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R&D consortia in competitive supply chains

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R&D consortia, which coordinate R&D activities of their member firms, have been successful in many industries. We study a model with two competing supply chains each consisting of a manufacturer and a supplier. The manufacturers compete in the final product market, and can conduct R&D to reduce unit product costs of their final products. The R&D can be done in three different ways: by the two manufacturers independently, by them jointly in a horizontal R&D consortium, or by the supplier and the manufacturer jointly in each supply chain in two vertical R&D consortia. We find that as compared to independent R&D, both the horizontal consortium and the vertical consortia lead to higher R&D effort, wholesale prices, and output quantities in the supply chains. However, different supply chain parties' preferences over the two types of consortia are not necessarily consistent. We then consider a game where the firms endogenously determine to form which type of R&D consortium in the industry. We show that vertical consortia emerge in industries with high R&D uncertainty and effort cost, and the horizontal consortium is likely to emerge otherwise. Our results provide plausible explanations on why different types of R&D consortium emerge and flourish in different industries and shed light on their potential benefits for consumers and social welfare.

Key words: R&D Consortium, Competition, Supply Chain Management, Cost Reduction

1. Introduction

The collaboration of distinct firms within consortia to coordinate the activities of its member firms raises concerns of competition suppression and is tightly regulated or even banned to protect social welfare. Yet policy makers allow an exception for research consortia. Research consortia bring different firms together to collaborate on R&D efforts that benefit all the consortium members but stop short of collusion on the market place. Such research consortia may serve society and the member firms in multiple ways. The firms in the research consortium benefit by pooling their knowledge and resources to achieve more promising innovations at a lower cost. Furthermore, innovations within a consortium propagate more quickly to its member firms, outpacing the market diffusion process resulting from positive externalities to R&D. Consequently, governments often support or even actively create research consortia through grants or collaboration with public research institutions.

An early and very successful example of a R&D consortium is SEMATECH. Founded in 1987 by the 14 largest chip makers in the US, the consortium performed research to reduce chip manufacturing costs and product defects for its members (Bez and Chesbrough 2020). The success of this consortium encouraged the government to promote the creation of further consortia such as the National Alliance for Advanced Transportation Battery Cell Manufacture (NAATBatt) in 2008 (Hof 2011). In a more recent example, the Partnership on AI (PAI) was established in 2016 by seven competing major US AI companies, including Google, Amazon, Facebook, and Microsoft, to research best practices for artificial intelligence systems (Bez and Chesbrough 2020). These consortia are horizontal in nature as they bring together firms directly competing in the same final product market.

In contrast, there are vertical R&D consortia which recruit their member firms amongst supply chain partners instead of competitors. Airbus itself was created from the collaboration of multiple European airspace firms designing and delivering different parts of the Airbus A300. The company continues to embrace close collaboration with its partners across the aviation value chain, such as its more recent collaboration with the SAF+ Consortium working on sustainable aviation fuel to achieve low-carbon flight (Airbus 2021). In the automobile industry, BMW joined forces with suppliers Intel and Mobileye in 2016 with the aim to develop an Autonomous Driving Platform capable of safe hands-off driving on highways and congested urban environments alike (BMW 2016). Competing automobile manufacturer Fiat-Chrysler, meanwhile, has chosen to partner with Waymo, a unit of Alphabet, to develop self-driving commercial vehicles (Wayland 2020).

These contrasting examples illustrate that both consortium types exist in practice, and beg the question as to which consortium type is attractive under which circumstances. Should a consortium bring together member firms from the same industry to work on problems of common interest, or should it gather partners along the supply chain with a shared interest in furthering their market share? To answer these questions, we develop a model with two competing supply chains. Each of the supply chains consists of one manufacturer and one supplier. The manufacturers produce products using the components supplied by their supplier and compete in the final product market. The manufacturers can invest R&D effort to reduce their unit production costs. In our model, the R&D can be conducted in three different ways: independent R&D without a consortium, horizontal consortium, or vertical consortium. With independent R&D, each manufacturer exerts R&D effort independently. With a horizontal consortium, the two manufacturers form a consortium to exert R&D effort jointly. With a vertical consortium, the manufacturer and the supplier in the same supply chain form a consortium to exert R&D effort jointly. Therefore, there could be two competing vertical consortia in the market in our model. We study and compare the equilibrium outcomes of these different R&D structures in terms of R&D effort levels, pricing and quantity decisions, and profits. We identify the factors shaping the optimal consortium structure. Our model and results make the following three contributions.

First, we demonstrate that a horizontal R&D consortium between the manufacturers is not anti-competitive, but rather results in higher total R&D spending than individual investment, with each firm spending more than they would on their own. However, we also observe that a horizontal consortium is not always preferred by the manufacturers. Surprisingly, our research highlights that a higher unit R&D cost decreases the benefits of the horizontal consortium to its members such that excessively high R&D costs may prompt the manufacturers to prefer conducting R&D individually. Another determinant of the manufacturers' preferences is the degree of competition as measured by the degree of product substitution and the R&D outcome uncertainty. The strong market competition caused by high product substitution reduces the benefits from cooperation: firms prefer to invest independently in R&D as the profit from a favorable R&D outcome realization outweighs the downsides of an unfavorable outcome. This asymmetric benefit is amplified with larger R&D uncertainty. The higher the R&D uncertainty, the less attractive it is to cooperate in a horizontal consortium.

Second, our results demonstrate the superiority of a vertical R&D consortium over individual R&D on all dimensions—total effort levels, order quantities and profits—for all parties. These benefits are so pronounced that in a vertical consortium consisting of a manufacturer and its supplier, the supplier is willing to bear more than half of the R&D cost incurred by the consortium. Unlike in the horizontal consortium, the market competition between the supply chains is retained in a vertical consortium as the two manufacturers will experience a different realized cost; therefore greater R&D uncertainty increases the expected profits of all firms.

Third and most interesting is the endogenous equilibrium that emerges from the interaction between the firms in the competing supply chains. While we know that vertical consortium dominates individual R&D for all firms, it does not dominate the horizontal consortium for the supplier as the supplier contributes over half of the R&D cost under a vertical consortium yet not at all under a horizontal consortium. We show that vertical consortia would emerge when the R&D uncertainty and effort cost are high, while the horizontal consortium is likely to emerge when the R&D uncertainty and effort cost are low. The supplier only prefers a vertical consortium if the R&D uncertainty is significant enough that competing on production cost is attractive. However, we find that the suppliers suffer from prisoner's dilemma and are forced in equilibrium to propose a vertical consortium to their manufacturers for a lower R&D uncertainty than they would prefer. This is beneficial to the manufacturers, who always prefer a vertical consortium over a horizontal consortium.

We illustrate the managerial implications of our results with the examples of research consortia listed above. SEMATECH is a highly successful example of a horizontal research consortium. Arguably, one reason for its success was its focus on process R&D to reduce the production costs of American semi-conductor firms to levels that would make them competitive against Japanese manufacturers. To the extent that such R&D efforts were geared towards more incremental and exploitative research they would display limited outcome uncertainty and variability, making a horizontal consortium profitable for the competitors. A more recent example of a horizontal research consortium, PAI, is attractive because the partner firms are not locked in strong competition in the product markets. Therefore, even though the research conducted by PAI is arguably more exploratory and hence subject to uncertainty and variability, the firms do not suffer from sharing the same cost reduction. Airbus, however, prefers working with its suppliers rather than with Boeing or other plane manufacturers as in the airspace industry, competition in the product market and variability of the R&D are high, both of which favor a vertical research consortium.

We review the literature in Section 2. The model is presented and solved for independent R&D efforts by the manufacturing firms in Section 3. We solve for exogenous horizontal and vertical consortium in Section 4, and endogenize the emergence of the consortium type in Section 5. We conclude in Section 6.

2. Literature Review

Our research mainly draws on two streams of literature from economics and operations management respectively. Scholars in the economics literature have studied research joint ventures (RJV) between firms competing in the product market and their impact on R&D efforts and social welfare. Spence (1984) identifies appropriability concerns as one of the main threats to a firm's incentive to invest in R&D in need of a solution. Consequently, in early papers on cooperative R&D, Katz (1986) and d'Aspremont and Jacquemin (1988) focus on the impact of RJVs on R&D effort levels and social welfare in the presence of spillovers. Both papers find that RJVs do not necessarily suppress competition but may increase total R&D levels if the externalities are significant, by internalizing the benefits from spillovers. Kamien et al. (1992) model the product market game explicitly and allow for information sharing which increases the spillover effect inside the RJV. Accordingly, they find that a cooperative RJV dominates all other forms, both from a social welfare and firm profit perspective. Choi (1993) further generalizes the results for settings in which R&D success is uncertain. This uncertainty increases the attractiveness of independent R&D as firms profit from a competitor's R&D failure. However, RJVs continue to emerge for large enough spillovers that reduce the benefit of competitor failure.

However, private interest and social welfare may not always be aligned. For example, in a model of international R&D cooperation, Ghosh and Lim (2013) confirm the results of spillover effects on the magnitude of cooperative R&D but find that the firms' preferences for R&D cooperation may not optimize social welfare in the presence of international trade costs. Suzumura (1992) compares R&D levels under competition and cooperation to socially optimal levels and concludes that R&D cooperation leads to insufficient investment, whereas competition in R&D may lead to either excessive or insufficient investment, for low and high levels of spillovers, respectively. Ishii (2004) adds supply chain concerns by considering two upstream and two downstream firms, where the downstream firms purchase from both suppliers equally. Each firm can invest in research to reduce their own costs, with vertical and horizontal spillovers. The authors find that a vertical RJV dominates all other forms from a social welfare perspective, but does not necessarily maximize the firms' profits.

The operations management literature has looked at how to organize joint R&D investment between firms in various ways. A large body of literature in operations management looks at contracts governing collaborative R&D development between two firms of a single jointly marketed product, determining revenue sharing parameters (Bhaskaran and Krishnan 2009), optimal payment terms (Xiao and Xu 2012), or buyout options and control rights (Savva and Scholtes 2014, Bhattacharya et al. 2015, Crama et al. 2017). We focus on the work that has looked at R&D investment within a supply chain setting. In that context, Chen et al. (2021) show how a manufacturer incentivizes its competing suppliers to source innovative components. Shalpegin et al. (2018) focus on the collaboration between a manufacturer and a supplier investing in innovation and study the timing and sequencing decisions of the innovation efforts. We look at competition in the product market but collaboration in innovation between supply chains. We follow the convention in the literature modeling supply chain competition by opting for a quantity competition model (Corbett and Karmarkar 2001, Adida et al. 2016, Korpeoglu et al. 2020). While these papers assume a constant cost structure to study market entry and outcomes, our work speaks to the body of literature studying the incentives and outcomes of cost reduction R&D.

Cho (2014) considers possible cost reduction created by operational synergies from horizontal mergers in a multi-tier supply chain with Cournot quantity competition in each tier. Cost reduction in our model differs as it is a result of the R&D effort exerted by firms in the supply chains. Bernstein and Kök (2009) have studied the suppliers' cost reduction R&D in a setting with a single buyer purchasing from multiple (possibly competing) suppliers. A properly calibrated target-price contract, in which the rate of decrease of purchase price is pre-specified, induces higher R&D investment by the supplier, yet still below socially optimal levels. The current practice at some car manufacturers to subsidize and support supplier R&D is shown to reduce or even eliminate inefficiency. Complementing these results, Krishnan et al. (2019) finds that for R&D reducing the manufacturer production cost, it is preferable for the supplier to be the investment anchor—however, it may lead to underinvestment in R&D and may not be the manufacturer's preferred choice. Other work investigates how the firms in the supply chain can collaborate on R&D. Ge et al. (2014) simplify the supply chain structure to a single supplier and buyer, but allow cost reduction R&D to take place in both firms, either separately or collaboratively in the presence of spillover effects. They show that the firms' profits are always highest under collaboration, and that there are always exists a path to reach a win-win solution regardless of the firms' initial characteristics. Hu et al. (2019) investigate whether a supplier and a manufacturer should invest independently or collaboratively in R&D to reduce manufacturer cost. They show that the optimal configuration depends on the relative cost factors of the firms, and that the firms prefer to collaborate if their cost factors are similar enough, even though collaboration is always preferable from a social welfare perspective. We add to the above papers by studying *competing* supply chains investing in *stochastic* R&D.

Some papers in operations management consider competition between supply chains. Plambeck and Taylor (2005) compares innovation in competing vertically integrated supply chains and decentralized supply chains with a contract manufacturer. They find that while the use of a contract manufacturer improves manufacturing efficiency through pooling, the level of innovation is below optimal. If manufacturers collaborate directly with each other on manufacturing, however, innovation levels can either be larger or smaller than optimal. Similar to our setting, Ha et al. (2011) study a model with two competing supply chains each consisting of one manufacturer and one retailer engaging in Cournot or Bertrand competition in the market. The production costs in the model exhibit diseconomies of scale, but cannot be reduced by R&D effort. While they consider possible collaboration between the competing supply chains in terms of information sharing, we consider possible collaboration between the supply chains in cost reduction R&D effort. Both Ishii (2004) and Bernstein and Kök (2009) model supply chain networks, with suppliers selling to multiple manufacturers or manufacturers buying from multiple suppliers. Competition increases the significance of spillover effects, which tend to increase R&D investment levels. However, these papers also do not allow for stochastic R&D outcomes. None of the papers above discuss how different R&D investment structures—competition or vertical or horizontal collaboration—arise in the industry.

3. Model

We consider a product market with two competing supply chains. Each supply chain consists of one manufacturer (she) and one supplier (he) who only buys from or sells to each other exclusively. All firms are risk neutral profit-maximizers. Each final product made by a manufacturer needs one component provided by a supplier. Let $q_i \geq 0$ be the total number of products manufacturer

$i \in \{1,2\}$ decides to sell in the market. The manufacturer i needs to order q_i components from her corresponding supplier $i \in \{1,2\}$. The supplier will charge a wholesale price, w_i for each unit of the component ordered by manufacturer i. Without loss of generality, we normalize the production cost of the component to zero for both suppliers.

The manufacturers are engaged in a Cournot competition in the market. The inverse demand function for manufacturer $i \in \{1,2\}$ is given as $p_i = \theta - q_i - \delta q_j$, $i, j \in \{1,2\}$ and $i \neq j$, where $\delta \in [0,1]$ represents the degree of substitutability between the two products sold by the two manufacturers. At one extreme with $\delta = 1$, the two products are perfect substitutes, and the inverse demand function is the same as the one in a traditional Cournot model. At the other extreme with $\delta = 0$, the two manufacturers' products are perfectly differentiated, and they do not compete at all in the market. Therefore, the parameter δ can be viewed as a measure of the degree of competition between the two supply chains.

The initial unit production cost for the two manufacturers is $\bar{c} > 0$, which is a constant and is symmetric for both manufacturers. Each manufacturer i can invest R&D effort e_i to reduce her initial unit production cost. The manufacturer accordingly incurs a quadratic cost of effort $\alpha e_i^2/2$. Each manufacturer i's final realized unit production cost is given by $c_i = \bar{c} - e_i + u_i$, where u_i is a random variable to capture the uncertain nature of R&D. We assume that $u_i \sim N(0, \sigma)$ and is independent between the two manufacturers. Once the R&D efforts are exerted, each manufacturer only observes her own realized cost, but not the realized cost of the other manufacturer. In other words, the realized cost of a manufacturer is private information of the manufacturer and her supplier. All other information is common knowledge.

To ensure the manufacturers' equilibrium R&D efforts in all models are positive and lower than the initial unit production cost $\bar{c}$, we impose a technical assumption that $\alpha \geq \max\{\frac{4[\bar{c}^2(4+\delta)+\theta\bar{c}(16-\delta^2)-5\theta^2(4-\delta)]}{\bar{c}(4-\delta)(4+\delta)^2(\theta\delta-4(\theta-\bar{c}))}, \frac{4(6+\delta)}{(4-\delta)^2(4+\delta)}\}$.

3.1. The Benchmark Model with Independent R&D

We first consider a benchmark model where the manufacturers conduct their cost reduction R&D independently. The sequence of events of the benchmark model is shown in Figure 1.

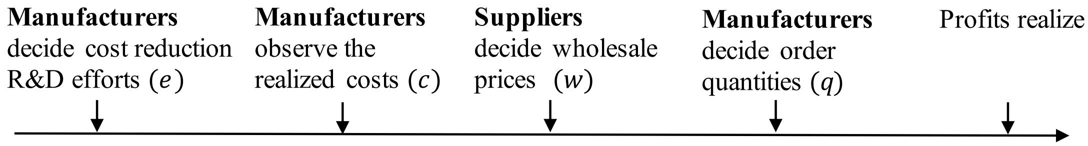

Figure 1 Sequence of Events of the Benchmark Model

In the first stage, the manufacturers decide their R&D efforts. Then, each manufacturer along with her supplier observes her realized unit production cost. In the second stage, each supplier sets the unit wholesale price to his manufacturer. In the third stage, the manufacturers decide their order quantities, and their profits will realize after the quantities are produced and sold in the market.

We now formulate the game and solve for the symmetric equilibrium by standard backward induction, starting from the manufacturers' optimal ordering quantities, followed by the supplier's wholesale price decision, and finally solve for the optimal research effort by each manufacturer.

In the third stage, the manufacturer i chooses her optimal quantity q_i given her own realized unit production cost c_i, and the rational expectation of her competitor's unit cost and quantity. The manufacturer i's ($i \in \{1,2\}$) expected profit can be written as:

$$\begin{aligned}\max_{q_i \geq 0} \Omega_i\,(c_i) &= (\mathrm{E}(p_i) - w_i - c_i)q_i \\ &= (\theta - q_i - \delta\,\mathrm{E}(q_j) - w_i - c_i)q_i,\end{aligned}$$

where $j \in \{1,2\}$ and $i \neq j$, and $\mathrm{E}(q_j)$ is the expected quantity of the other manufacturer. Note that without knowing her competitor's realized unit production cost, a manufacturer does not know the actual market price for her products. She can only use the expected market price for her products, based on her own quantity and the rational expectation of the quantity of her competitor. Consequently, we cannot apply a Cournot duopoly model which assumes perfect information. In the presence of imperfect information, the focal manufacturer's production quantity must consider the other manufacturer's expected quantity, which in turn is based on an expectation of the focal manufacturer's quantity, thus creating an infinite chain of expectations. Fried (1984) shows that this infinite series converges to an equilibrium and we use his technique to solve the models in this paper (see details in Appendix A). We present the manufacturer's optimal ordering quantity in the following Lemma.

LEMMA 1. *Conditional on her realized unit production cost c_i, and the expected quantity of her competitor $E(q_j)$, manufacturer i's optimal order quantity is*

$$q_i^*\,(c_i) = \frac{\theta - \delta\,\mathrm{E}(q_j) - w_i - c_i}{2}. \tag{1}$$

Proof: All proofs are in the Appendix.

We can see that the optimal ordering quantity increases in the market potential θ, and decreases in the competitor's expected quantity $\mathrm{E}(q_j)$, the wholesale price w_i, and the realized unit production cost c_i.

In the second stage, supplier i chooses the wholesale price w_i that will maximize his profit, based on the manufacturer's realized cost c_i, and anticipating the manufacturer's ordering quantity. We can write the supplier's profit maximizing problem as:

$$\max_{w_i \geq 0} S_i^*(w_i|c_i) = w_i q_i^*\,(c_i)\,,$$

The supplier's profit is the product of the wholesale price and his manufacturer's optimal order quantity conditional on the realized unit production cost as given in Lemma 1. The optimal wholesale price is defined in the following Lemma.

LEMMA 2. *Conditional on the realized unit production cost c_i for his manufacturer, the supplier i's optimal whole sale price is*

$$w_i(c_i) = \frac{\theta - \delta\,\mathrm{E}(q_j) - c_i}{2}. \tag{2}$$

The supplier i's optimal wholesale price increases in the market potential θ, and decreases in his manufacturer's realized unit production cost c_i and the competing manufacturer's expected quantity $\mathrm{E}(q_j)$.

In the first stage, each manufacturer i chooses a R&D effort e_i to maximize her expected profit:

$$\max_{0\le e_i\le \bar{c}} \Omega_i\,(e_i) = \mathrm{E}[(\theta - q_i(c_i) - \delta\,\mathrm{E}(q_j) - w_i(c_i) - c_i)q_i(c_i)] - \alpha e_i^2/2,$$

where the first expectation is taken on the random variable c_i. We derive the symmetric equilibrium of the benchmark model in the Appendix A, and present the expected equilibrium profits of the firms in the following proposition.

PROPOSITION 1. *There exists a unique symmetric Nash equilibrium in the benchmark model with independent R&D, and the expected profits for the manufacturers and the suppliers are, respectively,*

$$\Omega^N = \frac{\alpha(\theta-\bar{c})^2(\alpha(16-\delta^2)^2 - 32)}{(\alpha(4-\delta)(4+\delta)^2 - 8)^2} + \frac{\sigma^2}{16},$$

and

$$S^N = \frac{2(\theta-\bar{c})^2\alpha^2(16-\delta^2)^2}{(\alpha(4-\delta)(4+\delta)^2 - 8)^2} + \frac{\sigma^2}{8}.$$

It is worth noting that all firms' expected profits increase in the uncertainty of the cost reduction R&D, σ. This is because the realized profits are quadratic in the realized costs: while a worse-than-average cost reduction outcome reduces profit only slightly, a better-than-average cost reduction increases profit significantly. Hence, the uncertainty of the cost reduction R&D is actually beneficial to the firms as well as the supply chains in the benchmark model. We use Π^N to denote the equilibrium expected profit of the supply chain, which is simply the sum of the equilibrium expected profits of the manufacturer and the supplier in the supply chain, i.e., $\Pi^N = \Omega^N + S^N$.

4. Exogenous R&D Consortia

R&D is costly and uncertain. Firms often form various R&D consortia to jointly conduct R&D and share the costs as well as the outcomes of R&D. We will consider two types of R&D consortia: horizontal consortium and vertical consortium. In a horizontal consortium, the two manufacturers together form the consortium, whereas in a vertical consortium, a manufacturer forms the consortium with her own supplier. For either type of R&D consortium, the two manufacturers still compete in selling their products in the market.

In this section, we first consider the cases where a particular type of R&D consortium is exogenously given in the market. We then extend the models to study what type of R&D consortium will emerge endogenously in the market in the next section.

4.1. The Horizontal Consortium

The horizontal consortium is formed by the two manufacturers to conduct the cost reduction R&D jointly. The sequence of events of the horizontal consortium is shown in Figure 2. In the first stage, the consortium decides a cost reduction R&D effort, e, to maximize the joint expected profits of the consortium members, i.e., the two manufacturers in this case. The resulting effort cost $\alpha e^2/2$ is split equally between the two manufacturers, that is, each manufacturer pays $\alpha e^2/4$. In the second stage, after the consortium exerts the effort e, the realized unit production cost is given by $c = \bar{c} - e + u$, where $u \sim N(0, \sigma)$. Both manufacturers will share the same realized unit production cost, c. As a result, the realized unit production cost becomes common information in both supply chains. Then, in the subsequent stages 3 and 4, the suppliers decide wholesale prices, and the manufacturers decide order quantities to compete in the market similar to what they do in the benchmark model.

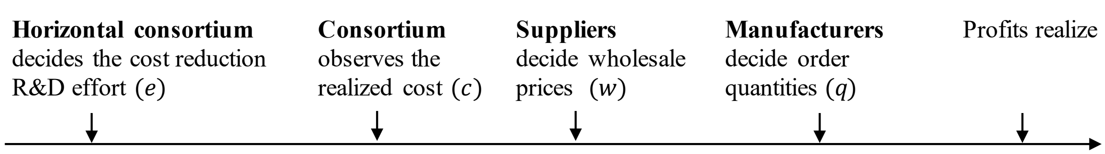

Figure 2 Sequence of Events of the Horizontal Consortium

It is useful to summarize the differences between the horizontal consortium and the benchmark model without a consortium. First, the R&D effort is exerted in a centralized way in the horizontal consortium which eliminates R&D competition for the manufacturers. Second, the horizontal consortium could create cost savings for the manufacturers as they share the R&D effort cost equally rather than both spending on R&D efforts separately. Third, manufacturers participating in the horizontal consortium will have the same unit production cost whereas they have different unit production costs when they conduct R&D independently. Note that these differences could cascade down the supply chains to influence the suppliers' decisions and payoffs.

We now formulate the game and solve for the symmetric equilibrium by backward induction for the horizontal consortium. We first analyze the manufacturers' quantity decisions conditional on the realized unit production cost c (which is the same for both manufacturers). Therefore, knowing each other's cost, the manufacturers can also anticipate each other's order quantity accordingly and they solve a standard common information Cournot model in the last stage. Replacing $\mathrm{E}(q_j)$ in equation (1) in Lemma 1 with q_j, each manufacturer i's optimal order quantity $q_i(c)$ is given as

$$q_i\left(c\right) = \frac{\theta - \delta q_j - w_i - c}{2}. \tag{3}$$

Given manufacturer i's order quantity above, we can obtain supplier i's optimal wholesale price by replacing $\mathrm{E}(q_j)$ in equation (2) in Lemma 2 with q_j:

$$w_i(c) = \frac{\theta - \delta q_j - c}{2}. \tag{4}$$

We can solve the symmetric equilibrium quantity and wholesale price in the stages 3 and 4 conditional on the realized unit production cost c as

$$q^*(c) = \frac{\theta - c}{4+\delta}, \tag{5}$$

and

$$w^*(c) = \frac{2(\theta - c)}{4+\delta}. \tag{6}$$

In the first stage, the consortium decides the optimal R&D effort e to maximize the joint expected profits of the two manufacturers. The consortium's problem is

$$\max_{0\leq e\leq \overline{c}} \Psi\left(e\right) = 2\,\mathrm{E}[(\theta - q^*(c) - \delta q^*(c) - w^*(c) - c)q^*(c)] - \alpha e^2/2,$$

where the expectation is taken on the random variable c. The first term is the total expected profit of the two manufacturers. Note that as they share the total R&D effort cost equally and have the same unit production cost regardless of the realization of c, the two manufacturers will receive symmetric expected profits. Thus, the consortium's problem above is equivalent to maximizing the individual manufacturer's expected profit. We solve for the optimal effort level, and substitute it into the expressions of the equilibrium order quantity and wholesale price in equations (5) and (6) to get the equilibrium. The details are shown in the Appendix A, and the following proposition presents the expected equilibrium profits for the firms. We use superscript "H" to denote the equilibrium of the horizontal consortium model.

Proposition 2. *There exists a unique symmetric Nash equilibrium in the Horizontal Consortium model, and the expected equilibrium profits for the manufacturers and suppliers are, respectively,*

$$\Omega^H = \frac{\alpha(\theta-\bar{c})^2}{\alpha(\delta+4)^2-4} + \frac{\sigma^2}{(4+\delta)^2},$$

and

$$S^H = 2\left[\frac{\alpha(4+\delta)(\theta-\bar{c})}{\alpha(4+\delta)^2-4}\right]^2 + \frac{2\sigma^2}{(4+\delta)^2}.$$

It is interesting to note that the positive contribution to the expected profits from the uncertainty of the cost reduction R&D effort, σ, is lower under a horizontal consortium *if* there is some degree of competition between the two manufacturers' products (or $\delta > 0$). This is due to the fact that under a horizontal consortium, the two manufacturers share the same realized unit production cost—this eliminates the possibility of a manufacturer with a better cost realization from her independent R&D gaining a cost advantage over her competitor. We can see that the reduction in contribution to the expected profits from σ becomes more severe as the manufacturers' products become more substitutable or competitive to each other (i.e., δ becomes higher). Proposition 3 compares the horizontal consortium with the benchmark model.

Proposition 3. *Compared to the benchmark model with independent R&D, the horizontal consortium (i) exerts higher cost reduction R&D effort, $e^H > e^N$, and results in higher actual R&D effort cost for each manufacturer than independent R&D does; (ii) leads to higher expected order quantity and wholesale price, $\mathrm{E}[q^H] > \mathrm{E}[q^N]$ and $\mathrm{E}[w^H] > \mathrm{E}[w^N]$; (iii) however, does not necessarily earn higher expected profits for the manufacturers, the suppliers and the supply chains.*

As mentioned before, the horizontal consortium conducts R&D in a centralized way and shares the cost of effort between the two manufacturers. Consequently, part (i) of Proposition 3 shows that the horizontal consortium is willing to exert higher R&D effort than an individual manufacturer would exert in the benchmark model. Interestingly, although only bearing half of the resulting R&D cost, the equilibrium R&D effort cost paid by a manufacturer in the horizontal consortium is actually higher than her equilibrium R&D effort cost under independent R&D in the benchmark model. In other words, joining the horizontal consortium makes each manufacturer spend more on R&D. Recall that the cost function of R&D effort is quadratic in effort, which increases quickly as effort becomes higher. This would discourage a manufacturer to exert higher effort under independent R&D. When pooling resources together in the horizontal consortium, it creates some kind of economies of scale in the presence of the quadratic cost to exert higher effort by effectively cutting the marginal cost of effort in half. Therefore, this reveals that the main purpose for the manufacturers to potentially form a horizontal consortium is *not* to save R&D effort cost, but to take the advantage of the centralized R&D for higher R&D effort.

Higher R&D effort then leads to a lower expected unit production cost for both manufacturers as compared to the cost under the benchmark model. The lower unit production cost for the manufacturers enables the suppliers to set higher wholesale prices according to part (ii) of Proposition 3. In other words, part of the gains from the lower cost due to the higher R&D effort will be captured by the suppliers. The comparison between the equilibrium quantity is not straightforward. Lower unit product cost from higher R&D effort would increase the manufacturers' quantities in the horizontal consortium. In addition, the reduced cost differentiation or increased competitiveness between the two manufacturers as they share the same unit production cost would also tend to increase the quantities. However, higher wholesale prices would reduce the manufacturers' quantities. Part (ii) shows that the net effect is that the equilibrium quantity would be higher under the horizontal consortium than in the benchmark model.

Part (iii) indicates that the manufacturers, the suppliers, as well as the supply chains do not necessarily earn higher expected profits with the horizontal consortium as compared to the benchmark with independent R&D. The manufacturers may not earn higher expected profits under the horizontal consortium because they face a trade-off: The horizontal consortium benefits them with a lower unit product cost (although part of this benefit is captured by the suppliers), but hurts them by eliminating the potential cost differentiation as we discussed before. For the suppliers, the horizontal consortium benefits them with higher wholesale prices as well as higher quantities. Intuitively, the expected profits for the suppliers should be higher as we normalized their own product costs to zero. Nevertheless, the drawback of the absence of cost differentiation between the manufacturers in the horizontal consortium could eventually cascade down the supply chains to potentially hurt the suppliers, thereby the supply chains.

Proposition 4. *(i) The manufacturer and the supplier, thereby the supply chains, all prefer the horizontal consortium to indepedent R&D when R&D uncertainty σ, product substitutability δ, cost coefficient of effort α and the initial unit production cost $\overline{c}$ are low, and the market potential θ is high; (ii) When the manufacturers prefer the horizontal consortium to independent R&D, both the suppliers and the supply chains always prefer the horizontal consortium as well. However, the opposite is not true.*

Part (i) of Proposition 4 specifies when the manufacturers, the suppliers, and the supply chains are likely to earn higher expected profits with the horizontal consortium, thereby preferring it to the benchmark with independent R&D. First, as we have discussed above, one drawback of the horizontal consortium is that it eliminates the possibility of cost differentiation between the two manufacturers. Therefore, the horizontal consortium would be more attractive under scenarios where this drawback is weaker. This happens when R&D uncertainty σ is low which implies that the possibility of cost differentiation is small in the first place, and/or the products are less substitutable (i.e., low δ) which implies that the products do not compete directly making cost differentiation irrelevant.

Second, one important benefit of the horizontal consortium is that it exerts higher equilibrium R&D effort than independent R&D. Hence, the horizontal consortium would be more attractive when this benefit is higher, i.e., when the difference between its equilibrium R&D effort and the one under independent R&D is larger. Surprisingly, the difference is larger when the R&D effort is cheaper, i.e., when α is lower, as we can show that $e^H - e^N$ is decreasing in α. For excessively high R&D effort cost, the horizontal consortium mostly yields an R&D cost sharing benefit, with only a limited boost to the manufacturing cost reduction over independent R&D. For a small R&D effort cost, however, the potential manufacturing cost reduction benefit is so great that manufacturers choose an R&D effort level resulting in a higher individual R&D cost *after* sharing. Consequently, the horizontal consortium is more attractive as R&D effort becomes cheaper to exert.

Third, a lower initial unit production cost makes the horizontal consortium more attractive. The supply chain profits are convex in the profit margin. Therefore, the increase in the profit margin from the higher R&D effort by the horizontal consortium yields a greater benefit the larger the initial product margin, i.e., the lower the initial unit production cost. Similarly, a market with larger potential (i.e., a higher θ) will also favor the horizontal consortium.

We illustrate part (i) of Proposition 4 in Figure 3, showing different stakeholders' preference between the horizontal consortium and independent R&D with no consortium for different combinations of relevant parameters. The first row of figures show the preferences in the α-σ space, while the second row of figures show the preference in the θ-δ space.

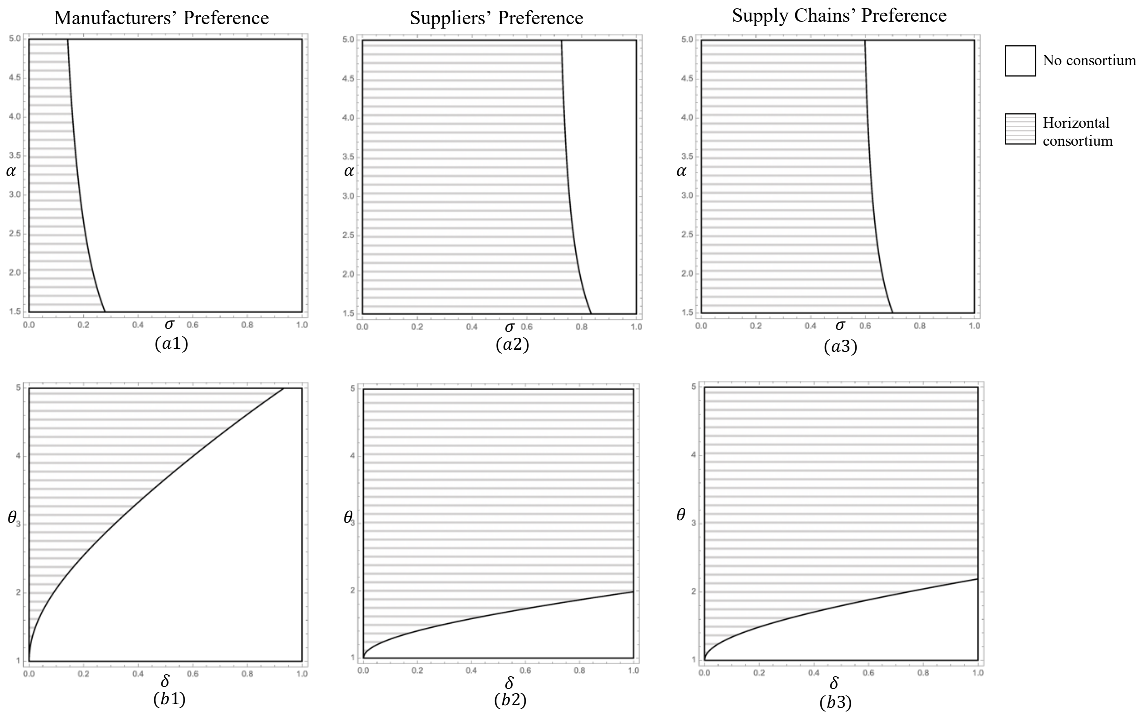

Figure 3 Preferences of the manufacturers, suppliers, and supply chains: horizontal consortium vs. no consortium ((a) $\bar{c}=1, \theta=1.5$, $\delta=0.5$, **(b)** $\sigma=1, \alpha=3, \bar{c}=1$ **)**

Interestingly, part (ii) of Proposition 4 indicates that among all the stakeholders in the supply chains, the suppliers are most likely to prefer the horizontal consortium to independent R&D with no consortium, despite not being members of the horizontal consortium. This also can be seen in Figure 3 where the shaded areas for which the suppliers prefer the horizontal consortium are all larger than their counterparts for the manufacturers and the supply chains. This is because the suppliers enjoy the indirect benefits of the horizontal consortium for free: the higher R&D effort leads to lower manufacturer unit production cost—which allows them to increase their wholesale prices while simultaneously getting higher order quantities from their manufacturers—without having to bear any R&D cost. In contrast, the manufacturers' trade-off is obviously much less clear cut. This comparison allows us to see that the interests of the different supply chain parties are subtle and not necessarily aligned perfectly.

4.2. The Vertical Consortium

A vertical consortium is formed by a manufacturer and her supplier in the supply chain. Note that the two members in the vertical consortium are vertical partners in the supply chain. Therefore, there are two separate competing vertical consortia in our model, one for each supply chain. In a vertical consortium, the manufacturer will conduct cost reduction R&D, while the supplier agrees to share part of the manufacturer's R&D effort cost.

The sequence of events of the vertical consortium model is illustrated in Figure 4. In the first stage, each supplier i offers his manufacturer i a cost share $\gamma_i \in [0,1]$, the percentage of the R&D effort cost the supplier is willing to share. In the second stage, the manufacturer then decides on the R&D effort to maximize her expected profit, while the supplier covers γ_i percent of the R&D effort cost. After observing the realized unit product cost in the third stage, each supplier sets their wholesale price in the fourth stage, after which in the fifth stage, each manufacturer makes their order quantity decision to compete in the market.

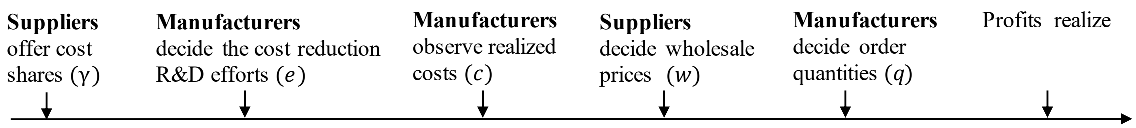

Figure 4 **Sequence of Events of the Vertical Consortium**

We now solve the game for the vertical consortium model using backward induction. First, note that conditional on the realization of the unit production cost, c_i, the manufacturer's order quantity problem and the supplier's wholesale price problem are identical to the problems under the benchmark model. Therefore, both Lemma 1 and Lemma 2 apply under the vertical consortium. Let $w_i^*(c_i)$ and $q_i^*(c_i)$ be the optimal order quantity and the wholesale price, respectively.

In the second stage, the manufacturers decide on their R&D effort to maximize their expected profits. Given the cost shares offered by the two suppliers, γ_i and γ_j, the manufacturer i's problem can be written as

$$\max_{0\le e_i \le \bar{c}} \Omega_i\left(e_i|\gamma_i,\gamma_j\right) = \mathrm{E}[(\theta - q_i(c_i) - \delta\,\mathrm{E}(q_j) - w_i(c_i) - c_i)q_i(c_i)] - (1-\gamma_i)\alpha e_i^2/2,$$

where $i,j \in \{1,2\}$ and $i \neq j$, and the first expectation is taken on the random variable c_i. Let $e_i^*(\gamma_i,\gamma_j)$ be the solution of the above optimization problem.

At stage 1, the supplier i decides cost share γ_i to maximize its expected profit as

$$\max_{0\le\gamma_i\le\bar{\bar{\gamma}}} S_i^*(\gamma_i) = \mathrm{E}[w_i^*(c_i)q_i^*\left(c_i\right)] - \gamma_i\alpha e_i^2(\gamma_i,\gamma_j)/2,$$

where $\bar{\bar{\gamma}} = 1 - \frac{32}{\alpha(16-\delta^2)^2}$, and the expectation is taken on the random variable c_i. The upper bound $\bar{\bar{\gamma}}$ is to ensure that the manufacturer's subsequent effort problem is well-defined.

We characterize the unique symmetric Nash equilibrium for the vertical consortium in Appendix A, and the following proposition shows the expected equilibrium profits for the firms. Define $B = \sqrt{(16-\delta^2)(16(36-\delta^2)+\alpha^2(16-\delta^2)^3 - 8\alpha(384-8\delta^2-\delta^4))}$. We use superscript "$V$" to denote the equilibrium of the vertical consortium model.

Proposition 5. *There exists a unique symmetric Nash equilibrium in the vertical consortium model in which the suppliers offer the cost share*

$$\gamma^V = \frac{4}{5} - \frac{4}{5\alpha(16-\delta^2)} - \frac{B}{5\alpha(16-\delta^2)^2}, \tag{7}$$

and the expected equilibrium profits for the manufacturers and the suppliers are

$$\Omega^V = \frac{(\theta-\bar{c})^2\alpha(1-\gamma^V)[\alpha(16-\delta^2)^2(1-\gamma^V)-32]}{[\alpha(4-\delta)(4+\delta)^2(1-\gamma^V)-8]^2} + \frac{\sigma^2}{16},$$

and

$$S^V = \frac{(\theta-\bar{c})^2 2\alpha[\alpha(16-\delta^2)^2(1-\gamma^V)^2-16\gamma^V]}{[\alpha(4-\delta)(4+\delta)^2(1-\gamma^V)-8]^2} + \frac{\sigma^2}{8},$$

respectively.

It is worth noting that unlike in the horizontal consortium, the contribution of the uncertainty of the cost reduction R&D effort, σ, to the expected profits in the vertical consortia stays the same as in the benchmark model because the manufacturers are still conducting their R&D separately from each other in the vertical consortia. As a result, the vertical consortia preserve the possibility of having different realized unit production costs for the manufacturers.

We next discuss some properties of the equilibrium cost share γ^V offered by the suppliers.

Corollary 1. *The equilibrium cost share γ^V offered by the suppliers in their vertical consortia is always higher than 50% (i.e., $\gamma^V > 1/2$), increasing in the product substitutability δ, and decreasing in the effort cost coefficient α.*

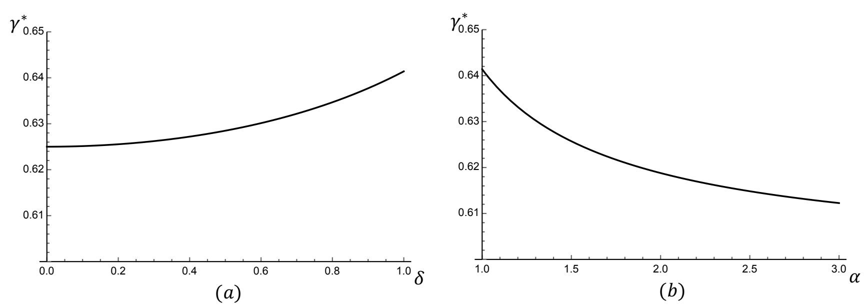

Figure 5 The equilibrium cost share γ^V as a function of δ and α ($\alpha=1$ for (a), $\delta=1$ for (b))

Surprisingly, the suppliers are always willing to share more than half of the R&D effort costs with their manufacturers in their vertical consortia even though the R&D effort is to reduce the manufacturers' unit production costs. This indicates that in the vertical consortia, the suppliers have strong incentives to support their manufacturers to exert higher effort to reduce their unit production costs to remain competitive in the market. As a result, a manufacturer's share of the R&D effort cost in a vertical consortium is actually less than her share in a horizontal consortium where she shares half of the effort cost. The suppliers are willing to share more of the R&D effort costs when the products are more competitive in the market, as remaining competitive in cost becomes more critical, and when the R&D effort is cheaper, which makes cost sharing less expensive.

The following proposition compares the vertical consortium with the benchmark model.

PROPOSITION 6. *As compared to the benchmark model with independent R&D, the vertical consortia always (i) exert higher cost reduction effort, $e^V > e^N$, and result in higher actual R&D effort cost for each manufacturer than independent R&D does; (ii) lead to higher expected order quantity and wholesale price $E[q^V] > E[q^N]$ and $E[w^V] > E[w^N]$; (iii) earn higher expected profits for the manufacturers, the suppliers, and the supply chains, $\Omega^V > \Omega^N$, $S^V > S^N$, and $\Pi^V > \Pi^N$.*

According to parts (i) and (ii) of Proposition 6, the comparisons between the vertical consortia and the benchmark model on the equilibrium R&D effort, expected quantity and wholesale price are similar to the ones between the horizontal consortium and the benchmark model in Proposition 3. However, some of the drivers behind these comparisons are quite different. First, as we discussed in Corollary 1, the suppliers share the R&D effort cost aggressively in the vertical consortia which certainly would incentivize higher R&D effort everything else equal. Second, it is well-known that decentralized supply chains suffer from inefficiencies such as double marginalization. A vertical consortium allows the members in a decentralized supply chain to collaborate on R&D decisions to a certain degree which partially helps to make the supply chain more efficient. In some sense, the vertical consortia provide the supply chains with a coordination mechanism that increases the equilibrium R&D effort as well as the equilibrium quantity. The suppliers anticipate that the lower expected unit production costs due to higher R&D effort will allow them to increase their wholesale prices while still receiving higher manufacturers' order quantities. This is why the suppliers are willing to share cost so aggressively in the vertical consortia. Similar to the horizontal consortium, the increase in R&D effort is so pronounced that a manufacturer's share of the total R&D cost in the vertical consortium is actually higher than her R&D cost with independent R&D.

Part (iii) of Proposition 6 shows that unlike the horizontal consortium, the vertical consortia create a win-win situation to all supply chain members as well as the supply chains as a whole. This is also a result of the coordination nature of the vertical consortia we discussed above. Everyone earns higher expected profit in a more coordinated supply chain in a vertical consortium than in a completely decentralized supply chain in the benchmark model with independent R&D. Therefore, all supply chain parties always prefer the vertical consortium to the benchmark model with independent R&D.

4.3. The Horizontal Consortium vs. The Vertical Consortium

We have compared each of the two types of consortia with the benchmark model with independent R&D separately. We now compare the horizontal consortium with the vertical consortium to highlight their differences.

PROPOSITION 7. *(i) The equilibrium R&D effort, quantity, and wholesale price are all higher in the vertical consortia than those in the horizontal consortium,* $e^V > e^H$*,* $q^V > q^H$*, and* $w^V > w^H$*; (ii) The equilibrium expected profit for the manufacturers is always higher under the vertical consortium than under the horizontal consortium,* $\Omega^V > \Omega^H$*. However, this is not necessarily true for the suppliers and the supply chains.*

The vertical consortia exert higher equilibrium R&D effort, and lead to higher equilibrium quantity and wholesale price than the horizontal consortium according to part (i) of Proposition 7. In addition to R&D cost sharing which is common in both types of consortia, the vertical consortium has an unique benefit: coordinating the supply chains to certain degree. This additional benefit results in higher equilibrium R&D effort, thereby lower expected unit production cost, in the vertical consortia than in the horizontal consortia. With lower expected unit production costs, the manufacturers will increase their quantities and the suppliers will increase their wholesale prices in the vertical consortia accordingly.

Part (ii) of Proposition 7 indicates that from a manufacturer's perspective, collaborating with her supplier in the vertical consortium is always better than collaborating with her competing manufacturer in the horizontal consortium. Collaborating with the supplier in the vertical consortium coordinates the supply chain and maintains the possibility of gaining a cost advantage over the competing manufacturer. Collaborating with the competing manufacturer would not offer these benefits. Therefore, between the two types of consortium, the vertical consortium is the dominant choice for the manufacturers. However, the equilibrium expected profits for the suppliers and the supply chains are not necessarily always higher under the vertical consortium due to the fact that the suppliers have to share more than half of the R&D costs that are furthermore incurred twice—once in each supply chain—which could offset the suppliers' and supply chains' benefits of the vertical consortium.

5. Endogenous R&D Consortia

Studying the exogenously given R&D consortia in the previous section allows us to understand the fundamental differences among the independent R&D, the horizontal consortium and the vertical consortium. Building on this knowledge, in this section, we will analyze what R&D consortium would emerge endogenously in the industry in equilibrium. Let superscript "o" denote the equilibrium solutions for the endogenous consortium game.

The sequence of events of the endogenous consortium game is illustrated in Figure 6. In the first stage, the suppliers offer their cost shares, $\gamma_i \in [0,1]$, $i \in \{1,2\}$ to their manufacturers. In the second stage, receiving the suppliers' offers, manufacturers will decide how to conduct their R&D, i.e., independently, in a horizontal consortium or in a vertical consortium. First, each manufacturer i has to respond to her supplier's offer γ_i by deciding whether to accept the offer or not. If the manufacturer accepts the offer, she will form a vertical consortium with her supplier and will not consider any other form of R&D in the future. If she rejects the offer, then she will choose between independent R&D and the horizontal consortium. However, she has to keep in mind that the horizontal consortium is only possible if the competing manufacturer also rejects her own supplier's offer and is willing to form the horizontal consortium. If any one of the two conditions or both do not hold, the horizontal consortium will not be a viable choice, and the only choice left is to do independent R&D. We use N, H and V to denote a manufacturer's choice of R&D forms, namely independent R&D, horizontal consortium and vertical consortium, respectively.

After the manufacturers decide the forms of their R&D, the subsequent stages of the game are similar to the ones in the exogenous models. Given the forms of the R&D chosen, then the manufacturers exert R&D efforts and observe the realized costs, suppliers decide wholesale prices, manufacturers decide order quantities, and profits are realized.

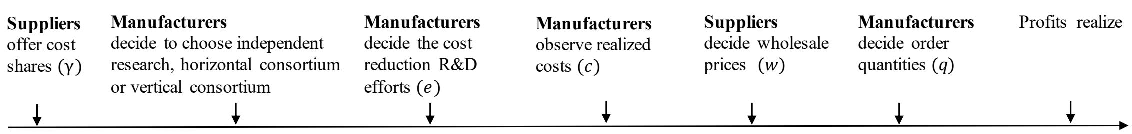

Figure 6 **Sequence of events of the endogenous consortium game**

The manufacturers' choices of the forms of their R&D in stage 2 can result in several possible outcomes. In the first case, both manufacturers reject the offers from the suppliers, and are not willing to form a horizontal consortium either. Therefore, both of them will conduct independent R&D, i.e., their choices are $[N,N]$. In this case, they will play the rest of the game as in the benchmark model. Each will earn the expected profit Ω^N given in Proposition 1.

In the second case, both manufacturers reject the offers from the suppliers, and form a horizontal consortium together, $[H,H]$. In this case, they will play the rest of the game as in the horizontal consortium model. Each will earn the expected profit Ω^H given in Proposition 2.

The third case is that one manufacturer accepts her supplier's offer to form a vertical consortium, while the other manufacturer rejects her supplier's offer. The manufacturer who rejects her supplier's offer can only do independent R&D because the other manufacturer—who accepted her supplier's offer—is not available for a possible horizontal consortium. Therefore, an asymmetric

R&D outcome emerges in the industry with one vertical consortium and one independent R&D, i.e., $[V,N]$ or $[N,V]$. We solve the equilibrium of this asymmetric game in the Appendix, and denote the expected equilibrium profits of the two manufacturers as $\Omega_i^*[V,N]$ or $\Omega_i^*[N,V]$, for $i \in \{1,2\}$.

The fourth case is that both manufacturers accept the offers, $\{\gamma_i, \gamma_j\}$, $i,j \in \{1,2\}$ and $i \neq j$. Two vertical consortia emerge in the industry, i.e., $[V,V]$. In this case, they will play the rest of the game as in the vertical consortium model. We solve the game conditional on the suppliers' offers $\{\gamma_i, \gamma_j\}$ in the Appendix, and denote expected equilibrium profits for the manufacturers as $\Omega_{Vi}^*(\gamma_i,\gamma_j)$ and $\Omega_{Vj}^*(\gamma_i,\gamma_j)$, respectively.

Note that the asymmetric outcomes like $[H,N]$ or $[N,H]$ and $[V,H]$ or $[H,V]$ are not possible because once a manufacturer chooses either V or N, she is no longer available, and H is not a viable choice for the other manufacturer anymore.

5.1. The Manufacturers' Strategies

The following proposition characterizes the equilibrium choices for the manufacturers given the suppliers' offers $\{\gamma_i, \gamma_j\}$. The equilibrium is illustrated in Figure 7.

PROPOSITION 8. *Given the suppliers' offers* $\{\gamma_i, \gamma_j\} \in [0,1]$, $i,j \in \{1,2\}$ *and* $i \neq j$, *for the manufacturers, (i) both accepting the offers to form two vertical consortia,* $[V,V]$ *is always an equilibrium; (ii) there exists a threshold* $\overline{\gamma} \in [0, \gamma^V)$ *such that if* $\gamma_i < \overline{\gamma}$ *and* $\gamma_j < \overline{\gamma}$, *both rejecting the offers and forming a horizontal consortium together,* $[H,H]$ *is also an equilibrium under which the manufacturers always earn higher expected profits than under the equilibrium* $[V,V]$*; (iii) any other cases such as* $[N,N]$, $[N,V]$, *or* $[V,N]$ *never can be an equilibrium.*

There can be multiple equilibria for the manufacturers depending on the suppliers' offers. For any given offers, part (i) of Proposition 8 shows that both manufacturers accepting the suppliers' offers to form two vertical consortia, $[V,V]$ is always an equilibrium for the manufacturers. The intuition is as follows. If a manufacturer wants to unilaterally deviate from $[V,V]$, the only choice would be conducting independent R&D, i.e. N, because the other manufacturer is playing V and is not available for a possible horizontal consortium, H. Therefore, this potential deviation will lead to either $[V,N]$ or $[N,V]$ which is certainly worse off than $[V,V]$ for the manufacturer conducting independent R&D. As we discussed before, V is a more coordinated version of N. Conducting independent R&D without any help from one's supplier cost sharing offer—no matter how small—in a decentralized way while competing with a more coordinated supply chain with cost sharing is certainly worse than choosing V as well to compete with V. As a result, no manufacturer would unilaterally deviate from $[V,V]$ which makes $[V,V]$ always an equilibrium strategy for the manufacturers regardless of the cost shares offered by the suppliers.

According to part (ii), if the cost shares offered by both suppliers are below a threshold, both manufacturers rejecting the offers and forming a horizontal consortium together, $[H,H]$, is another equilibrium strategy, in addition to $[V,V]$ Note that if one manufacturer deviates from H, the other manufacturer cannot continue to play H either and has to deviate too. If a manufacturer wants to unilaterally deviate from H to N, the competitor will respond by deviating to V according to what we discussed in part (i). Therefore, deviating to N to compete against V is not beneficial for the manufacturer. If a manufacturer chooses to unilaterally deviate from H to V, the competitor will respond by deviating to V too. They end up with $[V,V]$. However, when the cost shares offered by the suppliers are too low (below the threshold $\overline{\gamma}$), forming vertical consortia with the suppliers are not good deals. In fact, we can show that in this case, the manufacturers' expected profits under $[V,V]$ are always lower than their expected profits under $[H,H]$. As a result, such a unilateral deviation is also not beneficial to the manufacturer. Therefore, $[H,H]$ is an equilibrium for the manufacturers.

Furthermore, because the manufacturers earn higher expected profits under the equilibrium $[H,H]$ than under the equilibrium $[V,V]$, we assume that they will choose $[H,H]$ over $[V,V]$. This seems to contradict part (ii) of Proposition 7 which says that the manufacturers always prefer the exogenous vertical consortium to the exogenous horizontal consortium. However, recall that Proposition 7 applies when the suppliers are offering the equilibrium cost shares γ^V, which is higher than 50%, in the exogenous vertical consortia to the manufacturers, whereas Proposition 8 (ii) considers supplier cost shares $\gamma_i < \overline{\gamma} \leq \gamma^V$.

Part (iii) rules out the possibilities that $[N,N]$, $[N,V]$, or $[V,N]$ can be an equilibrium for the manufacturers. In sum, Proposition 8 indicates that regardless of the cost shares offered by the suppliers, both manufacturers will form a consortium either with each other horizontally or with their own supplier vertically, and will never choose to conduct R&D independently.

5.2. The Suppliers' Strategies and the Equilibrium

At stage 1 of the game, anticipating the manufacturers' strategies in Proposition (8), the suppliers will decide their cost share offers to their manufacturers. The suppliers' equilibrium cost share offers are characterized in the following proposition.

PROPOSITION 9. *There exists a threshold $\widehat{\sigma}$ which is a function of other parameters defined in the Proof. (i) Offering cost shares $\gamma^o = \gamma^V$ is always an equilibrium for the suppliers. (ii) If $\sigma \in [0, \widehat{\sigma})$, offering $\gamma^o = 0$ is an equilibrium under which the suppliers always earn higher expected profits than under the equilibrium $\gamma^o = \gamma^V$. (iii) If $\sigma \in [\widehat{\sigma}, \infty)$, offering cost shares $\gamma^o = \gamma^V$ is the unique equilibrium for the suppliers.*

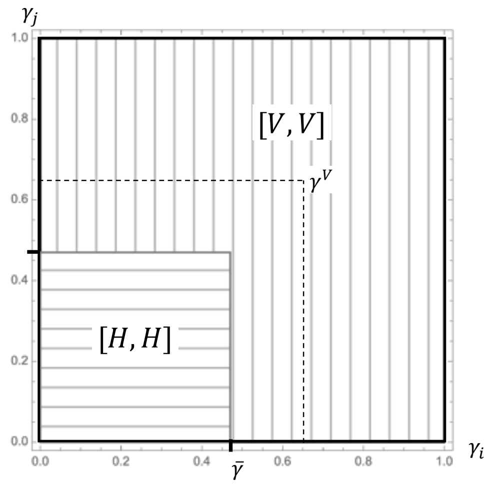

Figure 7 **The Manufacturers' equilibrium choices of R&D forms given the suppliers' offers** $\{\gamma_i, \gamma_j\}$ **(**$\alpha = 3, \delta = 0.7, \sigma = 0.1, \theta = 3, \overline{c} = 1$**)**

First, both offering the equilibrium cost share in the exogenous vertical consortium model, γ^V is always an equilibrium for the suppliers. No supplier would unilaterally deviate from this strategy, because given the other supplier offers γ^V to form a vertical consortium with his manufacturer, any deviation from γ^V would put the supplier at a disadvantage as his supply chain would be part of a suboptimal vertical consortium or no consortium unlike the competing supply chain.

Second, when the uncertainty of R&D is small (i.e., $\sigma < \widehat{\sigma}$), both offering zero cost shares is also an equilibrium strategy for the suppliers. In this case, there are two equilibria for the suppliers, $\gamma^o = 0$ and $\gamma^o = \gamma^V$. However, as part (ii) of Proposition (9) shows, the equilibrium $\gamma^o = 0$ dominates the equilibrium $\gamma^o = \gamma^V$ for the suppliers. Therefore, the suppliers will choose the equilibrium $\gamma^o = 0$. As we discussed before, when σ is small, the horizontal consortium becomes relatively more attractive to the manufacturers as the value of possible cost differentiation would be limited. For the suppliers, free-riding on the horizontal consortium formed by the manufacturers through higher wholesale prices can be a more profitable strategy than offering competitive cost shares to form vertical consortia with their manufacturer.

Combining the manufacturers' and the suppliers' equilibrium strategies, the following proposition summarizes and Figure 8 illustrates the equilibrium forms of R&D emerging endogenously in the supply chains.

PROPOSITION 10. *(i) If $\sigma \in [0, \widehat{\sigma})$, the manufacturers form a horizontal consortium together to conduct R&D, i.e., $[H, H]$ is the equilibrium. (ii) If $\sigma \in [\widehat{\sigma}, \infty)$, the manufacturers will accept the cost share offered by their own suppliers, $\gamma^o = \gamma^V$ and form two vertical consortia to conduct R&D, i.e., $[V, V]$ is the equilibrium.*

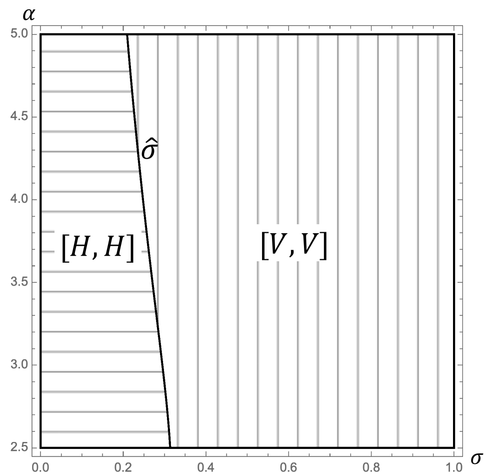

Figure 8 The equilibrium of the endogenous consortium game ($\bar{c} = 1, \theta = 4, \delta = 0.45$)

The equilibrium outcomes in Proposition (10) are illustrated in the $\alpha - \sigma$ space in Figure 8. When the uncertainty of R&D is low, the suppliers will not offer to form vertical consortia. Between the two options left, independent R&D or horizontal consortium, the manufacturers would choose the horizontal consortium. When the uncertainty of R&D is high, conducting R&D separately to enjoy the possible cost advantage over the competitor is more valuable for the supply chains. The suppliers will offer to share significant portions ($\gamma^V > 1/2$) of the R&D costs with their manufacturers, and vertical consortia will emerge. This result implies that in industries with drastic R&D opportunities, vertical collaborations among supply chain members would be more likely to occur, whereas in industries with incremental R&D opportunities, horizontal collaborations among competitors would be more likely to happen.

Interestingly, Figure 8 is structurally similar to the panels (a1)-(a3) in Figure 3 if we replace the blank areas representing the benchmark with no consortium by the vertical consortium. After all, the vertical consortia constitute weakly more coordinated versions of the supply chains in the benchmark with independent R&D. Therefore, the comparisons between them and the horizontal consortium are structurally similar. In fact, the results and their intuitions in part (i) of Proposition 4 about the preferences between the horizontal consortium and the benchmark with no consortium largely carry over here.

However, the boundary lines in these figures do not perfectly overlap. This implies that different parties' preferences and the equilibrium outcomes are not perfectly aligned. In the equilibrium outcomes, some parties could get their best choices among the three possible forms of R&D, while others might not. The following two propositions examine each supply chain party's preferences against the equilibrium outcomes.

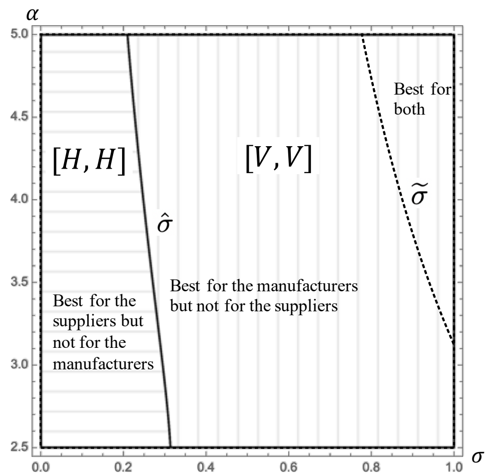

Figure 9 **The equilibrium and the best choices for the suppliers and the manufacturers ($\bar{c}=1, \theta=4, \delta=0.45$)**

Proposition 11. *(i) When $[H,H]$ is the equilibrium, it is the best choice for the suppliers, i.e., $S^o = \max\{S^H, S^V, S^N\}$, but not the best choice for the manufacturers, i.e., $\Omega^o < \max\{\Omega^H, \Omega^V, \Omega^N\}$; (ii) When $[V,V]$ is the equilibrium, there exists a threshold $\widetilde{\sigma} > \widehat{\sigma}$. If $\sigma < \widetilde{\sigma}$, then $[V,V]$ is the best choice for the manufacturers, i.e., $\Omega^o = \max\{\Omega^H, \Omega^V, \Omega^N\}$, but not the best choice for the suppliers, i.e., $S^o < \max\{S^H, S^V, S^N\}$. Otherwise, $[V,V]$ is the best choice for both the manufacturers and the suppliers, i.e., $\Omega^o = \max\{\Omega^H, \Omega^V, \Omega^N\}$ and $S^o = \max\{S^H, S^V, S^N\}$.*

Figure 9 illustrates the results in Proposition 11. Recall that the manufacturers always prefer vertical consortia to the horizontal consortium so that when $[H,H]$ emerges as the equilibrium, the manufacturers do not get their best choice. However, the horizontal consortium is the suppliers' best option and as the first mover of the game, the suppliers do not offer to share R&D costs to force the manufacturers to take their second best option to form the horizontal consortium.

However, it does not mean that the suppliers will always be able to get their best option either. When the uncertainty becomes higher (i.e., $\widehat{\sigma} < \sigma < \widetilde{\sigma}$), although both suppliers continue to prefer the horizontal consortium $[H,H]$, the competition between them would induce them to deviate to $[V,V]$ which is their second best option. In other words, the suppliers suffer from a classic prisoner's dilemma in this case. The manufacturers, however, indirectly benefit from the suppliers' dilemma as they would get their best option $[V,V]$.

Fortunately, there exist parameter values such that both the suppliers and the manufacturers get their best option. When the uncertainty becomes high enough (i.e., $\sigma \geq \widetilde{\sigma}$), the value of conducting R&D separately to achieve a possible cost advantage is high for all supply chain members so that all of them prefer the vertical consortium. The $[V,V]$ equilibrium outcome naturally emerges and everyone gets their best option.

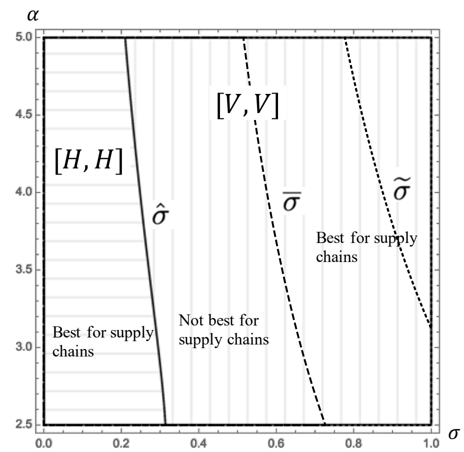

Figure 10 The equilibrium and the best choices for the Supply Chains ($\bar{c}=1, \theta=3, \delta=0.45$)

Proposition 12. *(i) When $[H,H]$ is the equilibrium, it is the best choice for the supply chains, i.e., $\Pi^o = \max\{\Pi^H, \Pi^V, \Pi^N\}$; (ii) When $[V,V]$ is the equilibrium, there exists a threshold $\overline{\sigma} \in (\widehat{\sigma}, \widetilde{\sigma})$. If $\sigma < \overline{\sigma}$, then $[V,V]$ is not the best choice for the supply chains, i.e., $\Pi^o < \max\{\Pi^H, \Pi^V, \Pi^N\}$. Otherwise, $[V,V]$ is the best choice for the supply chains, i.e., $\Pi^o = \max\{\Pi^H, \Pi^V, \Pi^N\}$.*

Proposition 12 compares the supply chains' preferences to the equilibrium outcomes. The results are illustrated in Figure 10. The equilibrium outcomes are consistent with the supply chains' best choice of R&D form when the uncertainty of R&D is either low (i.e., $\sigma \leq \widehat{\sigma}$) or high (i.e., $\sigma \geq \overline{\sigma}$)). When σ is low, the supply chains prefer the horizontal consortium and this is also the equilibrium that emerges in the industry. When σ is high, the supply chains prefer the vertical consortia which emerges as the equilibrium endogenously. However, when the uncertainty of R&D is moderate (i.e., $\widehat{\sigma} \leq \sigma \leq \overline{\sigma}$), the supply chains prefer the horizontal consortium, whereas the equilibrium outcome is vertical consortia.

As Propositions 11 and 12 jointly suggest, when the industry faces highly uncertain or drastic R&D opportunities, all supply chain parties' incentives are well aligned, and vertical consortia would be likely to form naturally. In this case, free market will work things out effectively, and little or no outside intervention or motivation is needed. In contrast, when the industry faces incremental R&D opportunities with low uncertainty, different supply chain parties' incentives are not well aligned, and the dynamics in the industry would be subtle and complex. To achieve stable and efficient outcomes, creative outside intervention, incentive, and motivation might be necessary.

6. Conclusion

We built a model to study the formation of R&D consortia within two competing supply chains consisting of one supplier and one manufacturer each. We investigate the impact of the different consortium choices on R&D effort levels, pricing and quantities, and profits earned by the supply chain partners assuming a wholesale price contract between the supplier and the manufacturer. We incorporate strategic behavior of the partners and set the supplier as the Stackelberg leader.

Our initial analysis of exogenous consortium configurations comparing the benchmark independent R&D case with the horizontal and vertical consortium respectively shows that the interests of the different parties may not always be aligned. In particular, we find that a horizontal consortium may not always be profitable for the manufacturers or the suppliers, whereas a vertical consortium is always beneficial to all the supply chain partners when compared to independent R&D. In all consortia, we observe heightened R&D effort levels, wholesale prices, and ordering quantities. This contrast underlies a first observation: the consortium structure shapes the factors driving the profits. Under a horizontal consortium, the manufacturers share a common marginal production cost, intensifying the competition between the two manufacturers, and indirectly between the two suppliers. This makes a horizontal consortium less attractive when the expected gains of cost differentiation are large, i.e., if the R&D outcome is highly uncertain or the market is more profitable. A vertical consortium, on the other hand, preserves the cost differentiation and allows a measure of coordination within each supply chain, and is therefore always preferred by all supply chain partners over independent R&D.

The observation that the exogenous consortium structures are not equally attractive to all the supply chain partners led us to focus on the study of how the consortium structure emerges in equilibrium. The suppliers act as Stackelberg leaders and choose whether to offer a vertical consortium to their own manufacturer and with what level of cost share. The manufacturers then optimally choose between accepting the vertical consortium offer or not, and whether to pursue independent R&D or engage in a horizontal consortium—assuming both manufacturers have rejected their supplier's offer. We observe that both consortia can emerge in equilibrium despite the manufacturer's preference for a vertical consortium. The consortium in equilibrium is largely determined by the level of competition between the supply chains resulting from the substitutability of the end products or the level of R&D uncertainty. For sufficiently low levels of R&D uncertainty and competition between the manufacturers, the supply chains are not very competitive. The suppliers find it unnecessary to maintain cost differentiation between the supply chains and let a horizontal consortium emerge by not offering a cost share to their manufacturer. Yet for intermediate levels of R&D uncertainty, the manufacturers may benefit from the prisoner's dilemma facing the suppliers: the anticipated competition between the supply chains induces the suppliers to propose a vertical consortium despite their preference for a horizontal consortium to forestall profitable deviation by their competitor. For highly competitive supply chains, the suppliers and the manufacturers are aligned in preferring the vertical consortium, which also emerges in equilibrium.

Our results demonstrate the benefits of allowing R&D consortia to form and exist. Regardless of whether a horizontal or a vertical R&D consortium emerges in equilibrium, consumer welfare increases compared to the case of independent R&D given the greater order quantities placed by the manufacturers, which will result in lower prices in the product market. While benefiting the member firms, R&D consortia also create value for consumers and the society as they stop short of colluding on the product market. Therefore, such consortia should be tolerated or even encouraged by policy-makers.

Note that in our results a consortium will always emerge. This is driven by our abstraction from potential frictions that may arise within consortia which would reduce the incidence of consortia in practice. Such frictions could take the form of administrative overhead costs by participating consortium firms or inefficient usage of resources due to moral hazard issues. However, it is to be noted that while such concerns will reduce the attractiveness of consortia overall, they will affect both types of consortia similarly, such that the drivers identified above—competition between the supply chains as determined by the substitutability of the end products and R&D uncertainty—do not change significantly and most of our qualitative results will continue to hold.

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