behavior of the suppliers can lead to collaboration between suppliers if the associated cost is affordable. The maximum affordable level that reflects each supplier's collaboration burden becomes mild when the suppliers possess a similar capability and secure a sufficient margin. Unlike the manufacturer, who always benefits from suppliers engaged in collaboration, collaborative suppliers require more restricted conditions to generate a higher profit. We also examine the effectiveness of an additional lever, the manufacturer's financial support or subsidy for supplier-supplier collaboration. Our result indicates that if the subsidy is inappropriately determined, it could become a waste of resources.

Keywords Supplier-supplier collaboration · Order allocation policy · Supplier selection · Cost reduction · Supply chain management

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1 Introduction

Recently, the manufacturing industry has been experiencing substantial change in terms of customer needs and technological advancement. The more sophisticated the product or process technologies the manufacturer requires, the more it needs to rely on suppliers who possess the necessary skills and resources to cope with today's market changes (Wang et al., 2020; Yoo & Cheong, 2018). For example, the most critical component in electric vehicle (EV) manufacturing is the battery, which accounts for more than one-third of the entire vehicle value. Thus, the battery suppliers directly impact the performance and price competitiveness of EVs (Matousek, 2020; Mullaney, 2020). Given the increasing significance of suppliers, it is a challenging but important task for manufacturers to improve their suppliers' operational performance for the market success of their end products.

One effective way to enhance suppliers' performance in operations is to induce them to engage in collaborative interactions. For example, they can resolve operational problems more effectively by sharing problem-solving ideas, technical advice, and managerial know-how. As each supplier has different knowledge and experience (Gupta & Govindarajan, 2000), collaborative interactions between suppliers offer vast opportunities to find better answers for operational problems, which can lead to a reduction in production cost, a reduction in the number of defects, and an improvement in component quality (Wu et al., 2010). Such enhancement positively affects the end product manufacturing and sales. Indeed, in many industries, manufacturers with highly advanced supply chain management spend much time and effort to facilitate collaboration between suppliers for higher operational performance (Basole, 2016; Potter & Wilhelm, 2020; Sako, 2004; Usta et al., 2015). For example, Toyota sets a supplier association and pursues strengthening cooperation and knowledge sharing between members (Bernstein et al., 2015; Toyota, 2016). In regards to the recent transition towards green vehicle innovation, a substantial rise in the number of co-patents within the Toyota supplier association exemplifies the beneficial outcomes generated through the suppliers' collective capabilities (Borgstedt et al., 2017; Potter & Graham, 2020). As another example, in the electronics industry, supplier-supplier collaboration spurs active knowledge creation and transfer, which provides performance benefits spilling over to the buyer. Most reputable high-performing firms (e.g., Apple and Samsung Electronics) are known for their effective supply networks that exhibit greater interaction and collaboration among the entities (Basole, 2016). Likewise, in many industries such as semiconductor, defense, and automotive, manufacturers encourage and facilitate supplier-supplier collaboration for higher operational performance (Sako, 2004; Usta et al., 2015).

While supplier-supplier collaboration is continuously observed in practice, even between competing suppliers (Wilhelm, 2011), it is not easy to induce voluntary participation from the suppliers (Hamel et al., 1989; Zhang et al., 2019). Even if the suppliers understand the benefits of collaboration, they naturally have burdens that supplier-supplier collaboration can bring, such as infrastructure building to facilitate smooth communication and the dissipation of superiority (Huo et al., 2019; Li & Wan, 2017). This leads us to an important question: How can we facilitate the collaboration between self-interested suppliers in a supply chain where the suppliers primarily care about their own profits? The primary purpose of this study is to find a way to trigger supplier-supplier collaboration and thereby improve the profits of the supply chain players. Among many types of supplier-supplier collaboration, we focus on process-improving activities that can ultimately reduce the supply chain's production cost.

One of the most effective instruments to control the suppliers' actions is the order allocation policy, especially when suppliers compete for more orders. By strategically allocating orders, a manufacturer can induce suppliers to act in a desired manner, such as making them adopt cost-cutting or quality enhancement measures (Cachon & Zhang, 2007; Li et al., 2013). Thus motivated, we utilize the order allocation policy as a means for manufacturers to facilitate collaboration between suppliers. To this end, we set a game-theoretic model of a triadic supply chain that consists of a manufacturer and two asymmetric suppliers. In our model, supplier asymmetry is modeled in terms of production efficiency (high- and low-cost suppliers) to reflect the gap in their knowledge and experiences. Despite the suppliers' burdens associated with collaboration, the manufacturer would be motivated to step in and facilitate collaboration between the suppliers, as the enhancement in the suppliers' operational performance would reduce its purchase cost. In our model, for the purpose of inducing collaboration, the manufacturer ponders when to announce its allocation policy that specifies the order-splitting proportion (how much will be allocated to each supplier). Specifically, the manufacturer chooses the timing of the order allocation policy announcement either before or after the suppliers' collaboration engagement. In other words, the manufacturer may or may not commit to the order-splitting proportion prior to the realization of the purchase cost, as in Li and Wan (2017) and Adhikari and Bisi (2020). Hereafter, we term these two alternatives the *ex-ante* order allocation policy announcement and the *ex-post* order allocation policy announcement, respectively.

With the above model setup, we first compare the results obtained under the ex-ante and ex-post order allocation policy announcements to study the impact of the timing of the announcement on supplier-supplier collaboration. We also investigate the factors that allow an easier facilitation of supplier-supplier collaboration. Next, we pay attention to whether the collaboration benefit can be translated into the profit improvement of the suppliers as well as the manufacturer, as a high-profit level can sustain the effort for mutual prosperity. Lastly, we examine the effectiveness of an additional lever, the manufacturer's financial support (subsidy), for supplier-supplier collaboration as exemplified by Toyota (Bernstein et al., 2015; Sako, 2004). More precisely, we ask if the subsidy creates a synergy with the order allocation policy to expedite the collaboration and benefit the manufacturer.

Through the rigorous examination of our analytical results, we find that the timing of the order allocation policy announcement plays a vital role in facilitating collaboration between suppliers. We show that the ex-post announcement cannot induce a desirable outcome and ends up granting all the order volumes to the low-cost supplier. However, the outcomes of the ex-ante announcement would be much different if the required amount of investment for supplier-supplier collaboration was affordable. In that case, the ex-ante announcement can induce a concerted collaboration of suppliers by signaling that the future transaction will embrace both low- and high-cost suppliers (i.e., the orders are allocated to both suppliers). From the examination of factors that affect the maximum affordable level of fixed investment for collaboration, we determine that the supplier-supplier collaboration becomes easy to induce when (i) the suppliers have similar capabilities in production cost, (ii) the suppliers secure sufficient unit margins, and (iii) the collaboration benefit is substantial. We also show that the manufacturer always earns a higher profit when the suppliers are engaged in collaboration, whereas more restricted conditions are needed to achieve a win–win situation for all supply chain members. In addition, through the analysis on the effectiveness of the manufacturer's subsidy, we identify the optimal subsidy level and the conditions under which a subsidy would improve the manufacturer's profit.

While paying attention to the performance improvement based on horizontal collaboration, our results provide lessons for how to persuade suppliers engaged in rivalry to help each other and seek co-prosperity. First, to induce voluntary collaboration from the suppliers, the manufacturer needs to consider making an ex-ante policy announcement to signal that it will not exclude either one of them from the transaction (order allocation) instead of waiting for the outcome of wholesale price competition. By leveraging the benefit of supplier-supplier collaboration (reduction in the production cost), the manufacturer can boost product sales, which leads to an increase in order volume and incentivizes the suppliers to endure the fixed cost of collaborative activities. Next, as well as the primary merit of collaboration (cost reduction), the suppliers' capability gap and the manufacturer's bargaining power (unit margin) affect how impactful the ex-ante policy announcement will be. Unlike the other two factors (level of cost reduction and unit margin), the capability gap between suppliers surpassing a certain threshold makes it more difficult to facilitate supplier-supplier collaboration. Last, the manufacturer can expedite supplier-supplier collaboration by subsidizing the initial burden of collaboration. However, for the desirable use of limited resources, the manufacturer ought to keep in mind that an inappropriately chosen level of subsidy becomes just a waste of resources. Depending on conditions, sometimes the ex-ante announcement of the order allocation policy is enough.

2 Literature review

This study hinges on three distinct research streams: supplier-supplier collaboration, order allocation as an instrument to influence multiple suppliers, and performance improvement through a certain commitment to ordering policy. This section reviews relevant papers related to the three streams of research and discusses their key distinctions with our work.

As the competitive landscape changes rapidly and technological innovation accelerates, inter-organizational collaboration is becoming an essential source of effective performance improvement. The fundamental idea of collaboration benefit is a chance to access a wider pool of knowledge resources and learn best practices (Gupta & Govindarajan, 2000; Raweewan & Ferrell, 2018). Although relatively less attention has paid to supplier-supplier collaboration compared to the manufacturer-supplier situation (e.g., Aoki & Wilhelm, 2017; Bahinipati & Deshmukh, 2012), several studies consider operational performance improvement with a focus on the relationship between suppliers. For instance, Kamath and Liker (1994) report that many Japanese automakers cultivate committed suppliers and encourage them to collaborate for higher value creation while securing each party's status. According to Sako (2004), Toyota and Honda strikingly similarly leverage their suppliers' capabilities. Persuading supplier-supplier collaboration is one way of strengthening the suppliers' operational performance, which in turn turns into the buyer's benefit (i.e., Toyota and Honda).

Choi et al. (2002) classify three types of supplier-supplier relationships and emphasize the buyer firm's role in configuring those relationships while revealing the pros and cons of each type. Especially when the suppliers perceive that it is necessary to work with competitors for easier learning and market expansion, supplier-supplier collaboration effectively enhances both parties' competitiveness as well as the overall efficiency of the entire supply chain. Wu and Choi (2005) identify five unique supplier-supplier relationship structures through eight case studies, illustrating the antecedent conditions resulting in such configurations and the eventual performance implications. To facilitate successful supplier-supplier collaboration, the manufacturer should create a consistent and clear transaction policy for its suppliers to accept the outcomes fair.

In another study, Wu et al. (2010) empirically study the buyer's role in supplier-supplier relationships and examine the overall supplier performance. They show that buyers can affect the relationship between suppliers. For example, the buyer would have the motivation to instigate collaboration between suppliers if there is a need to relieve the tension between suppliers to solve operational problems. Recently, by using the concepts and measures of social network analysis, Basole (2016) examines the electronic industry and reveals that high-performing firms have supply networks that exhibit greater interaction and collaboration among the entities. Potter and Wilhelm (2020) analyze the data of Toyota's 219 core suppliers and identify the relationship between supply network structure and supplier-supplier innovations. According to their results, a supplier's ability to generate supplier-supplier innovations depends on its degree of centrality in the network. Despite their efforts to better understand supplier-supplier collaboration, most studies are specific case studies that lack deterministic inference. In this regard, this study adopts the game-theoretic reasoning and extends this stream of research by identifying the conditions that motivate competing suppliers to participate voluntarily in collaboration.

The current study views the order allocation policy as a supplier control mechanism facilitating supplier-supplier collaboration. In the literature, we can find two basic types of order allocation: the *winner-takes-it-all* (WTA) type, where a single supplier wins the total order quantity, and the *split-award* (SA) type, where the order is divided between two or more suppliers (Anton & Yao, 1989; Elmaghraby, 2000). Although the WTA order allocation seems consistent with the general economies of scale (Murray, 2009), a stream of research considers the SA-based order allocation capable to induce the desired supplier behavior (Basu et al., 2018; Li, 2019; Li et al., 2013). Basu et al. (2018) study the buyer's order-allocation problem with a focus on production learning and cost reduction as well as the suppliers' investments for improvement in the production process. Li (2019) considers the unobservable behavior of the suppliers to find that information asymmetry provides incentivizes to the suppliers to exert cost reduction efforts. Li et al. (2013) consider the moral hazard problem of suppliers to solve the infinite-horizon contracting problem, where the manufacturer allocates its business volume between two suppliers. They characterize the optimal performance-based contract as incentivizing in a multi-period supply chain setting. The current study considers an incentive scheme but incorporates the manufacturer's commitment into the order allocation while further assessing the effect of the direct incentive (subsidy) given to suppliers.

Several studies relevant to the order allocation policy closely examine the manufacturer's performance improvement through proactive intervention before the transaction between the parties in a supply chain. Lin and Wan (2017) examine the commitment to a procurement mechanism to find a balanced trade-off between the suppliers' improvement efforts and competition. They compare three commitment scenarios: (i) no commitment, (ii) full commitment, and (iii) partial commitment. They find that a commitment benefits the manufacturer and enhances the performance of dual sourcing. Regarding inventory sharing, Li and Chen (2020) conduct human-subject experiments to investigate the effect of different commitment types and identify several behavioral irregularities. For the transfer price commitment, they consider two different settings—the ex-ante and ex-post setting—depending on when the transfer price is committed in relation to demand realization. Adhikari & Bisi (2020) consider the role of the cost-sharing and profit-sharing contract in inducing a supplier's effort to improve green-related quality.

Overall, extending the previous studies, we consider how to facilitate supplier-supplier collaboration rather than instigating fierce competition. Facilitating collaboration can be more desirable in terms of efficient acquisition and the dissemination of knowledge resources. Specifically, we examine how the timing of the order allocation policy announcement affects the suppliers' collaboration decisions under competition.

3 Model

Our model considers a triadic supply chain consisting of a manufacturer and two suppliers producing perfectly substitutable components, such as electric vehicle battery cells. These critical components affect the overall cost and quality of the finished product. The two suppliers are assumed to be capable of meeting the manufacturer's quality standard. Indeed, large manufacturers such as Toyota, Honda, Samsung Electronics, and Tesla commonly have a supply base with more than one supplier for each critical component (Bernstein et al., 2015; Kane, 2020; Lee & Kim, 2018).

The market demand Q is assumed to be negatively affected by the sales price. That is, $Q(p) = a - p$, where a is the exogenous market potential and p denotes the unit sales price. To sell Q units to consumers, the manufacturer needs to procure an amount of components from two suppliers, S1 and S2. The quantity procured from each supplier depends on the manufacturer's decision regarding the order-splitting proportion, denoted by $\theta \in [0, 1]$. That is, the orders to the two suppliers are allocated in the ratio θ, where θQ is assigned to S1 and $(1 - \theta)Q$ is allocated to S2. If θ is either 0 or 1, the manufacturer would allocate orders in the WTA manner, under which one supplier is in charge of all the component procurement. Otherwise, if $\theta \in (0, 1)$, the orders are allocated in the SA manner under which both suppliers supply the component to the manufacturer.

In practice, suppliers are asymmetric in their production efficiency, as they have different knowledge and experience. To reflect this capability gap in the model without loss of generality, we assume that S1 is superior to S2 in production efficiency. That is, $c_1 < c_2$, where c_i indicates the unit production cost of supplier $i \in \{1, 2\}$ (1 and 2 for S1 and S2, respectively). As in a typical buyer-led supply chain with long-term relationships for critical components, the manufacturer and each supplier know the cost elements to a certain degree, and hence, the manufacturer does not allow the suppliers to set their component prices alone (Handfield, 2006). For instance, Toyota and Honda have accumulated extensive knowledge about their suppliers' detailed cost structures and manufacturing know-how (Liker & Choi, 2004; Sako, 2004). Based on such information, the two automotive manufacturers are able to precisely specify the component price upon which the suppliers can also agree while meeting the internal cost target (Kreps, 2019). To reflect these industry practices, we assume that the manufacturer-specified component margin m is given to the suppliers. That is, the manufacturer transfers the purchase price $c_i + m$ to supplier i.

In a supply chain where two suppliers are responsible for a critical component, a supplier can reduce its production cost by using complementary knowledge and experience obtained through collaborative interactions with the other supplier. However, supplier-supplier collaboration requires a fixed investment to build pathways for effective knowledge exchanges that surpass organizational boundaries (Dyer & Nobeoka, 2000; Gimeno, 2004). They may also incur disutility from inefficient communication or unintended knowledge leakage. Thus, supplier-supplier collaboration occurs only when all the participating suppliers agree to participate. We use the indicator $x \in \{0, 1\}$ to denote whether there is an agreement on collaboration: $x = 1$ indicates that both suppliers have reached an agreement, while $x = 0$ indicates that they have not reached an agreement. If the suppliers agree to participate in supplier-supplier collaboration (i.e., $x = 1$), both suppliers expect a collaboration benefit, which reduces their unit production costs by $\delta \in (0, c_1)$ while incurring the same F, which is

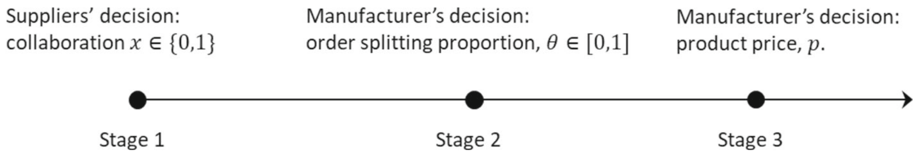

Fig. 1 Sequence of events: the ex-post order allocation policy announcement

the fixed investment related to collaboration.[1] This cost reduction will be the manufacturer's benefit in the form of reduced purchase cost; that is, $c_i + m - x\delta$, where $x \in \{0, 1\}$.

From the above settings, we can define the profits of the manufacturer and two suppliers as follows:

$$\Pi_M = \theta Q \cdot (p - (c_1 + m - x\delta)) + (1 - \theta)Q \cdot (p - (c_2 + m - x\delta)) \tag{1}$$

$$\Pi_1 = m \cdot \theta Q - xF; \Pi_2 = m \cdot (1 - \theta)Q - xF \tag{2}$$

With this model set-up, we carry out the analysis in Sect. 4.

4 Impact of order allocation timing on supplier-supplier collaboration

In this section, we first present the effects of the ex-post allocation policy announcement when the order-splitting proportion is set following the suppliers' decisions regarding collaboration (Sect. 4.1). We then investigate the order-allocation problem under the ex-ante policy announcement when the order-splitting proportion is committed before observing the suppliers' behavior (Sect. 4.2). In Sect. 4.3, we compare the outcomes generated under each case to see whether a particular commitment to order allocation induces collaboration between suppliers and enhances the value creation (profit improvement) of the three supply chain players.

4.1 The ex-post allocation policy announcement

In general, the manufacturer selects the supplier(s) and allocates an order to each supplier considering the information gathered from selected suppliers such as technical capability and transaction cost (Ravindran et al., 2010). Motivated by this reality, we consider the ex-post policy announcement where the manufacturer allocates orders after realizing the purchase costs in accordance with whether the collaborative interactions are formed between suppliers. This scenario can be regarded as a case of no proactive intervention from the manufacturer. The sequence of events proceeds as shown in Fig. 1.

Working backward, we derive the equilibrium decision of the manufacturer and the two suppliers. The manufacturer maximizes its profit in stage 3 by setting its market price p. The optimal price p is obtained as

$$p = \frac{1}{2}(a - x\delta + \theta(c_1 + m) + (1 - \theta)(c_2 + m)). \tag{3}$$

[1] This setting is assumed to focus on the production cost asymmetry between the suppliers. In the appendix, we relax this assumption and investigate the case involving asymmetry in the fixed investment (Appendix A) and in the cost reduction amount (Appendix B) to determine whether the key insights continue to hold.

By inserting p in Eq. (3) into Eq. (1), we can rewrite the manufacturer's profit $\Pi_M(\theta, x)$ as follows:

$$\Pi_M(\theta, x) = \frac{1}{4}(a + x\delta - \theta(c_1 + m) - (1 - \theta)(c_2 + m))^2. \quad (4)$$

The manufacturer chooses its optimal order-splitting proportion θ in stage 2. From Eq. (4), the manufacturer can directly choose the WTA allocation. In other words, because $c_1 < c_2$, the manufacturer can maximize its own profit by allocating all requirements to the low-cost supplier S1 by setting $\theta = 1$. Therefore, the manufacturer can fully benefit from the lowest purchase cost.

Each supplier checks whether supplier-supplier collaboration is profitable to him/her in stage 1. Since the suppliers know that the manufacturer would choose WTA allocation, the high-cost supplier S2 has no reason to agree to participate, which involves a fixed investment, and there would be no collaboration between the suppliers (i.e., $x = 0$). We summarize the decisions of the manufacturer and the suppliers in equilibrium as well as their corresponding profits in Proposition 1.

Proposition 1 *Under the ex-post policy announcement, the suppliers decide not to collaborate* ($x^* = 0$)*, and the manufacturer chooses WTA allocation* ($\theta^* = 1$) *in equilibrium. Thus, the manufacturer obtains the profit* $\Pi_M^* = \frac{1}{4}(a - m - c_1)^2$ *while the two suppliers earn profits* $\Pi_1^* = \frac{1}{2}m(a - m - c_1)$ *and* $\Pi_2^* = 0$*, respectively.*

Proposition 1 suggests that supplier-supplier collaboration cannot occur if the manufacturer announces its ordering policy after observing the suppliers' decisions regarding collaboration. The high-cost supplier knows that the manufacturer would choose WTA order allocation (procuring from S1 only) and hence has no incentive to incur the fixed investment. Thus, the low-cost supplier S1 would miss the possible opportunity of the potential synergy generated through collaboration. At the same time, the manufacturer cannot enjoy a reduced purchasing cost, which is an outcome of collaborating suppliers. This motivates us to address the following questions in Sect. 4.2: Is the manufacturer's commitment to a particular order allocation policy effective in inducing collaboration between suppliers? If so, would all supply chain members benefit from supplier-supplier collaboration?

4.2 The ex-ante allocation policy announcement

To examine how a commitment to an order allocation (i.e., the ex-ante policy announcement) influences the suppliers' behavior and hence the manufacturer's profit, we consider the sequence of events in Fig. 2. Note that the sequence differs from that considered in the previous section in terms of the timing of the allocation policy announcement. First, the order allocation policy indicates whether WTA or SA allocation will be applied. Simultaneously, if the SA type allocation is chosen, it indicates the proportion of orders that will be allocated

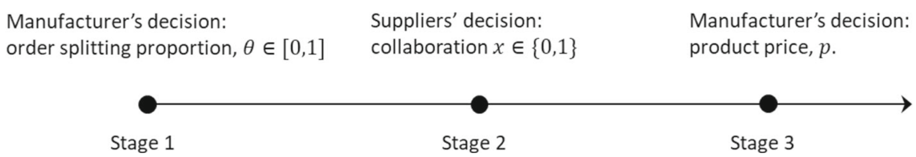

Fig. 2 Sequence of events: the ex-ante order allocation policy announcement

to each supplier. After observing this allocation policy announcement, the suppliers make their decisions about collaboration. A similar commitment-based order allocation policy is considered in the literature (e.g., Li & Wan, 2017; Li et al., 2013).

Given that the stage 3 analysis (setting market price p) is identical to the no commitment model, we begin our analysis by considering the two suppliers' collaboration decisions at stage 2. The decision on collaboration (i.e., $x = 1$ or 0) depends on whether the two suppliers find participation profitable at the expense of incurring a fixed investment F. In other words, $\Pi_i(\theta, 1) > \Pi_i(\theta, 0)$ needs to be ensured for a given θ in order to implement supplier-supplier collaboration. Thus, we obtain

$$\Pi_1(\theta, 1) - \Pi_1(\theta, 0) = \frac{1}{2}\delta\theta m - F \tag{5}$$

$$\Pi_2(\theta, 1) - \Pi_2(\theta, 0) = \frac{1}{2}\delta(1-\theta)m - F \tag{6}$$

Equations (5) and (6) clearly show that the suppliers' incentives depend on the order-splitting proportion θ proposed by the manufacturer. Supplier S1 has an incentive to participate in collaboration if the order-splitting proportion θ is higher than the threshold $\underline{\theta}$, which can be defined as $\underline{\theta} := \frac{2F}{\delta m}$ from Eq. (5). Conversely, in Eq. (6), S2 can be incentivized to collaborate with S1 if the order-splitting proportion is not highly biased in favor of S1—θ, lower than the threshold:

$$\overline{\theta} := 1 - \frac{2F}{\delta m} \tag{7}$$

In sum, supplier-supplier collaboration is viable only if the order-splitting proportion falls within the range of $\theta \in \left[\underline{\theta}, \overline{\theta}\right]$. Otherwise, collaboration between suppliers cannot occur. One can easily verify that condition $\overline{\theta} > \underline{\theta}$ holds only if the fixed investment for supplier-supplier collaboration F is sufficiently lower than

$$F_S := m\delta/4 \tag{8}$$

In other words, supplier-supplier collaboration can be induced if the fixed investment is affordable and each supplier is guaranteed to obtain a certain allocation. Lemma 1 summarizes this result.

Lemma 1 *If $F > F_S$, then the two suppliers do not agree on supplier-supplier collaboration for any given order-splitting proportion θ. Thus, each player earns the same profit presented in Proposition 1. However, when $F < F_S$, supplier-supplier collaboration occurs when θ is within the range $[\underline{\theta}, \overline{\theta}]$, where $\underline{\theta} = \frac{2F}{\delta m}$ and $\overline{\theta} = 1 - \frac{2F}{\delta m}$.*

The manufacturer determines the order-splitting proportion $\theta \in [0, 1]$ in stage 1 in order to maximize its profit. We first consider the case where $F > F_S$. Here, since collaboration cannot be implemented for any $\theta \in [0, 1]$, choosing WTA allocation (i.e., setting $\theta = 1$) is the optimal decision for the manufacturer, as in the previous section. Note that reducing θ to below 1 merely increases the procurement cost without collaboration, and the manufacturer has no reason to do so.

We next consider the case where the fixed investment for engaging in collaborative activities is sufficiently low; that is, $F < F_S$. As for the possible choice of $\theta \in [\underline{\theta}, \overline{\theta}]$, $\theta = \overline{\theta}$ is optimal for the manufacturer. Clearly, once supplier-supplier collaboration is induced, the manufacturer prefers to allocate a volume as high as possible to S1 in order to reduce its procurement cost, as can be observed from Eq. (4). The manufacturer's profit Π_M at $\theta = \overline{\theta}$ will then become

$$\Pi_M(\overline{\theta}) = \frac{(m\delta(a-(m+c_1-\delta)) - 2F(c_2-c_1))^2}{4m^2\delta^2}. \quad (9)$$

In line with the ex-post policy announcement case, if the manufacturer does not intend to induce supplier-supplier collaboration, then its optimal decision would be to allocate the whole volume to S1 by setting $\theta = 1$ to earn profits, as shown in Eq. 10:

$$\Pi_M(1) = \frac{(a-(c_1+m))^2}{4} \quad (10)$$

In sum, given the possible choice of $\theta \in [0, 1]$, the candidates for the optimal decision are narrowed down to $\theta = 1$, corresponding to WTA allocation, and $\theta = \overline{\theta}$, corresponding to SA allocation. We cannot determine directly which of the two allocation types gives the best outcome to the manufacturer. With supplier-supplier collaboration under SA allocation ($\theta = \overline{\theta}$), the manufacturer would enjoy a reduction in the unit purchase cost but has to purchase a certain portion from the high-cost supplier S2. However, with no collaboration between the suppliers under WTA allocation ($\theta = 1$), there would be no cost reduction, and the manufacturer can purchase the whole volume from the low-cost supplier S1.

Under the restriction $F < F_S$, a comparison between Eqs. (9) and (10) shows that one cannot always dominate the other. Supplier-supplier collaboration under SA allocation yields a higher profit than no supplier-supplier collaboration under WTA allocation if and only if the fixed investment is sufficiently lower than

$$F_M := \frac{m\delta^2}{2(c_2-c_1)} \quad (11)$$

The above threshold reflects the manufacturer's perspective. That is, we obtain F_M in Eq. (11) by comparing $\Pi_M(\overline{\theta})$ and $\Pi_M(1)$ in a similar manner as we derive F_S in Eq. (8). The value of $\overline{\theta}$ specified in Lemma 1 decreases as F increases, implying that a higher level of fixed investment F would result in S2 claiming a sufficient portion of allocation to compensate for the heavy burden of supplier-supplier collaboration. In other words, the manufacturer has no choice but to endure an increase in the average unit purchase cost to induce collaboration between suppliers. Accordingly, the manufacturer encourages supplier-supplier collaboration under SA allocation only if the fixed investment is sufficiently low (i.e., $F < F_M$).

In sum, we obtain Proposition 2, which characterizes each player's equilibrium decision with the corresponding profit.

Proposition 2 *Under the ex-ante policy announcement, each player's decision and the corresponding* profit at the equilibrium are determined as follows:

(i) If $F > min[F_S, F_M]$, the manufacturer chooses the order-splitting proportion $\theta^* = 1$(WTA allocation) and thus does not induce supplier-supplier collaboration. Accordingly, the profits of the manufacturer and the two suppliers are obtained as $\Pi_M^* = \frac{1}{4}(a-m-c_1)^2$, $\Pi_1^* = \frac{1}{2}m(a-m-c_1)$, and $\Pi_2^* = 0$.

(ii) If $F < min[F_S, F_M]$, the manufacturer chooses the order-splitting proportion $\theta^* = 1 - \frac{2F}{m\delta}$ (SA allocation) and thus induces supplier-supplier collaboration. Accordingly, the profits of the manufacturer and the two suppliers are obtained as $\Pi_M^* = \frac{(m\delta(a-m+\delta)+(2F-m\delta)c_1-2Fc_2)^2}{4m^2\delta^2}$, $\Pi_1^* = \frac{(2F-m\delta)(2F(c_2-c_1)-m\delta(a-m-c_1+\delta))}{2m\delta^2} - F$, and $\Pi_2^* = \frac{F(m\delta(a-m+\delta)+(2F-m\delta)c_1-2Fc_2)}{m\delta^2} - F$.

Proposition 2 shows that, if the fixed investment F is significantly high, the ex-ante policy announcement yields the same outcome as the ex-post policy announcement. Otherwise, when the fixed investment is sufficiently low, the manufacturer will be able to persuade the suppliers to help each other by choosing SA allocation, which splits the procurement volume between the two suppliers. We remark that the key insights in Proposition 2 carry over if we introduce asymmetric unit cost reduction between the suppliers to the model (i.e., $\omega\delta$ ($0 < \omega < 1$) for S1 and δ for S2). Furthermore, we observe that the supplier-supplier collaboration region shrinks as S2 enjoys a greater benefit compared to S1 (i.e., ω decreases). See Appendix C for the detailed analysis of this extension.

Next, we focus on the two thresholds, F_S and F_M. To elicit meaningful outcomes and sustain the collaborative relationship, supplier-supplier collaboration requires both tangible and intangible infrastructure to facilitate effective communication while controlling unintended knowledge leakage. These thresholds can be interpreted as the maximum acceptable levels of fixed investment that determines the incentive for supplier-supplier collaboration from the perspective of each party in the supply chain: the two suppliers (F_S) and the manufacturer (F_M). From Eqs. (8) and (11), we can realize the relationships between the threshold levels and the three factors of (i) the collaboration benefit (δ), (ii) the unit margin (m), and (iii) the capability gap between suppliers ($c_2 - c_1$). We report these relationships in Proposition 3.

Proposition 3 *We define $\overline{F}$ as the maximum acceptable level of fixed investment for supplier-supplier collaboration, i.e., $\overline{F} := min\{F_M, F_S\}$. While $\overline{F}$ is increasing in the scales of supplier-supplier-collaboration benefit and unit margin for a component, it is a non-decreasing function of the capability gap between suppliers.*

Given both parties' perspectives, $\overline{F}$ measures how easily the manufacturer can facilitate the supplier-supplier collaboration. In other words, the larger value of $\overline{F}$ implies that suppliers are more likely to agree on collaboration even at a higher fixed investment level, and thus, the manufacturer can induce supplier-supplier collaboration. As summarized in Table 1, the facilitation of supplier-supplier collaboration becomes easier when at least one of the following conditions are met: (i) the collaboration benefit is substantial, (ii) the suppliers secure a generous level of unit margin, and (iii) the suppliers have a similar level of capabilities.

Figure 3 shows the joint impact of each factor and the fixed investment at a glance. Unlike the increment in collaboration benefit (Fig. 3a) and unit margin (Fig. 3b) that improve both parties' motivation, the capability gap (Fig. 3c) has no impact on the suppliers' motivation. Yet, the manufacturer would have a weaker motivation to embrace both suppliers if

Table 1 Impact of three factors on the motivation for collaboration and on the difficulty of collaboration facilitation

	Increment of	Collaboration benefit (δ)	Unit margin (m)	Capability gap ($c_2 - c_1$)
Impact on	Suppliers' motivation (F_S)	↑	↑	–
	Manufacturer's motivation (F_M)	↑	↑	↓
	The difficulty of collaboration facilitation ($\overline{F}$)	↓	↓	Non-increasing

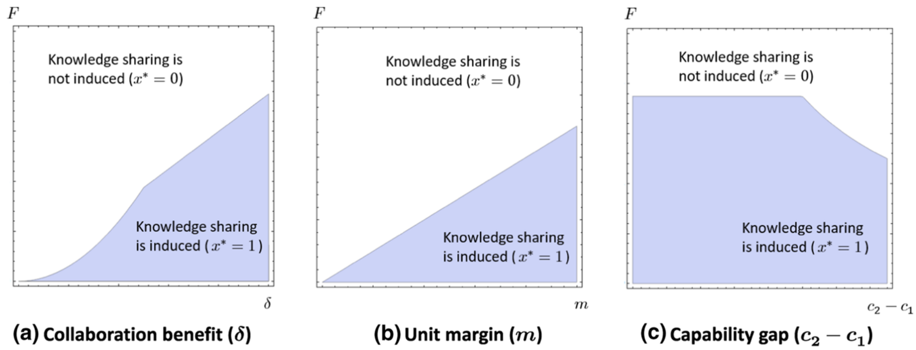

Fig. 3 Area of supplier-supplier collaboration under the ex-ante policy announcement

the suppliers' capability levels are substantially different. Thus, the difficulty of collaboration facilitation possibly varies with the capability gap by weakening the manufacturer's motivation.

4.3 Value of the ex-ante allocation policy announcement

In the previous section, we found that the ex-ante order allocation policy enables the manufacturer to induce collaboration between suppliers unless the associated fixed cost is substantial. However, this does not necessarily mean that all the supply chain members, including the manufacturer, will always profit through ex-ante allocation policy implementation and the subsequent supplier-supplier collaboration. Thus, while noting the significance of aligning the supply chain members' interests for sustaining the co-prosperity of the entire supply chain (Kam & Lai, 2018), this section evaluates the value of the ex-ante order allocation announcement to determine whether it profits both the supplier and the manufacturer.

To find the impact of both the ex-ante and ex-post order allocation policy announcements on the profit generation of all supply chain players, we compare Π_i^{EA} and Π_i^{EP}, which are the profits that each player $i \in \{M, 1(S1), 2(S2)\}$ earns under the different timings of the order allocation policy announcement. Note that Π_i^{EA} and Π_i^{EP} are the same as Π_i^* presented in Propositions 1 and 2, while superscripts EA and EP denote the ex-ante and ex-post policy announcements, respectively. Player i's profit gap Δ_i is written as

$$\Delta_M := \Pi_M^{EA} - \Pi_M^{EP}; \Delta_1 := \Pi_1^{EA} - \Pi_1^{EP}; \Delta_2 := \Pi_2^{EA} - \Pi_2^{EP}.$$

The above comparison leads to Proposition 3, which is illustrated in Fig. 4.

Proposition 4 *The profit changes of each supply chain member from the ex-post order allocation policy announcement and ex-ante announcement are obtained as follows.*

(i) *If $F > \overline{F}$, regardless of the policy types, all the supply chain members' profits remain the same: i.e., $\Delta_M = \Delta_1 = \Delta_2 = 0$.*
(ii) *If $F < \overline{F}$, compared to the ex-post policy announcement, the ex-ante policy announcement guarantees a higher profit both for the manufacturer and the high-cost supplier S2: i.e., $\Delta_M > 0$ and $\Delta_2 > 0$. However, the low-cost supplier S1's profit improves, i.e., $\Delta_1 > 0$, only when $a > \widehat{a}$and $F < \widehat{F}$. The thresholds are $\widehat{a} := m - 2\delta + 2c_1 -$*

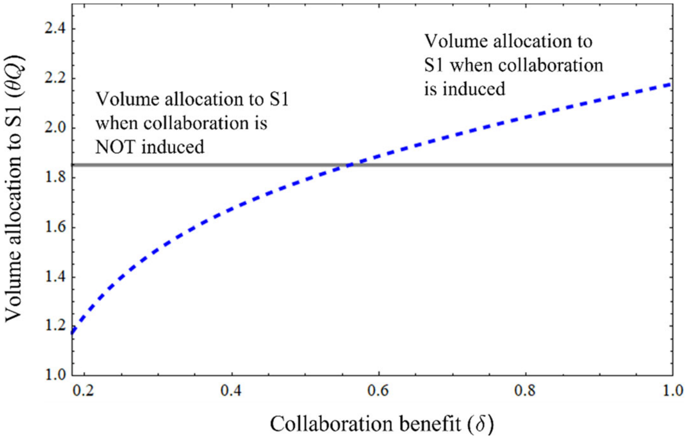

Fig. 4 Collaboration benefit and volume allocation to the low-cost supplier (S1)

$c_2 + 2\sqrt{\delta(c_2 - c_1)}$ *and* $\widehat{F} := m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2 - c_1)}$, *while both satisfy the following:* $\widehat{a} > 0$ *and* $0 < \widehat{F} < \min[F_S, F_M]$.

If the fixed investment is substantial, it is unable to induce the collaboration between suppliers regardless of the timing of the policy announcement. Nobody in the supply chain can enjoy the benefit of supplier-supplier collaboration, and thus variation in the allocation policy announcement timing will lead to the same results ($\Delta_M = \Delta_1 = \Delta_2 = 0$), as presented in Proposition 4. However, if the fixed investment level is affordable, such that $F < \overline{F}$, the ex-ante allocation policy announcement will make a difference, because it induces supplier-supplier collaboration whereas the ex-post policy announcement does not. Since the manufacturer allocates a certain part of the orders to the high-cost supplier S2 to elicit her participation in collaboration, S2 (who earns zero profit under the ex-post policy announcement) will make a higher profit. That is, $\Delta_M > 0$ and $\Delta_2 > 0$.

However, the ex-ante policy impact on the low-cost supplier S1 is not straightforward. If the market size is fairly small, such that $a < \widehat{a}$, supplier-supplier collaboration cannot lead to a significant sales increment; thus, the demerits such as the fixed investment associated with the collaboration becomes more conspicuous for the low-cost supplier S1. However, in the case of a sufficiently large market ($a > \widehat{a}$, it may turn out to be worth bearing additional expenses and participating in the supplier-supplier collaboration. Unlike the ex-post policy, under which the low-cost supplier S1 takes all the orders from the manufacturer, the ex-ante policy splits the orders between the two suppliers to facilitate their collaboration. From the low-cost supplier S1's perspective, the ex-ante policy enabling collaboration may deteriorate its profit generation in that it leads to a smaller order proportion and imposes a certain level of relational burdens. On the other hand, cost reduction through collaboration positively impacts the demand for the product, which ultimately raises the total order quantity. Thus, S1's sales can vary depending on the level of collaboration benefit, as shown in Fig. 4.

For a given size of orders, it depends on the levels of collaboration benefit and the fixed investment for collaboration whether S1 can be better off under the ex-ante policy. Accordingly, different from the manufacturer and S2, the low-cost supplier S1 can improve her profit only when the fixed investment is further low and/or the outcome of the supplier-supplier collaboration is more impactful. In sum, as Fig. 5 depicts, the supplier-supplier collaboration region under the ex-ante policy announcement is divided into two regions: (i) the misaligned

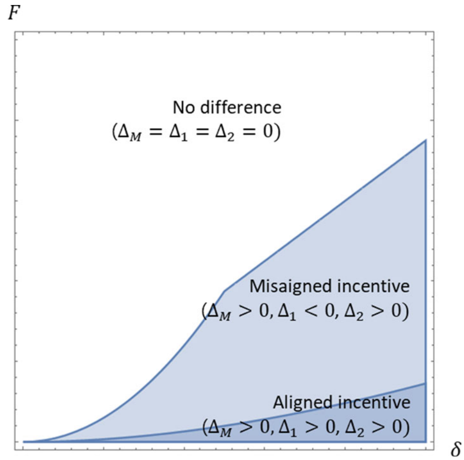

Fig. 5 Profit comparison: impact of allocation policy announcement timing on each player

incentive region and (ii) the aligned incentive region. Interestingly, the aligned incentive region implies that merely changing the policy announcement timing would give all the supply chain players a higher profit under certain conditions. In other words, the ex-ante announcement can create a win–win situation for all.

5 Manufacturer's subsidy for supplier-supplier collaboration

Besides the order allocation policy, large manufacturers often employ an additional tool to facilitate collaboration between suppliers. A commonly adopted practice is to subsidize the suppliers to motivate their participation. By using both financial and nonfinancial means, Toyota and Honda subsidize their suppliers' collaborative interactions to stimulate the collective capability improvement of the suppliers (Dyer & Nobeoka, 2000; Sako, 2004). Besides the Japanese automakers' examples, a subsidy is a widely adopted means to initiate certain non-spontaneous behaviors. For example, to increase consumer buy-in for eco-friendly vehicles, the US government provides tax credits for the purchase of qualified electric vehicles. Many other countries (e.g., Germany, South Korea, the UK, Austria, and China) have instituted similar subsidy programs to increase the purchase of electric vehicles due to growing attention to environmental value (McKerracher, 2022). Furthermore, in consignment vendor-managed inventory (VMI) operations, a retailer's subsidy, given to the supplier for the supplier's excess production, plays an important role in mitigating supply uncertainties by enticing the supplier's capacity decision that favors both parties (He & Zhao, 2016). Likewise, in our context, subsidies are offered to ensure that the suppliers realize the benefits of participation by alleviating the hurdles of supplier-supplier collaboration. However, one cannot guarantee that subsidies enhance the manufacturer's profit, even though it might result in collaboration between suppliers. Paying a subsidy to suppliers is meaningful for the manufacturer only if the total subsidies given to the suppliers result in a greater benefit for the manufacturer (e.g., a sufficient reduction in the purchase cost due to collaboration between the suppliers). Thus, this section explores the effectiveness of subsidies by extending the previous order allocation model under the ex-ante policy announcement.

We extend our main model in Sect. 4 to consider a situation where the manufacturer financially supports supplier-supplier collaboration, as in the case of Toyota. The manufacturer pays a one-time subsidy to both suppliers on the condition that they collaborate with each other. Then, the profit functions of the manufacturer and suppliers would be:

$$\Pi_M = \theta Q(p - ((c_1 + m) - x\delta)) + (1 - \theta)Q(p - ((c_2 + m) - x\delta)) - 2xf$$

$$\Pi_1 = m\theta Q - x(F - f); \Pi_2 = m(1 - \theta)Q - x(F - f)$$

First, the manufacturer determines the order-splitting proportion and the subsidy level. Next, the suppliers decide on supplier-supplier collaboration. Finally, the manufacturer sets its product price. For our analysis, we impose the technical assumption $a > 2m+c_1$, assuming that the market size is sufficiently large. This assumption allows us to obtain a closed form solution and carry out the analysis.

We begin our analysis at the third stage of the game. This stage relates to the manufacturer's pricing decision, as shown in Sect. 4.2. At the second stage, we check whether the two suppliers agree on supplier-supplier collaboration. Recall that, in Sect. 4.2, they agree on participation (i.e., x=1) only when it benefits both of them: that is, when $\Pi_i(1) > \Pi_i(0)$ for $i \in \{1, 2\}$. The difference from the ex-ante policy announcement model in Sect. 4.2 is that each supplier reduces her investment in collaboration upon receiving the subsidy f. That is, the comparison yields

$$\Pi_1(1) - \Pi_1(0) = \frac{1}{2}m\delta\theta - (F - f);$$

$$\Pi_2(1) - \Pi_2(1) = \frac{1}{2}m\delta(1 - \theta) - (F - f)$$

By jointly solving $\Pi_1(1) - \Pi_1(0) \geq 0$ and $\Pi_2(1) - \Pi_2(0) \geq 0$ with respect to θ and f, we characterize the conditions under which supplier-supplier collaboration is induced in the following lemma.

Lemma 2 *Given the manufacturer's subsidy f and order-splitting proportion θ, the suppliers' collaboration decisions are represented as:*

$$x^*(\theta, f) = \begin{cases} 1, \ \theta \in \left[\frac{2(F-f)}{\delta m}, 1 - \frac{2(F-f)}{\delta m}\right] \text{and } f \geq \max\{F - F_S, 0\} \\ 0, \ \text{otherwise.} \end{cases}$$

Lemma 2 shows that the manufacturer's subsidy can significantly impact the suppliers' decisions regarding whether or not to participate in collaboration. From condition $f \geq \max\{F - F_S, 0\}$ in Lemma 3, we consider two cases relevant to the fixed investment F for supplier-supplier collaboration. First, we consider the case of $F > F_S$. Without a subsidy, this condition yields the same solution we derived in the order-allocation problem under the ex-ante policy announcement. That is, supplier-supplier collaboration does not occur, as already shown in Lemma 1. The manufacturer intending to induce collaboration between suppliers in this case will have to offer a subsidy f of at least $F - F_S$. Otherwise, no supplier-supplier collaboration would occur in any order-splitting proportion, θ. Next, we consider the case of $F < F_S$. The manufacturer can induce supplier-supplier collaboration for any $f \geq 0$ by setting the order-splitting proportion at $\theta \in \left[\frac{2(F-f)}{\delta m}, 1 - \frac{2(F-f)}{\delta m}\right]$. Note that the range of the order-splitting proportion is larger compared to the condition of no subsidy in Lemma 1, that is, $\theta \in \left[\frac{2F}{\delta m}, 1 - \frac{2F}{\delta m}\right]$. This means that the subsidy option gives the manufacturer more flexibility to determine how to split the order volume. In sum, the subsidy makes it easier for the manufacturer to induce supplier-supplier collaboration.

The manufacturer needs to determine f and θ at the first stage to optimize its profit $\Pi_M(\theta, f, x)$. By applying x as a function of θ and f in Lemma 3, the manufacturer's profit becomes

$$\Pi_M(\theta, f) = \begin{cases} \frac{(a-m)(a-m-2(\theta c_1+(1-\theta)c_2)-\delta)+(\theta c_1+(1-\theta)c_2)^2}{4} - 2f, & if\ x = 1 \\ \frac{(a-\theta(c_1+m)-(1-\theta)(c_2+m))^2}{4}, & if\ x = 0. \end{cases}$$

Clearly, the manufacturer's profit depends on the suppliers' collaboration decisions $x \in \{0, 1\}$. However, with x as a function of θ and f in Lemma 3, the manufacturer can impact the suppliers' decisions regarding collaboration by adjusting θ and f. To derive the manufacturer's optimal decision, we have to compare two cases: (i) the optimal choice from among the possible sets of (θ, f), which induces no supplier-supplier collaboration ($x = 0$), and (ii) the optimal choice from among the possible sets of (θ, f), which induces supplier-supplier collaboration ($x = 1$). We summarize the equilibrium decision and the corresponding profit of the manufacturer in Proposition 5.

Proposition 5 *When the manufacturer devises the allocation policy and subsidy, its optimal decision is characterized as follows.*

(i) *Case* $m < \max\left\{\frac{c_2-c_1}{2}, \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}\right\}$ *: The manufacturer chooses* $(\theta^*, f^*) = (1, 0)$ *if* $F > max\{F_1, F_2\}$. *Otherwise, the manufacturer's optimal decision is given as* $(\theta^*, f^*) = (1, F)$.

(ii) *Case* $m > max\left\{\frac{c_2-c_1}{2}, \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}\right\}$ *: For* $F > \max\{F_1, F_2\}$, *the manufacturer's optimal decision is obtained as* $(\theta^*, f^*) = (1, 0)$. *For* $\delta m/4 < F < \max\{F_1, F_2\}$, $(\theta^*, f^*) = (1, F)$ *if* $\delta < \min\{\delta_1, c_1\}$. *Otherwise,* $(\theta^*, f^*) = (0.5, F - F_S)$. *For* $F < m\delta/4$, $(\theta^*, f^*) = (1, F)$ *if* $\delta < min\{\delta_2, c_1\}$. *Otherwise,* $(\theta^*, f^*) = \left(1 - \frac{2F}{m\delta}, 0\right)$. *The thresholds are defined as:* $F_1 := \frac{\delta(2a-2m+\delta-2c_1)}{8}$, $F_2 := \frac{4\delta(2a+\delta)-3c_1^2-4(a-m+\delta)c_2+c_2^2+2c_1(2a-2m-2\delta+c_2)}{32}$, $\delta_1 := \frac{(4a-4m-3c_1-c_2)(c_2-c_1)}{4(2m+c_1-c_2)}$, *and* $\delta_2 := \frac{2\left(a+\sqrt{a^2+8F+(m-2a)c_1+c_1^2-mc_2}\right)-c_1-c_2}{2}$.

We illustrate Proposition 5 in Fig. 6 to display the full picture of the equilibrium decision on subsidy f^*. The manufacturer's subsidy decision is affected by three factors: (i) the fixed investment for supplier-supplier collaboration F, (ii) the benefit of collaboration δ (the cost reduction amount), and (iii) the suppliers' unit margin m. In a broad sense, the manufacturer's decision can be classified into two cases: (i) the case with the suppliers' low margin (Proposition 5(i) and Fig. 6a), and (ii) the case with the suppliers' high margin (Proposition 5(ii) and Fig. 6b). In the ex-ante policy announcement model with no subsidy option in Sect. 4.2, we observe that a higher unit margin results in a higher level of maximum affordable fixed investment, making it easier to establish the collaborative supply network (see Lemma 2). Likewise, when the suppliers' unit margin is low, the suppliers' fixed investment needs to be fully subsidized to induce supplier-supplier collaboration (i.e., $f^* = F$), as shown in Proposition 5(i). However, if the suppliers' margin level is high, it would be better to reduce the optimal subsidy level, as presented in Proposition 5(ii). Accordingly, the no subsidy ($f^* = 0$) or partial subsidy ($f^* = F - F_S$) option appears beneficial, depending on the unit margin and fixed investment level conditions.

Also, the manufacturer offers a smaller subsidy as the benefit of collaboration increases for a given fixed investment F. For example, see the fixed investment level F at 0.3 in Fig. 6b. If δ, the benefit of supplier-supplier collaboration, is sufficiently small, the manufacturer needs to fully subsidize the suppliers, that is, $f^* = F$, to induce the suppliers' participation. However, at the same F, the manufacturer can reduce the subsidy level to $f^* = F - \frac{m\delta}{4}$ with

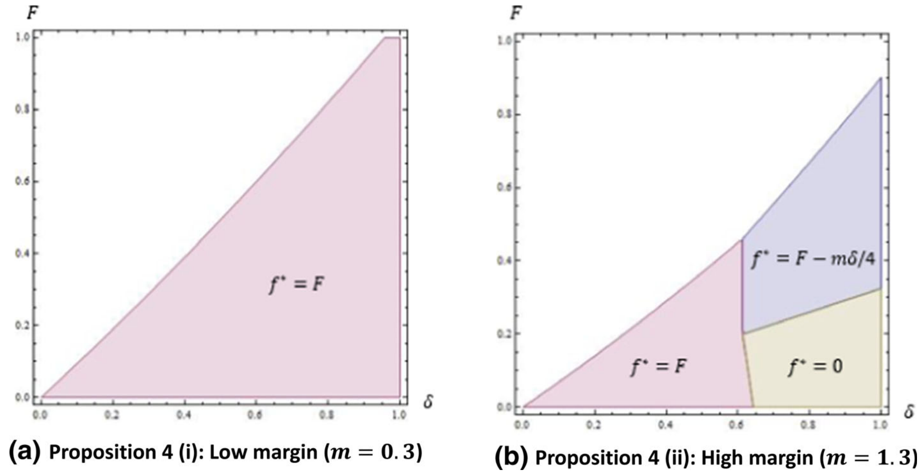

Fig. 6 Area of supplier-supplier collaboration and the manufacturer's optimal subsidy[2]

[2]The parameter values used are $a = 5$, $c_1 = 1$, $c_2 = 1.5$, and $m = 0.3$.

a higher δ. If δ increases further, the manufacturer has no incentive to set off the additional lever and sets $f^* = 0$. Suppliers expecting a high level of benefit (δ) are likely to engage in supplier-supplier collaboration even without the manufacturer's financial support.

Overall, our results suggest that the subsidy can be combined with the ex-ante policy announcement to provide an effective tool for the manufacturer to improve her profit further, as exemplified by Toyota and Honda. However, at the same time, the manufacturer does not always need to provide a subsidy, such as when the suppliers are well-motivated to participate in collaboration owing to the low fixed investment, sufficient collaboration benefit, and generous unit margin (see the lower right-hand side of $f^* = 0$ in Fig. 6b with low F and high δ). Thus, the manufacturer needs to pay close attention to the conditions under which a subsidy is worth considering.[3]

[3] One may doubt whether the full-subsidy outcome $(\theta^*, f^*) = (1, F)$ (subsidizing all the cost associated with collaboration without allocating any volume to the high-cost supplier) is practically realistic. Our model is set to cover all the possibilities, including that a supplier may participate in collaboration as a pure knowledge provider. However, given that the fixed investment measures all the associated burdens that supplier-supplier collaboration can bring, from the infrastructure building to unintended knowledge leakage, it may be more realistic to constrain the range of subsidy offerings by imposing its upper bound. Specifically, the manufacturer is unable to cover all but can relieve them to a certain degree, i.e., $f \in [0, F - \epsilon]$ where $\epsilon > 0$. Under the new constraint on the subsidy, among the three candidates for optimal decision (θ^*, f^*) characterized in Proposition 5, the full-subsidy one $(1, F)$ is modified as $\left(1 - \frac{2\epsilon}{m\delta}, F - \epsilon\right)$, and it becomes an optimal decision contingent upon factors such as fixed cost and collaboration benefit. In other words, the previous full-subsidy outcomes may not arise with an upper bound of subsidy. Furthermore, it is easily expected that the modified full-subsidizing area with the decision $\left(1 - \frac{2\epsilon}{m\delta}, F - \epsilon\right)$ shrinks and the other two (partial- and no subsidy) enlarge, while the key insight of the model holds. That is, an inappropriately chosen subsidy is a waste of limited resources.

6 Conclusion

The manufacturing industry has witnessed rapid technological advancement. Given that it has become increasingly difficult for a firm to respond quickly and effectively to the demands of this competitive environment, large manufacturers are seeking ways to develop and utilize their suppliers' inherent competitiveness. In this regard, we study the manufacturer's problem to induce collaboration between two suppliers under competition. We consider two different timings of the order allocation policy announcement, which are termed "the ex-ante announcement" and "the ex-post announcement" depending on whether the order-splitting proportion is agreed upon before or after the decision on supplier-supplier collaboration that leads to the realization of the purchase cost. We compare the two timings of the announcement to see if one of them can effectively control the mechanism inducing supplier-supplier collaboration while improving the profits of all players in a supply chain. We also consider the manufacturer's subsidy offered to suppliers to expedite supplier-supplier collaboration, and we characterize the optimal subsidy level with the appropriate conditions.

The findings of this study provide practical insights into how the manufacturer can motivate two suppliers to collaborate with each other, given that the outcome of the collaboration (e.g., production cost reduction) benefits all the entities in a supply chain. Since suppliers have no direct benefit of engaging in collaboration with other suppliers under competition, the manufacturer's intervention becomes necessary. From our findings, merely changing the timing of the order allocation policy announcement (i.e., from ex-post to ex-ante) leads to higher profits for the manufacturer as well as for both suppliers by signaling to the suppliers that neither of them will be excluded from the allocation. In addition, the manufacturer's subsidy offer can lighten the suppliers' capital burden and act as a catalyst for supplier-supplier collaboration. However, the manufacturer's subsidy offer considerations should be balanced between the benefits and expenses of collaboration. If the subsidy level is inappropriate, it would be nothing but a waste of resources. Specifically, the manufacturer would not have to subsidize the suppliers when the suppliers can enjoy a generous unit margin, a sufficient level of collaboration benefit, and a relatively small fixed investment. In this case, the ex-ante policy announcement would be sufficient. Accordingly, practicing managers are encouraged to examine the outcomes in this study carefully before trying to induce knowledge sharing between suppliers.

This study contributes to the literature on horizontal collaboration in a supply chain by underscoring the value of the ex-ante order allocation policy announcement. While most studies focus on fostering supplier competition as a means to lighten the purchasing cost burden (e.g., Li & Wan, 2017), this study proposes that the manufacturer's performance can be improved by managing the collaborative interaction between suppliers. Methodologically, this study utilizes game-theoretic reasoning and strives to deliver implications through an analysis of the phenomenon. To the best of our knowledge, our approach is novel in that most studies on supplier-supplier collaboration are limited to reporting current practices and performing case analysis (Raweewan et al., 2018). We believe that the results of this study can be a practical guide for managers seeking new opportunities to enhance the overall performance of a supply chain, especially by facilitating the knowledge sharing of suppliers.

Notwithstanding the novel findings and implications of this study, it bears several limitations. First, we realize the benefit of supplier-supplier collaboration through reduction in the suppliers' production costs. Cost reduction is a major reason for adopting knowledge sharing, but there are various other types of benefits as well, such as component quality enhancement. Since the quality improvement of a product improves consumer valuation directly, an investigation from the perspective of quality would be a worthy future research direction.

Appendix A Asymmetric fixed investment costs

In practice, suppliers presumably incur different levels of hassles and expenses to take advantage of collaborative improvement. Thus motivated, we consider that S1 and S2 incur asymmetric fixed investments F_1 and F_2, respectively, and investigate how this relaxed assumption affects the results presented in Propositions 1 and 2.

As S1 and S2 incur the fixed investment F_1 and F_2, their profit function can be revised as. and their profit function can be written as

$$\Pi_1 = m\theta Q - xF_1; \Pi_2 = m(1-\theta)Q - xF_2 \tag{A1}$$

With this change in the model setup, the equilibrium outcomes under the ex-ante and the ex-post announcement are characterized as obtained in Proposition A1.

Proposition A1 *Suppose that the fixed cost of knowledge sharing for S1 and S2 are given as F_1 and F_2, respectively. The equilibrium outcomes under the policies are obtained in Table A1.*

The results summarized in Table A1 first shows that the result of Proposition 1 remains robust. The ex-post policy announcement still cannot induce collaboration, even if each supplier's fixed investment is set to be different, because the relaxed assumption on the fixed investment does not affect the manufacturer's incentive in its order allocation. Under the ex-post announcement, the implementation of knowledge sharing precedes the order allocation, and thus the manufacturer would always find it optimal to grant all volumes to the low-cost supplier S1 after enjoying the fruit of collaboration. Knowing this, the high-cost supplier S2 opts not to participate in collaboration.

The results also confirm that the asymmetric fixed investment does not qualitatively alter the outcome of the ex-ante announcement (Proposition 2). The ex-ante policy announcement can induce collaboration if the fixed investment is sufficiently low. The difference with the same fixed investment model ($F_1 = F_2 = F$) comes from a change in the condition for collaboration. Different from the previous condition $F < \min[F_S, F_M]$ in Proposition 2, the current condition $F_2 < \min\left[F_M, \frac{m\delta}{2} - F_1\right]$ puts more emphasis on the high-cost

Table A1 Equilibrium outcomes under asymmetric fixed investment costs

Fixed Investment	Ex-Ante Announcement		Ex-Post Announcement
	$F_2 < \min\left\{F_M, \frac{m\delta}{2} - F_1\right\}$	$F_2 > \min\left\{F_M, \frac{m\delta}{2} - F_1\right\}$	For all F_2
x^*	1	0	0
θ^*	$1 - \frac{2F_2}{m\delta}$	1	1
Π_M^*	$\frac{(m\delta(a-m+\delta-c_1)-2F_2(c_2-c_1))^2}{4m^2\delta^2}$	$\frac{1}{4}(a-m-c_1)^2$	$\frac{1}{4}(a-m-c_1)^2$
Π_1^*	$\frac{(2F_2-m\delta)(2F_2(c_2-c_1)-m\delta(a-m+\delta-c_1))}{2m\delta^2} - F_1$	$\frac{1}{2}m(a-m-c_1)$	$\frac{1}{2}m(a-m-c_1)$
Π_2^*	$\frac{F_2((a-m-c_1)m\delta-2F_2(c_2-c_1))}{m\delta^2}$	0	0

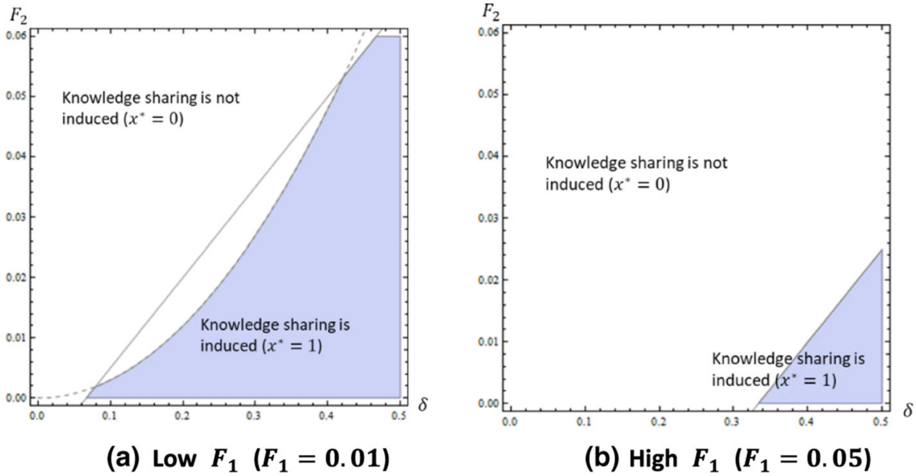

Fig. A1 Asymmetric fixed investment and knowledge sharing

supplier S2's incentive. From the manufacturer's perspective, a key to enjoying the desired benefit is to make the high-cost supplier S2 participate in collaboration while keeping the average unit purchase cost low. That is, to induce collaboration, the manufacturer should allocate reasonably sufficient volume to S2 (i.e., setting $1-\theta$ sufficiently high) to compensate for her fixed investment (i.e., make $\Pi_2 = m \cdot (1-\theta)Q - F_2 \geq 0$). Accordingly, the threshold that characterizes the manufacturer's decision on whether to facilitate collaboration for waste reduction, $F_2 = \min\left[\frac{m\delta}{2} - F_1, \frac{m\delta^2}{2(c_2-c_1)}\right]$, is written as the high-cost supplier's fixed investment F_2. Figure A1 illustrates the results.

Lastly, comparing the ex-ante and the ex-post announcements' outcomes, we see that the former becomes more favorable for the manufacturer's profit generation only when the associated fixed investment is sufficiently lowered. As discussed, the asymmetric fixed investment makes no difference to the manufacturer's payoff structure, while the timing of the policy announcement determines whether the suppliers can reach a consensus on collaboration. Hence, we again confirm that the manufacturer has an incentive to announce its order allocation policy before purchase cost realization (the outcome of collaboration) given the conditions incentivizing the suppliers' collaborative waste and cost reduction based on collaboration.

Appendix B Proofs

Proof of Proposition 3

We define $\overline{F} := \min\left\{\frac{m\delta^2}{2(c_2-c_1)}, \frac{m\delta}{4}\right\}$. Since $\frac{m\delta^2}{2(c_2-c_1)}$ and $\frac{m\delta}{4}$ are increasing in m and δ, $\overline{F}$ is increasing in $\overline{F}$. Also, as $\frac{m\delta^2}{2(c_2-c_1)}$ is decreasing in $c_2 - c_1$, $\overline{F}$ is non-increasing in $\overline{F}$.

Proof of Proposition 4

For $F < \overline{F}$, a comparison of the manufacturer's profit generated under each timing of announcement $\Pi_M^{EP} - \Pi_M^{EA}$ yields

$$\Pi_M^{EP} - \Pi_M^{EA} = \frac{m^2\delta^2(a-m-c_1)^2 - (m\delta(a-m+\delta) + (2F - m\delta)c_1 - 2Fc_2)^2}{4m^2\delta^2}$$

Now, $\Pi_M^{EP} - \Pi_M^{EA} < 0 \iff F < \overline{F}$, where $\Pi_M^{EP} - \Pi_M^{EA}$ is convex for F. As regards the high-cost supplier S2 under the ex-ante announcement, S2 earns profit as $\Pi_2^{EA} = \frac{F((a-m)m\delta + (2F-m\delta)c_1 - 2Fc_2)}{m\delta^2} > 0$ for $F < \overline{F}$. Since supplier S2 is excluded from the ex-post announcement transaction, the ex-ante policy announcement clearly enables the manufacturer and high-cost supplier S2 to generate a higher profit than would the ex-post policy announcement.

To see whether supplier S1 also can improve its profit under the ex-ante policy announcement, we compare $\Pi_1^{EA} = \frac{m(1-\frac{2F}{m\delta})(m\delta(a-m+\delta-c_1)-2F(c_2-c_1))}{2m\delta} - F$ and $\Pi_1^{EP} = \frac{1}{2}m(a-m-c_1)$ as follows:

$$\Pi_1^{EP} - \Pi_1^{EA} = \frac{m\delta\left(2F(a-m+2\delta) - m\delta^2\right) + 2F(2c_1(F-m\delta) - c_2(2F-m\delta))}{2m\delta^2} \quad \text{(B1)}$$

It is immediate that (B1) is a quadratic concave function with respect to F. By solving $\Pi_1^{EP} - \Pi_1^{EA} = 0$, we obtain two solutions, $F^\dagger = \frac{m\delta(a-m+2\delta-2c_1+c_2) - m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}}{4(c_2-c_1)}$ and $F^\ddagger = \frac{m\delta(a-m+2\delta-2c_1+c_2) + m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}}{4(c_2-c_1)}$. Knowing that $(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1) < 0 \Leftrightarrow a < m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2-c_1)}$ there are two cases to consider: (i) $a < m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2-c_1)}$ and (ii) $a > m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2-c_1)}$.

- $a < m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2-c_1)}$ case: In this case, $\Pi_1^{EP} < \Pi_1^{EA}$ holds regardless of F level.
- $a > m - 2\delta + 2c_1 - c_2 + 2\sqrt{\delta(c_2-c_1)}$ case: It is immediate that $0 < F^\dagger < F^\ddagger$. In (B2), (B3), (B4), and (B5), we confirm that $0 < F^\dagger < \min[F_S, F_M] < F^\ddagger$ is satisfied.

$$F_M - F^\dagger = \frac{-m\delta(a-m-2c_1+c_2) + m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}}{4(c_2-c_1)} > 0 \quad \text{(B2)}$$

$$F_S - F^\dagger = \frac{-m\delta(a-m+2\delta-c_1) + m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}}{4(c_2-c_1)} > 0 \quad \text{(B3)}$$

$$F_M - F^\ddagger = \frac{-m\delta\left(a-m-2c_1+c_2) - m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}\right)}{4(c_2-c_1)} < 0 \quad \text{(B4)}$$

$$F_S - F^\ddagger = \frac{-m\delta\left(a-m+2\delta-c_1) - m\delta\sqrt{(a-m+2\delta-2c_1+c_2)^2 - 4\delta(c_2-c_1)}\right)}{4(c_2-c_1)} < 0 \quad \text{(B5)}$$

Thus, in this case, we have $\Pi_1^{EP} < \Pi_1^{EA}$ if $F \in \left[0, F^\dagger\right]$; otherwise, $\Pi_1^{EP} > \Pi_1^{EA}$.

Proof of Lemma 2

Optimizing the manufacturer's profit in (9) for p yields

$$p = \frac{1}{2}(a + m - x\delta + \theta c_1 + (1 - \theta)c_2) \tag{B6}$$

Given the optimal p in (A6), by sharing their knowledge, that is, $x = 1$, suppliers S1 and S2 earn profits as follows:

$$\Pi_1(\theta, f|x = 1) = \frac{1}{2}m\theta(a - m + \delta - \theta c_1 - (1 - \theta)c_2) - F + f$$

and.

$\Pi_2(\theta, f|x = 1) = \frac{1}{2}m(1 - \theta)(a - m + \delta - \theta c_1 - (1 - \theta)c_2) - F + f.$

If suppliers S1 and S2 do not share their knowledge, that is, $x = 0$, their profit levels will be

$$\Pi_1(\theta, f|x = 0) = \frac{1}{2}m\theta(a - m - \theta c_1 - (1 - \theta)c_2)$$

and

$$\Pi_2(\theta, f|x = 0) = \frac{1}{2}m(1 - \theta)(a - m - \theta c_1 - (1 - \theta)c_2)$$

For given θ and f, suppliers S1 and S2 would share their knowledge if the following conditions are met:

$$\Pi_1(\theta, f|x = 1) - \Pi_1(\theta, f|x = 0) = \frac{m\delta\theta}{2} - (F - f) \geq 0 \tag{B7}$$

and

$$\Pi_2(\theta, f|x = 1) - \Pi_2(\theta, f|x = 0) = \frac{1}{2}m\delta(1 - \theta) - (F - f) \geq 0 \tag{B8}$$

The above conditions in (B7) and (B8) are satisfied for $\theta \in \left[\frac{2(F-f)}{m\delta}, 1 - \frac{2(F-f)}{m\delta}\right]$, where $\frac{2(F-f)}{m\delta} \leq 1 - \frac{2(F-f)}{m\delta}$ holds if and only if $f \geq \max\left\{F - \frac{m\delta}{4}, 0\right\}$. Note that $0 \leq \frac{2(F-f)}{m\delta}$ and $1 - \frac{2(F-f)}{m\delta} \leq 1$, since $f \leq F$. Therefore, we can characterize the suppliers' decision on knowledge sharing in equilibrium as

$$x^*(\theta, f) = \begin{cases} 1, \ \theta \in \left[\frac{2(F-f)}{m\delta}, 1 - \frac{2(F-f)}{m\delta}\right] \text{and } f \geq \max\left\{F - \frac{m\delta}{4}, 0\right\} \\ 0, \ \text{otherwise} \end{cases} \tag{B9}$$

Proof of Proposition 5

Given the optimal p in (B6), if suppliers S1 and S2 choose to share their knowledge, that is, $x = 1$, then the manufacturer's profit will be.

$$\Pi_M(\theta, f) = \frac{1}{4}\left((a - m + \delta)^2 - (\theta c_1 + (1 - \theta)c_2)(2(a - m + \delta) - (\theta c_1 + (1 - \theta)c_2)) - 8f\right)$$

For $\theta > 0$, $\Pi_M(\theta, f)$ increases in θ, and therefore maximizing $\Pi_M(\theta, f)$ gives the optimal θ as

$$\theta(f) = 1 - \frac{2(F - f)}{m\delta} \tag{B10}$$

By inserting the optimal θ in (B10) into $\Pi_M(\theta, f)$, we obtain.

$$\Pi_M(f) = \frac{m^2\delta^2\left((a-m+\delta)^2 - 8f\right) - (2m\delta(a-m+\delta) - (m\delta - 2(F-f))c_1 - 2(F-f)c_2)((m\delta - 2(F-f))c_1 - 2(F-f)c_2)}{4m^2\delta^2} \quad \text{(B11)}$$

Under the condition in (B11), we find the optimal f that maximizes $\Pi_M(f)$ by considering two cases, $F > \frac{m\delta}{4}$ and $F < \frac{m\delta}{4}$.

(a) Case $F > \frac{m\delta}{4}$ In this case, the range of f is restricted to $f \in \left[F - \frac{m\delta}{4}, F\right]$. Given that $\frac{\partial^2 \pi_M(f)}{\partial f^2} = \frac{2(c_1-c_2)^2}{m^2\delta^2} < 0$, $\Pi_M(f)$ is convex for f, and so we need to compare $\Pi_M\left(F - \frac{m\delta}{4}\right)$ and $\Pi_M(F)$ to obtain the optimal f for the manufacturer's profit. When $\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right)$ is calculated as $\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right) = \frac{(4(a-m+\delta)-3c_1-c_2)(c_2-c_1)-8m\delta}{16}$, solving $\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right) = 0$ for δ would yield

$$\delta^\dagger = \frac{(4a - 4m - 3c_1 - c_2)(c_2 - c_1)}{4(2m + c_1 - c_2)} \quad \text{(B12)}$$

where $\frac{\partial\left(\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right)\right)}{\partial\delta} = \frac{-(2m+c_1-c_2)}{4}$. To check whether $\delta^\dagger$ in (B12) is positive, we examine two subcases, $2m + c_1 - c_2 < 0$ and $2m + c_1 - c_2 > 0$.

(a-1) Subcase $2m + c_1 - c_2 < 0$ If $2m + c_1 - c_2 < 0$, $\Pi_M(F) > \Pi_M\left(F - \frac{m\delta}{4}\right)$ always holds where $\delta^\dagger < 0$ and $\frac{\partial\left(\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right)\right)}{\partial\delta}$ >0. When the manufacturer induces the suppliers' knowledge sharing, that is, when $x = 1$, $\Pi_M(F) = \frac{1}{4}((a - m + \delta)^2 - c_1(2(a - m + \delta) - c_1) - 8F)$ becomes the manufacturer's optimal profit. Otherwise, that is, when $x = 0$, the manufacturer makes the optimal profit $\Pi_M^0 = \frac{1}{4}(a - m - c_1)^2$, the same as that derived under the ex-post policy announcement. Then, we calculate $\Pi_M(F) - \Pi_M^0$ as

$$\Pi_M(F) - \Pi_M^0 = \frac{1}{4}(\delta(2a - 2m + \delta) - 2\delta c_1 - 8F) \quad \text{(B13)}$$

and realize $\Pi_M(F) > \Pi_M^0$ if and only if $F < F_1 = \frac{\delta(2a-2m+\delta-2c_1)}{8}$.

(a-2) Subcase $2m + c_1 - c_2 > 0$ We have $\delta^\dagger > 0$ and $\frac{\partial\left(\Pi_M(F) - \Pi_M\left(F - \frac{m\delta}{4}\right)\right)}{\partial\delta} < 0$, and hence $\Pi_M(F) > \Pi_M\left(F - \frac{m\delta}{4}\right) \Leftrightarrow \delta <$. If $\delta <$, then calculating $\Pi_M(F) - \Pi_M^0$ leads to the same result presented in (B11). That is, $\Pi_M(F) > \Pi_M^0$ if and only if $F < F_1$. Otherwise, when $\delta >$, we compare $\Pi_M\left(F - \frac{m\delta}{4}\right)$ and Π_M^0 as shown as below:

$$\Pi_M\left(F - \frac{m\delta}{4}\right) - \Pi_M^0 = \frac{4\left(2a\delta + \delta^2 - 8F\right) + c_1\left(4\left(a - m - \delta\right) - 3c_1 + 2c_2\right) - c_2\left(4\left(a - m + \delta\right) - c_2\right)}{16} \quad \text{(B14)}$$

Investigating $\Pi_M\left(F - \frac{m\delta}{4}\right) - \Pi_M^0$ yields

$$\Pi_M\left(F - \frac{m\delta}{4}\right) > \Pi_M^0 \Leftrightarrow F < F_2 = \frac{4\delta\left(2a + \delta\right) - 4c_2\left(a - m + \delta\right) + 2c_1\left(2a - 2m - 2\delta + c_2\right) - 3c_1^2 + c_2^2}{32}$$

To appropriately find the manufacturer's optimal profit, we compare F_1, F_2, and $\frac{m\delta}{4}$ as

$$F_1 - \frac{m\delta}{4} = \frac{\delta(2a - 4m + \delta - 2c_1)}{8}; F_2 - \frac{m\delta}{4} = \frac{(4a - 4m + 2\delta - 3c_1 - c_2)(2\delta + c_1 - c_2)}{32}$$

and

$$F_1 - F_2 = \frac{(4(a - m + \delta) - 3c_1 - c_2)(c_2 - c_1) - 8m\delta}{32}$$

If we assume that the market size is sufficiently large, such that $a > 2m + c_1$, then $\min\{F_1, F_2\} \geq \frac{m\delta}{4}$, while $F_1 > F_2 \iff \delta <$. Meanwhile, a comparison of $\delta^\dagger$ and c_1 yields $\min\{\delta^\dagger, c_1\} = \iff m > \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}$. In sum, we can characterize the manufacturer's optimal profit Π_M^* as follow:

When $2m + c_1 - c_2 < 0$: If $F < F_1$, then $\Pi_M^* = \Pi_M(F)$. Otherwise, $\Pi_M^* = \Pi_M^0$.

When $2m + c_1 - c_2 > 0$:

If $\delta < \min\{\delta^\dagger, c_1\}$ and $F < F_1$, then $\Pi_M^* = \Pi_M(F)$. Otherwise, $\Pi_M^* = \Pi_M^0$.

If $\min\{\delta^\dagger, c_1\} < \delta < c_1$ and $F < F_2$, then $\Pi_M^* = \Pi_M\left(F - \frac{m\delta}{4}\right)$. Otherwise, $\Pi_M^* = \Pi_M^0$.

(b) Case $F < \frac{m\delta}{4}$ In this case, we consider $f \in [0, F]$. To find the manufacturer's optimal profit, we compute $\Pi_M(F) - \Pi_M(0)$, to obtain

$$\Pi_M(F) - \Pi_M(0) = \frac{F\left((c_2 - c_1)(m\delta(a - m + \delta) - (m\delta - F)c_1 - Fc_2) - 2m^2\delta^2\right)}{m^2\delta^2} \tag{B15}$$

By solving $\Pi_M(F) - \Pi_M(0) = 0$ for F, we obtain two solutions, $F = 0$ and $F = \frac{m\delta((a-m+\delta-c_1)(c_2-c_1)-2m\delta)}{(c_1-c_2)^2}$, where $\frac{\partial^2(\Pi_M(f=F)-\Pi_M(f=0))}{\partial F^2} = -\frac{2(c_1-c_2)^2}{m^2\delta^2} < 0$. For notational convenience, we assume that

$$F_3 \equiv \frac{m\delta((a - m + \delta - c_1)(c_2 - c_1) - 2m\delta)}{(c_1 - c_2)^2}.$$

Given that $\frac{\partial^2 F_3}{\partial \delta^2} = -\frac{2m(2m+c_1-c_2)}{(c_1-c_2)^2}$ and $F_3 = 0$ has two solutions at $\delta = 0$ and $\delta = \frac{(a-m-c_1)(c_2-c_1)}{2m+c_1-c_2}$, we calculate the difference between F_3 and $\frac{m\delta}{4}$ as follows:

$$F_3 - \frac{m\delta}{4} = \frac{4m\delta((a - m + \delta - c_1)(c_2 - c_1) - 2m\delta) - m\delta}{4(c_1 - c_2)^2} \tag{B16}$$

We obtain two solutions of (A14) as $\delta = 0$ and $\delta =$, where

$$\frac{\partial^2\left(F_3 - \frac{m\delta}{4}\right)}{\partial \delta^2} = -\frac{2m(2m + c_1 - c_2)}{(c_1 - c_2)^2} \tag{B17}$$

These results suggest that we need to consider the two subcases $2m + c_1 - c_2 < 0$ and $2m + c_1 - c_2 > 0$.

(b-1) Subcase $\boldsymbol{2m + c_1 - c_2 < 0}$ Given that $\Pi_M(F) > \Pi_M(0) \iff F < F_3$, from (B12) and (B17), we know that $\delta^\dagger < 0$ and $F_3 - \frac{m\delta}{4}$ is a convex function. That is, $F_3 > \frac{m\delta}{4}$ always holds, and we so can conclude that $\Pi_M(F) > \Pi_M(0)$ under $F < \frac{m\delta}{4}$. To establish the manufacturer's optimal decision, we need to compare $\Pi_M(F)$ and Π_M^0. We derive results similar to that in (A11); thus, $\Pi_M(F) > \Pi_M^0$ if and only if $F < F_1$. Since $\frac{m\delta}{4} < F_1$, $\Pi_M(F) > \Pi_M^0$ holds for all F, and we consider (i.e., $F < \frac{m\delta}{4}$).

(b-2) Subcase $2m + c_1 - c_2 > 0$ In this case, F_3 is a concave function and $F_3 > 0$ for $\delta \in \left[0, \frac{(a-m-c_1)(c_2-c_1)}{2m+c_1-c_2}\right]$. Given (B12) and (B16), we know that $F_3 - \frac{m\delta}{4}$ is also a concave function and $F_3 > \frac{m\delta}{4}$ for $\delta \in [0,]$. Since $\delta^\dagger < \frac{(a-m-c_1)(c_2-c_1)}{2m+c_1-c_2}$, $F_3 < \frac{m\delta}{4}$ for $\delta >$. In sum, we can say that $\Pi_M(F) > \Pi_M(0)$ holds when.

(i) $\delta <$ and (ii) $\delta >$, and $F < F_3$ ($\Leftrightarrow \delta < \frac{2\left(a+\sqrt{a^2+8F+(m-2a)c_1+c_1^2-mc_2}\right)-c_1-c_2}{2}$). Under the conditions satisfying $\Pi_M(F) > \Pi_M(0)$, a comparison of $\Pi_M(F)$ and Π_M^0 yields the same results as in (b-1).

Next, when $\Pi_M(F) < \Pi_M(0)$, we compute $\Pi_M(0) - \Pi_M^0$ as

$$\Pi_M(0) - \Pi_M^0 = \frac{(m\delta(a-m+\delta) + (2F - m\delta)c_1 - 2Fc_2)^2 - m^2\delta^2(a-m-c_1)^2}{4m^2\delta^2}$$

Then, $\Pi_M(0) < \Pi_M^0$ holds for $F \in \left[\frac{m\delta^2}{2(c_2-c_1)}, \frac{m\delta(2a-2m+\delta-2c_1)}{2(c_2-c_1)}\right]$ while $\frac{\partial^2(\Pi_M(0)-\Pi_M^0)}{\partial F^2} = \frac{2(c_2-c_1)^2}{m^2\delta^2}$. Given that $\frac{m\delta^2}{2(c_2-c_1)} > \frac{m\delta}{4} \iff \delta > \frac{c_2-c_1}{2}$, $\Pi_M(0) > \Pi_M^0$. Note that $\delta^\dagger > \frac{c_2-c_1}{2}$.

(1) When $2m + c_1 - c_2 < 0$:

- $\Pi_M^* = \Pi_M(F)$

(2) When $2m + c_1 - c_2 > 0$:

- For $\delta \in [0,]$, $\Pi_M^* = \Pi_M(F)$.
- For $\delta \in \left[, \frac{(a-m-c_1)(c_2-c_1)}{2m+c_1-c_2}\right]$, $\Pi_M^* = \Pi_M(F)$ if $F < F_3$. Otherwise, $\Pi_M^* = \Pi_M(0)$.
- For $\delta > \frac{(a-m-c_1)(c_2-c_1)}{2m+c_1-c_2}$, $\Pi_M^* = \Pi_M(0)$.

We end this proof by combining the results of the above two cases. Recall that $\min\{\delta^\dagger, c_1\} = \delta^\dagger \Leftrightarrow m > \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}$. Also, δ cannot exceed c_1. Therefore, we characterize the manufacturer's optimal subsidy decision as follows:

1) $m < \max\left\{\frac{c_2-c_1}{2}, \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}\right\}$:

- If $F < \max\{F_1, F_2\}$, then $\Pi_M^* = \Pi_M(F)$. Otherwise, $\Pi_M^* = \Pi_M^0$.

2) $m > \max\left\{\frac{c_2-c_1}{2}, \frac{(c_2-c_1)(4a+c_1-c_2)}{4(c_1+c_2)}\right\}$:

- For $F < \frac{m\delta}{4}$, $\Pi_M^* = \Pi_M(F)$ if $\delta < \min\left\{\frac{2\left(a+\sqrt{a^2+8F+(m-2a)c_1+c_1^2-mc_2}\right)-c_1-c_2}{2}, c_1\right\}$. Otherwise, $\Pi_M^* = \Pi_M(0)$.
- For $\frac{m\delta}{4} < F < \max\{F_1, F_2\}$, $\Pi_M^* = \Pi_M(F)$ if $\delta < \min\{, c_1\}$. Otherwise, $\Pi_M^* = \Pi_M\left(F - \frac{m\delta}{4}\right)$.
- For $F > \max\{F_1, F_2\}$, $\Pi_M^* = \Pi_M^0$.

Appendix C Asymmetric benefits of knowledge sharing

In this section, we examine the case where the knowledge sharing benefit goes to each supplier is asymmetric. Suppose that the benefit of knowledge sharing for S1 and S2 are given as $\omega\delta$

$(0 < \omega < 1)$ and δ, respectively. Then the manufacturer's profit is written as

$$\Pi_M = \theta Q(p - ((c_1 + m) - x \cdot \omega\delta)) + (1 - \theta)Q(p - ((c_2 + m) - x \cdot \delta)),$$

while the two suppliers' profits remain the same.

We first derive the range of θ to induce knowledge sharing by using a backward induction. At Stage 3, the pricing decision is obtained as:

$$p = \frac{1}{2}(a + m - x\delta(1 - \theta(1 - \omega)) + \theta c_1 + (1 - \theta)c_2).$$

Plugging this into $Q = a - p$, Q becomes a function of ω.

$$Q = \frac{1}{2}(a - m + x\delta(1 - \theta(1 - \omega)) - \theta c_1 - (1 - \theta)c_2).$$

This shows that raising ω clearly increases sales quantity if knowledge sharing is induced.

We then compare S1's profit with and without knowledge sharing. The difference between the two, $\Pi_1(1) - \Pi_1(0)$, is expressed as:

$$\Pi_1(1) - \Pi_1(0) = \frac{m\delta\theta(1 - \theta(1 - \omega))}{2} - F,$$

which is a concave function of θ. Under an assumption that $F < \frac{m\delta}{8(1-\omega)}$, the roots of $\Pi_1(1) - \Pi_1(0) = 0$ are obtained as:

$$\left(\theta_1^L, \theta_1^H\right) = \left(\frac{1 - \frac{\sqrt{m\delta - 8F(1-\omega)}}{\sqrt{m\delta}}}{2 - 2\omega}, \frac{1 + \frac{\sqrt{m\delta - 8F(1-\omega)}}{\sqrt{m\delta}}}{2 - 2\omega}\right).$$

It is immediate that $\theta_1^L > 0$ and $\theta_1^H > 1$. We thus can say that S1 has an incentive to share her knowledge with its opponent if $\theta \in [\theta_1^L, 1]$. Furthermore, lower bound $\theta_{min}(\equiv \theta_1^L)$ is decreasing in ω since

$$\frac{d\theta_1^L}{d\omega} = \frac{-m\delta + +4F(1 - \omega) + \sqrt{m}\sqrt{\delta}\sqrt{m\delta - 8F(1 - \omega)}}{2\sqrt{m}\sqrt{\delta}\sqrt{m\delta - 8F(1 - \omega)}(1 - \omega)^2} < 0.$$

We next compare S2's profit w/ and w/o knowledge sharing. The difference between the two, $\Pi_2(1) - \Pi_2(0)$, is expressed as:

$$\Pi_2(1) - \Pi_2(0) = \frac{m\delta(1 - \theta)(1 - \theta(1 - \omega))}{2} - F,$$

which is a convex function of θ. Assuming that $F < \frac{m\delta}{8(1-\omega)}$, the roots of $\Pi_2(1) - \Pi_2(0) = 0$ are obtained as:

$$\left(\theta_2^L, \theta_2^H\right) = \left(\frac{m\delta(2 - \omega) - \sqrt{m\delta\big(8F(1 - \omega) + m\delta\omega^2\big)}}{2m\delta(1 - \omega)}, \frac{m\delta(2 - \omega) + \sqrt{m\delta\big(8F(1 - \omega) + m\delta\omega^2\big)}}{2m\delta(1 - \omega)}\right).$$

It is immediate that $0 < \theta_2^L < 1$ and $\theta_2^H > 1$ are satisfied. We thus can say that S1 has an incentive to share her knowledge with its opponent if $\theta \in [0, \theta_2^L]$. Furthermore, upper bound $\theta_{max}(\equiv \theta_2^L)$ is increasing in ω since

$$\frac{d\theta_2^L}{d\omega} = \frac{-4F(1 - \omega) - m\delta\omega + \sqrt{m\delta\big(8F(1 - \omega) + m\delta\omega^2\big)}}{2(1 - \omega)^2\sqrt{m\delta\big(8F(1 - \omega) + m\delta\omega^2\big)}} > 0.$$

The difference $\Delta(\omega) = \theta_{max} - \theta_{min}$ is expressed as

$$\Delta(\omega) = \frac{m\delta(1-\omega) + \sqrt{m\delta}\left(\sqrt{m\delta - 8F(1-\omega)} - \sqrt{8F(1-\omega) + m\delta\omega^2}\right)}{2m\delta(1-\omega)}.$$

At the boundary value $\omega = 1 - \frac{m\delta}{8F}$, $\Delta(\omega) = \frac{m^2\delta^2}{8F} - m\delta\sqrt{1 + \left(1 - \frac{m\delta}{8F}\right)^2} > 0 \iff F < \frac{m\delta}{8}$. Together with the fact that $\theta_{max} - \theta_{min}$ is increasing in $\omega \in [1 - \frac{m\delta}{8F}, 1]$, we can conclude that knowledge sharing region $[\theta_{min}, \theta_{max}]$ exists if $F < \frac{m\delta}{8(1-\omega)}$.

From Lemma 1, it follows that the manufacturer can entice suppliers to share their knowledge each other by setting its order-splitting ratio $\theta \in [\theta_{min}, \theta_{max}]$. Within this range of θ, it can be easily shown that the manufacturer's choice is θ_{max} considering that θ is the procurement portion from the low-cost supplier. Then, the manufacturer's optimal order-splitting ratio decision boils down to the comparison between θ_{max} and 1, i.e., $\theta^* \in \{\theta_{max}, 1\}$. The comparison of the manufacturer's profit under the two cases, i.e., $\Pi_M^S(\theta_{max})$ and $\Pi_M^N \equiv \frac{(a-(c_1+m))^2}{4}$.

Lemma C1 *Define* $F_S \equiv \frac{m\delta}{8(1-\omega)}$. *When* $F > F_S$, *then the two suppliers do not agree on supplier-supplier collaboration for any given order-splitting proportion* θ. *However, when* $F < F_S$, *supplier-supplier collaboration occurs if* $\theta \in [\theta_{min}, \theta_{max}]$, *where* $\theta_{min} = \frac{1 - \frac{\sqrt{m\delta - 8F(1-\omega)}}{\sqrt{m\delta}}}{2-2\omega}$ *and* $\theta_{max} = \frac{m\delta(2-\omega) - \sqrt{m\delta(8F(1-\omega) + m\delta\omega^2)}}{2m\delta(1-\omega)}$. *Also, the lower bound* θ_{min} *is decreasing in* ω, *whereas* θ_{max} *is increasing in* ω.

Within the range of $0 < F < F_S$, one can easily verify that $\theta_{max}(F)$ is decreasing in F and $\theta_{max}(F)$ converges to 1 as F approaches to zero. Together with the fact Π_M^S is a continuous function of F for $F \in [0, F_S]$, we see that $\lim_{F \to 0} \Pi_M^S(\theta_{max}) > \Pi_M^N$ is satisfied. Also, as we have seen that $\frac{\partial \Pi_M^S(\theta)}{\partial \theta} > 0$ and $\frac{\partial \theta}{\partial F} > 0$, it holds that $\frac{\partial \Pi_M^S(\theta(F))}{\partial F} = \frac{\partial \Pi_M^S(\theta(F))}{\partial \theta} \cdot \frac{\partial \theta}{\partial F} > 0$. Lastly, for $F > F_S$, the manufacturer's optimal θ choice becomes 1. Collectively, we can say that there exists a threshold $\overline{F} \in (0, F_S]$ such that $\Pi_M^S(\theta_{max}(F)) > \Pi_M^N \iff F < \overline{F}$. More specifically, $\overline{F} < F_S$ if $\Pi_M^S(\theta_{max}(F_S)) > \Pi_M^N$ and otherwise $\overline{F} = F_S$. This leads to the following proposition.

Proposition C1 *Under the ex-ante policy announcement, there exists the threshold* $\overline{F}$ *satisfying the following claims.*

(i) *If* $F > \overline{F}$, *the manufacturer chooses the order-splitting proportion* $\theta^* = 1$ *(WTA allocation) and thus does not induce supplier-supplier collaboration*

(ii) *If* $F < \overline{F}$, *the manufacturer chooses the order-splitting proportion* $\theta^* = \frac{m\delta(2-\omega) - \sqrt{m\delta(8F(1-\omega) + m\delta\omega^2)}}{2m\delta(1-\omega)}$ *(SA allocation) and thus induces supplier-supplier collaboration.*

The proposition suggests that the structural properties of Proposition 2 remain the same if we allow asymmetric cost reductions (i.e., $\omega\delta$ and δ) for the suppliers. Also, one can easily infer that raising ω (weakly) enlarges the supplier-supplier collaboration.

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