Buyer-Induced Supplier Collaboration through Commitment to Low Prices and Diversified Sourcing

Mericcan Usta, Feryal Erhun, Warren Hausman

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(Authors' names blinded for peer review)

How can a powerful buyer in development-intensive industries utilize supplier collaboration? To answer this question, we formulate a stylized game-theoretic model of two suppliers, focal and partner, with varying technological capabilities, where the focal supplier has a greater business power than the partner supplier. We analyze supplier collaboration by studying the trade-off between cost-improvement synergies and uncertain coordination costs, where this trade-off may not only be altered by the buyer's operational decisions, but also by suppliers' power structure and technological capabilities. Our results confirm that supplier collaboration may be preferred by the buyer. To enable such a collaboration, our analysis suggests two strategies for the buyer. Supported by examples from the semiconductor and defense industries, one strategy is a commitment to procure at competitively low prices. Such a price pressures the suppliers financially, persuades them to coordinate and form a consortium to generate profit. The other strategy we propose is a commitment to egalitarian allocations—allocations that favor the partner supplier when suppliers can collaborate, but fail to do so. In the face of coordination cost uncertainty, egalitarian allocations, in combination with the commitment to low prices, can effectively deal with the regret of suppliers and maintain the collaboration. In response to the buyer's strategies, the focal supplier agrees to collaborate with the partner supplier for moderate values of business power and technology leadership. In addition, such collaborations benefit the health of the supplier base particularly because the partner supplier can take part in large development efforts without the necessity to invest in providing a generous allocation of the supply.

Key words: sourcing relationships and strategy, supplier collaboration, research consortia

1. Introduction

In many development-intensive industries, equipment suppliers ("she") play a key role within their industry supply chains (Anderson and Fine 1999). Collective research and development (R&D) and manufacturing capabilities of equipment suppliers can substantially determine the product development capabilities of the supply chain (Utterback and Suarez 1993). Consortia, alliances, and joint research ventures (or Open Research, in Chesbrough's (2003) parlance) are effective ways to address the challenge of meeting technology and cost targets in product development (Hagedoorn et al. 2000). Evidence also suggests that supplier partnerships with strong synergies eventually benefit their respective supply chains (Austin 2000, Lee 2002). In this paper, we study *how* a prominent buyer ("he") in development-intensive industries can utilize such synergies.

High-technology and defense are two particular industries that are development-intensive. Both industries are also consolidated: a few market-dominating, prominent buyers work with a few major suppliers, one or more of which have preferential status (Kempf 2011, Levenson 2014). Moreover, these prominent buyers can usually set product standards through supplier qualification programs (Chaturvedi et al. 2014) and established roadmaps, such as Intel's "tick-tock model" (Intel Corporation 2012) and the DoD's high-technology roadmaps (U.S. DoD 2013), to indicate their sourcing requirements and economic projections over clearly set time frames. The buyer's expectations about the developments of his suppliers typically steeply rise with time as best manifested in the geometric growth prescribed by "Moore's Law" (Moore 1965). Roadmaps in these particular industries have an established legacy over several decades and are well internalized by the supplier base (Kostoff and Schaller 2001, Mowery 2012). In response to the increasingly costly challenge of meeting development goals and the consistently increasing need to economize, suppliers seek alternative avenues such as collaborating with other suppliers.

Indeed, semiconductor and defense industries show a strong trend of increasing collaboration within a spectrum of cohesion ranging from intellectual property exchanges to consortium formation and to merger of equals. Furthermore, more coherent forms of collaboration occur, especially when stakes are higher (Eisenhardt and Schoonhoven 1996), such as during the ongoing transition of the semiconductor industry from a 300 mm to a 450 mm wafer size (Global 450 Consortium (http://www.g450c.org/)) or during the transition of the defense industry from steel to advanced composites (The Composites Consortium (http://cmtc.scra.org/tcc.html)). As the defense and semiconductor industries are reportedly reaching maturity and their talent pools are shrinking (Bauer et al. 2011), and as expectations of the buyers continue to rise, highly coherent collaborations concurrently take place even among the strongest suppliers. Applied Materials (AMAT) and Tokyo Electron (TEL), two of the three largest chip equipment suppliers, declared the reason of their merger of equals initiated in late 2013 as the "need to meet new technological challenges with better solutions quickly at lower cost" (TEL 2013) and "to solve device performance yield and the cost factors our customers are looking for" (AMAT 2013). A proposed defense industry merger of equals between Airbus Group (named EADS at the time) and BAE Systems made headlines in 2012, justified with similar reasons among others, only to be stopped by political forces (Anonymous 2012).

Inspired by the recently increasing trend of collaborative behavior in the semiconductor and the defense industries accompanied with the increasing presence of industry roadmaps and the buyer's ever increasing role in product development strategies (e.g., Sobrero and Roberts (2002). Azadegan et al. (2008) offers a literature review), we demonstrate that the prominent buyer can utilize supplier collaboration in development-intensive industries by setting ambitious cost targets so that the suppliers' combined development efforts can create economic synergies. In particular, such targets enable supplier participation by putting them in a position of having to collaborate or perish. This collaboration may be prone to relationship shocks related to uncertainties about the costs of collaboration. In such a case, we show that an additional commitment to egalitarian project allocations, allocations that favor the less powerful partner supplier, can effectively maintain the collaboration. To substantiate our claims, a thorough, operational analysis of the suppliers' collaboration dynamics is crucial. Therefore, we delineate the impact of the buyer's policy in the trade-off between collaboration synergies and uncertain collaboration costs as a function of the suppliers' business power structure and relative technological capabilities. We then conclude that the two policies can be effectively utilized to benefit a powerful buyer and keep the entire supplier base active in research and production, channeling their efforts to collaborative product development rather than elaborating excessively on their relationship.

The remainder of this paper is organized as follows. We review the relevant literature in §2. We formulate the pricing, allocation, collaboration, and development decisions in §3. We provide the solutions for these decisions in non-trivial parameter settings and present our structural results in §4. We summarize our findings, outline their managerial implications, and further discuss some of our results in §5. All proofs are deferred to appendices.

2. Literature Review

The study of supplier collaborations goes hand in hand with the history of collusions and cartels, which has an extant stream of literature stemming from theory (Tirole 1988) and practice (Grossman 1988). This stream of literature studies collaboration as a means of price-setting or standard-setting power for suppliers. Most recently, a line of literature (e.g., Nagarajan and Sošić (2007, 2008) and Bernstein and Nagarajan (2012)) has extensively studied operational aspects of cartel formation using collaborative game theory. Collusive behavior exhibited by a sizable subset of collaborations continues to pique the interest of empirical researchers (Duso et al. 2014) and regulators (U.S. DOJ 2005) alike. However, in our case, we rule out collusive power as a motive for collaboration. Our suppliers genuinely consider collaboration to keep up with the technology requirements and cost targets set by the buyer.

A recent stream of literature investigates dyadic collaborations in the operations management context while avoiding collusive incentives for collaboration. Particularly, Bhaskaran and Krishnan (2009) and Kim and Netessine (2013) rigorously study various mechanisms of collaboration between two co-developing entities under various forms of delegation and information asymmetry without regard to a third party's actions vertically along the supply chain. In contrast, we posit a single collaboration mechanism and focus on situations where the buyer is an active decision maker that is not directly involved with product development.

The idea that development efforts can be triggered vertically across a supply chain is also not new. Harhoff (1996) not only shows that a powerful supplier can contribute to downstream product improvements by providing incentives which downstream firms use as a substitute for their own R&D efforts, but also predicts that "one can apply this basic principle easily to industries with ... monopsonistic players who may seek to induce price reductions among their suppliers." In this regard, the study closest to ours in the operations management literature is Li (2013). In the absence of collaboration, Li shows that similar capacity investment in suppliers and low price commitments are effective strategies for the buyer to foster supplier competition. On the contrary, we demonstrate that supplier collaboration is preferable under the face of similar supply allocations and low price commitments.

Economists have also been studying the structural impact of a policy that can reduce profitability, including our proposed strategy of imposing low prices. In retrospect, they have long argued that lack of profitability is a strong contributor to firm exit and industry consolidation (Gabszewicz and Thisse 1980). However, the study of whether R&D efforts, technological capabilities, or buyer power can alleviate firm exits is a relatively recent development. A notable theoretical work is that of Klepper (1996), who predicts that firms increase effort over time but the number of firms organically shrink. Researchers predict that buyer power spurs (Inderst and Wey 2006) or inhibits (Farber 1981) supplier innovation. Empirical studies from U.S. and Norwegian (Klette and Kortum 2004), and Japanese (Harada 1996) data suggest a positive relationship between business longevity and collaboration efforts as well as R&D, whereas a study by Cefis et al. (2009) on Italian data finds that coordination provides product availability but less R&D. We contribute to this literature in two ways. First, our analysis demonstrates that the presence of buyer power and sizable value appropriation in the supplier base may economize product development through collaboration and prevent firm exit. More importantly, inclusion of various operational factors including technological capability, pricing, and value allocation allows us to describe additional managerial limits of the powerful buyer's policymaking, such as disproportionate business power of the focal supplier.

3. Model Description

We consider a prominent, i.e., price and standard setting, buyer who needs to source a proprietary component ("supply") to serve demand in a single selling season. His supply requirement is normalized to unity without loss of generality, and has a projected value of v. The currently available technology allows production of the supply at the cost of γ. To avoid trivial cases, we assume that the buyer always has some gains from the trade with his suppliers; that is, $v > \gamma$. As mentioned in §1, the typical buyer usually sources his critical equipment from a single supplier or a few qualified suppliers (Kempf 2011). Thus, the buyer sets the wholesale price α and allocates the supply between two qualified suppliers ($i \in \{1, 2\}$): the focal supplier (she, $i = 1$) who has a greater business power and obtains an x share of the supply, and the partner supplier (she, $i = 2$) who gets the remaining $1 - x$.

If one of the suppliers refuses to participate, the buyer sources the supply fully from the remaining supplier. The suppliers may also choose to collaborate and form a consortium, in which case the buyer fulfills his supply requirement entirely from the consortium (thus overriding the buyer's allocations x and $1 - x$).

The suppliers' decision to form a consortium does not only depend on the price α and the allocations x and $1 - x$ committed by the buyer. It also involves trade-offs among cost reduction economies offered by each supplier, uncertain organizational difficulties, and the suppliers' business power structure. In the following subsections, we describe how we incorporate such factors into our model. In the light of discussions below, Table 1 summarizes the model notation and Figure 1 illustrates the model setting.

3.1 Independent Suppliers

The cost of producing the component for each supplier, $c_i := \gamma - r_i$ linearly depends on the amount of cost-reducing effort, $r_i \geq 0$ exerted by each supplier on the currently available technology with production cost $\gamma > 0$. We assume that the cost-reducing effort involves quadratic costs to the exerting supplier, that is, $K_1(r_1) := \frac{pAr_1^2}{2}$ and $K_2(r_2) := \frac{Ar_2^2}{2}$ with $A > 0$ and $p > 0$. Doing so, we specifically allow unequal marginal costs to account for the impact of asymmetries in technological capabilities in consortium formation. In particular, $p \leq 1$ if the focal supplier has the technological lead, since she has lower marginal costs for a given effort, and $p > 1$ if the partner supplier has the technological lead.

A similar structure of cost functions linking cost of production and cost-reducing effort were used by numerous works in the literature (e.g., Kamien et al. (1992b), Piccione and Tan (1996), Ceccagnoli (2005), Bhaskaran and Krishnan (2009), and Li (2013)). The convex cost (or decreasing returns) of the effort, sufficient for our managerial insights to hold, is indeed well motivated by empirical studies (Scherer 1965, Mank and Nystrom 2001, Graves and Langowitz 2006).

Table 1 Definition of indices, decision variables (actions), parameters, and identities

Indices	**Description and range**
$i^\dagger$	Supplier index, $i = 1$ for the focal supplier, $i = 2$ for the partner supplier
m	Mode of supplier collaboration, $m = C$ for suppliers in collaboration and $m = N$ for non-collaborating/independent suppliers
Decision variables	
x	Share of the supply awarded by the buyer to the independent focal supplier, $0 \leq x \leq 1$
α	Buyer's committed wholesale price, $\alpha \geq 0$
r_i	Cost-reducing R&D effort of supplier i, $r_i \geq 0$
Parameters	
γ	(Common) cost of the supply prior to cost-reducing effort, $\gamma > 0$
v	Value of the supply to the buyer, $v > \gamma$
f	Relative business power of the focal supplier; fraction of the consortium benefits retained by the focal supplier, $f \in [\frac{1}{2}, 1)$
p	Relative technological capability of the partner supplier; cost multiplier of the focal supplier (as a multiple of the partner), $0 < p \leq 1$ if the focal supplier has the technological lead, and $p > 1$ if the partner supplier has the technological lead
A	Partner supplier's development cost multiplier, $A > 0$ (focal supplier's multiplier is $pA > 0$)
B	Expected coordination cost multiplier, $B > 0$
ξ_i	Random collaboration cost shock of supplier i; $E[\xi_i] = 0, V[\xi_i] < \infty$
Identities	
r_C	Total development effort of the consortium, $r_1 + r_2$
c_i	Final cost of the supply for the non-collaborating supplier i, $\gamma - r_i$
c_C	Final cost of the supply for the consortium, $\gamma - r_C = \gamma - r_1 - r_2$
K_i	(Asymmetric) cost of R&D effort for supplier i, $K_1 := \frac{pAr_1^2}{2}, K_2 := \frac{Ar_2^2}{2}$
K_{iC}	Integration cost of collaborating suppliers for supplier i, $\frac{Br_C^2}{2} + \xi_i$, $E_{\xi_i}[K_{iC}] = \frac{Br_C^2}{2}$
π_B	Profit of the buyer, $\pi_B := v - \alpha$
π_{im}	Profit of supplier i under collaboration mode m; e.g., $\pi_{1C} := f(\alpha - c_C) - K_1 - K_{1C}$, $\pi_{1N} := x(\alpha - c_1) - K_1$
$\underline{\alpha}_{1N}(x)$	Zero-profit price for the non-collaborating focal supplier, $\gamma - \frac{x}{2Ap}$
$\underline{\alpha}_{2N}(x)$	Zero-profit price for the non-collaborating partner supplier, $\gamma - \frac{(1-x)}{2A}$
$\underline{\alpha}_{1C}$	(Expected) zero-profit price for the collaborating focal supplier, $\gamma - \frac{A^2fp(f+(1-f)p)+AB(f^2+2(1-f)fp+(1-f)(3f-1)p^2)-B^2(1-2f)^2p}{2Af(B+(A+B)p)^2}$
$\underline{\alpha}_{2C}$	(Expected) zero-profit price for the collaborating patner supplier, $\gamma - \frac{A^2(1-f)p(2f+(1-f)p)+AB(f^2(-3+p)(1+p)+2f(1+p-p^2)+p^2)-B^2(1-2f)^2}{2A(1-f)(B+(A+B)p)^2}$

†: i^- denotes the complement of i

3.2 Collaborating Suppliers

The (common) cost of producing the component for the consortium, $c_C = \gamma - r_C$ linearly depends on the *total* amount of cost-reducing effort, $r_C := r_1 + r_2$ exerted by the collaborating suppliers on the currently available technology (with production cost $\gamma > 0$). Given the convex form of the cost of effort, suppliers can collectively economize on cost-reducing effort through a consortium. This feature reflects the fundamental benefits of consortium formation including "cooperative specialization" (Alchian and Demsetz 1972), "access to complementary sources to better exploit existing resources" and "risk pooling" (Hagedoorn et al. 2000), and "relation-specific investments" (Dyer 2000), which may allow collaboration under the technological lead of the focal supplier as we later observe in §4.

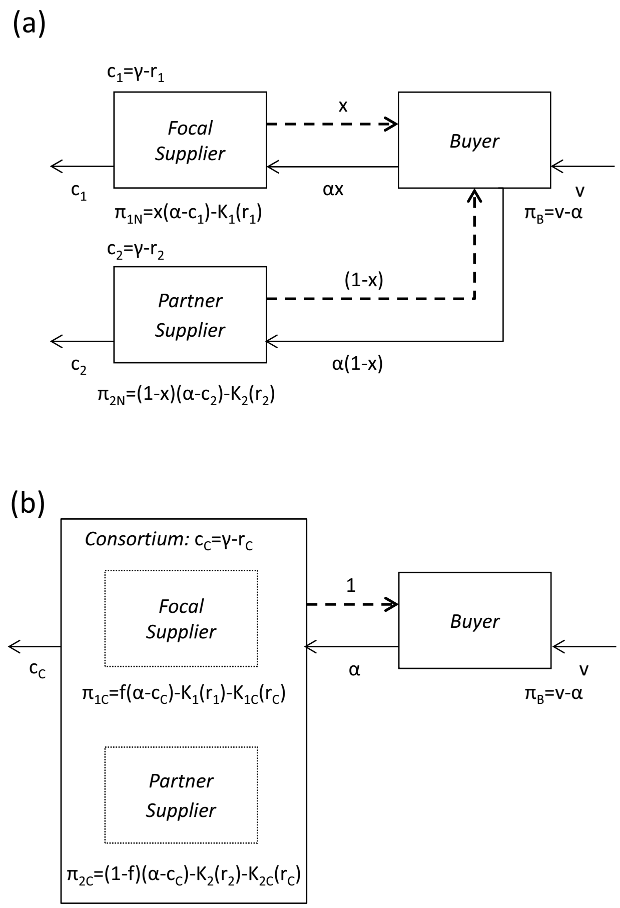

Figure 1 **The general model setting (a) when the suppliers act independently and (b) if the suppliers decide to collaborate. Dashed (solid) lines represent product (financial) flows.**

On the other hand, collaboration entails costs in addition to $K_i, i \in 1,2$ in accord with the efforts exerted by each collaborating supplier. Forming a consortium between suppliers entails uncertain coordination costs for each supplier $K_{iC} := \frac{Br_C^2}{2} + \xi_i, B \geq 0$ that consists of an expected cost $\frac{Br_C^2}{2}$ plus a random cost shock ξ_i (with zero mean and finite variance) that typically realizes shortly following consortium formation, in concordance with the conceptual frameworks developed by Park and Russo (1996) and White (2005) and motivated by the early experiences of major industry collaborations such as SEMATECH (Carayannis and Alexander 2004) and the F-35 Joint Strike Fighter (Kapstein 2004).

The cost shock accounts for the positive regret of collaboration that occur "mostly in the formative stages" (George and Farris 1999) —therefore with little or no sunk costs— as a consequence of changes in perceived collaboration costs due to a plethora of reasons including dissatisfaction from the realized governance structure (Williamson 1979), perceived partnership uncertainty (Bensaou and Venkatraman 1995), cultural incongruities (Park and Ungson 2001), or lack of trusting actions (Inkpen and Currall 2005). As a result, the supplier may find her profit in the consortium less than she would make under no collaboration. Incorporation of such a shock is thus conducive for an effective study of the buyer's ability to alleviate the risk of reneging and/or renegotiation after formation of a consortium (in §4.1). Nevertheless, the expected costs are sufficient to analyze the decision to form a consortium.

More importantly, the presence of such a coordination cost renders the efforts of each supplier substitutable. In §4, we find that the best-responses of each collaborating supplier are decreasing in the other supplier's effort because of the integration cost $K_{iC}(\cdot)$. In this sense, this "transaction cost" (Williamson 1981) or "coordination cost" (Artz and Brush 2000) element can be anticipated as a proxy for the difficulties of distributed development (à la Bhaskaran and Krishnan (2009)) or various barriers to integration (as mentioned by Ragatz et al. (2002)), or "free-riding on each other" (in the parlance of Kamien et al. (1992a)).

Appropriations and proceeds of each supplier in a consortium closely depends on the power structure of the suppliers (Harrigan and Newman 1990). Evidence also suggests that the principle of sharing in R&D collaborations is based on one where either "each member's payoffs are a function of its ... tangible and intangible contributions, costs incurred, and so forth" or one where "each party receives an equal share of the payoff" (Jap 2001). In our setting, we follow the latter approach; that is, the focal supplier retains a fraction $f \in [\frac{1}{2}, 1)$ of the consortium's net profit (net of the consortium's cost of production) in proportion with its share of business power and the partner supplier gets the remaining $1 - f$ fraction.

We choose to refrain from considering a separate cost sharing dimension apart from what revenue sharing implies and assume that each supplier pays the full cost of integration and development associated with its effort decision for three reasons. First, from a practical standpoint, suppliers "that collaborate with their competitors are conscious of the danger of strengthening the competitor's advantage at their own expense" (Un et al. 2010). Hence, we expect that suppliers are reluctant to directly pay for other suppliers' development efforts "to safeguard the knowledge base from unintended appropriation and imitation" (Knudsen 2007), let alone those with asymmetric marginal costs (Hamel et al. 1989, Hamel 1991, Zeckhauser 1996). Second, the literature suggests (e.g., Bhaskaran and Krishnan (2009)) considering cost sharing a viable strategy only under "predominant timing uncertainty," which is largely ruled out in our setting through the presence of roadmaps, as "when the project involves the launch of a product with incremental revenues, revenue sharing is sufficient to facilitate the collaboration." Third, the outcome of and the extra costs associated with such a cost sharing agreement can be accounted for as part of the integration cost. As we show later in §4, revenue sharing already entails a form of development and integration cost sharing that can be altered by adjusting the expected integration cost and/or the individual development costs.

Suppliers maximize the following profit function:

$$(\pi_{1m}, \pi_{2m}) = \begin{cases} (f(\alpha - c_C) - K_1(r_1) - K_{1C}(r_C), (1-f)(\alpha - c_C) - K_2(r_2) - K_{2C}(r_C)) & \text{if } m = C, \\ (x(\alpha - c_1) - K_1(r_1), (1-x)(\alpha - c_2) - K_2(r_2)) & \text{if } m = N. \end{cases}$$

And the buyer maximizes his profit $\pi_B := v - \alpha$.

Prominent buyers in development-intensive industries are not by default willing to incentivize research consortia that unnecessarily carry supplier integration costs downstream or increase the power of the suppliers in the longer term (Grindley et al. 1994, Franck and Melese 2008). Nonetheless, the (future) availability and affordability of the supply are crucial for the buyer's business prospects (Kempf 2012). Hence, the buyer would commit to strategies tailored towards supplier collaboration only when any of the suppliers do not offer a promising alternative in terms of cost. Thus, our sequence of events is as follows:

(1) The buyer sets the unit price α and the allocation of the supply to be awarded to suppliers so as to maximize his profit π_B. In particular, he allocates x fraction of the supply to the focal supplier and $1-x$ fraction to the partner supplier.

(2) The suppliers decide on whether to honor the buyer's request given his committed price, and whether to collaborate to form a consortium, under which the suppliers anticipate uncertain additional integration costs $K_{iC}(\cdot)$ and agree to share the net profit with fractions f and $1-f$ to the focal supplier and the partner supplier (rendering the buyer's decision x obsolete) in exchange for a potentially greater cost reduction.

(3) The integration cost uncertainty and associated regrets are realized if suppliers have decided to form a consortium in (2). *(We first assume that a positive regret of collaboration does not trigger renegotiation and suppliers continue to commit to the consortium as-is; we then relax this assumption in §4.1.)*

(4) Given the supplier structure as consortium ($m = C$) or independent ($m = N$), the buyer's unit price and the supply/revenue allocation, suppliers simultaneously decide on the cost-reducing research and development efforts r_i that maximize their profits, π_{iC} or $\pi_{iN}(x)$, respectively.

(5) The costs and revenues are accrued, the orders delivered/received.

Both the suppliers and the buyer maximize their expected profits; all parties are risk neutral. All parameters and decisions are common knowledge. We assume complete information, the implications of which are discussed in §5. We apply the subgame-perfect Nash equilibrium (SPNE) concept to characterize the equilibrium. When necessary, we break ties in favor of honoring the contract offered by the buyer (as opposed to non-participation) and working independently (in comparison with forming a consortium). We normalize the reservation profits of the suppliers to zero with no directional change in our results.

4. Analysis and Results

This section analyzes the model to describe the impact of the buyer's pricing and allocation strategies on suppliers' collaboration as a function of the suppliers' technological capabilities, uncertain collaboration costs, and business power structure. Because the suppliers' (buyer's) payoffs under both structures are increasing (decreasing) functions of the price set by the buyer, the participation decisions of each supplier can be characterized as a function of α alone. Indeed, we can define four such critical prices $\underline{\alpha}_{1N}$, $\underline{\alpha}_{2N}$, $\underline{\alpha}_{1C}$, and $\underline{\alpha}_{2C}$ (expressed in Table 1) that describe supplier participation, where the expected profit of supplier i at structure m crosses zero precisely at $\underline{\alpha}_{im}$.

Of possible supplier structures, the analysis under the case of independent suppliers is straightforward. The following proposition states the buyer's and suppliers' optimal decisions if collaboration is ruled out.

Proposition 1. *If we rule out the possibility of supplier collaboration:*

(i) Each participating supplier can independently maximize her profit through optimal investments $(r_{1N}^*, r_{2N}^*) := \left(\frac{x}{Ap}, \frac{1-x}{A}\right)$ *in cost-reducing effort;*

(ii) Let $\underline{\alpha}_{1N}(x) := \gamma - \frac{x}{2Ap}$ $(\alpha \geq \underline{\alpha}_{2N}(x) := \gamma - \frac{1-x}{2A})$ *be the critical price of the independent focal (partner) supplier under no collaboration* $(m = N)$*. The focal (partner) supplier participates if* $\alpha \geq \underline{\alpha}_{1N}(x)$ $(\alpha \geq \underline{\alpha}_{2N}(x))$*, and does not participate if* $\alpha < \underline{\alpha}_{1N}(x)$ $(\alpha < \underline{\alpha}_{2N}(x))$*;*

(iii) The buyer maximizes his profit by setting the price $\alpha^* = \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0)\}$ *and single sourcing from the supplier having the technological lead (that is, from the focal supplier if* $p \leq 1$ *and the partner supplier if* $p > 1$*). Therefore,*

$$x^* = \begin{cases} 1 & p \leq 1, \\ 0 & p > 1. \end{cases}$$

Independent suppliers offer larger price cuts in proportion with the share of the supply offered. Thus, the buyer can optimize his profits by simply sourcing from the supplier having the technological lead whenever suppliers do not choose to collaborate and by inducing supplier collaboration through competitively low prices only when he sees an opportunity for collaboration. It is this commitment that pressures the independent suppliers to coordinate and form a consortium to generate profit.

Next, we characterize how the SPNE behavior of the suppliers and the buyer change under the possibility of a consortium. For now, we disregard the possibility that realized uncertainty in the integration cost ξ_i may trigger reneging of the suppliers or renegotiation between collaborating suppliers after they form a consortium. We study this aspect further in §4.1.

Proposition 2. *If we allow the suppliers to commit to a consortium:*

(i) Each supplier within a consortium maximizes her expected profit through the equilibrium investments $(r^*_{1C}, r^*_{2C}) := \left(\frac{(A+B)f-B(1-f)}{A(B+(A+B)p)}, \frac{(Ap+B)(1-f)-Bf}{A(B+(A+B)p)}\right)$ *in cost-reducing effort,*

(ii) Let $\tilde{\alpha}_i := \min\{\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}, \underline{\alpha}_{iN}(x)\}$. *Supplier i prefers to produce her allocated/agreed share of the supply only if the buyer commits to a price* $\alpha \geq \tilde{\alpha}_i$. *Moreover, supplier i is willing to collaborate only when* $E_{\xi_i}[\pi_{iC}] > \pi_{iN}(x)$.

(iii) The buyer can attain optimal profits by committing to single source from the independent supplier having the technological lead and by committing to the price $\alpha^* = \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\}$. *Suppliers collaborate when* $\alpha^* = \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$. *Otherwise, the buyer sources from a single supplier.*

The total anticipated investment of the consortium can be expressed as $r^*_C := \frac{f+(1-f)p}{B+(A+B)p}$. This quantity is always less than the maximum total investment under no collaboration, $\max\{\frac{1}{pA}, \frac{1}{A}\}$, as a consequence of the asymmetry between the technological capabilities of the suppliers combined with coordination problems imposed through the integration costs. Because the optimal investment levels for each supplier involve sharing of the development effort, evidence (Dyer 2000, Ragatz et al. 2002), as well as economic theory (Kamien et al. 1992a, Kamien and Zang 2000) have long suggested that the total development under collaboration is less than the total that can be obtained under competition. In this regard, inefficiencies due to "problems" including anticipated "start-up investments," "coordination and agency costs," 'asymmetries in "assessment of partner's input" and "control of information flows between partners" are commonly cited (Veugelers 1998). Presence of the integration cost $K_{iC}(\cdot)$ and asymmetric technological capabilities p reflects this fact as one of our results. Only as $B \to 0^+$ do the equilibrium investments become proportional to the profit sharing terms f and $(1-f)$ imposed by the relative business power of the focal supplier. Moreover, the equilibrium total investment approaches the maximum possible investment under no collaboration ($m = N$) only when $p = 1$.

The buyer's profit is decreasing with the price he offers. Therefore, the profit-maximizing buyer chooses to set the lowest possible price that ensures fulfillment of the supply regardless of the supplier structure. Moreover, the buyer can continue to maximize his profits by committing to single source from the most capable supplier whenever they decide not to collaborate.

Indeed, the analysis of the suppliers' behavior as a consequence of the buyer's decisions promises more interesting results. The policy in Proposition 2(iii) leads to different economic outcomes as a function of the focal supplier's relative productivity p, the focal supplier's relative business power f, and the expected coordination cost multiplier (normalized by the research cost multiplier), B/A. In particular, we can outline six distinct regions in Figure 2 where the suppliers choose to collaborate in three (C1, C2, C3) and fail to collaborate in the remaining three (N1, N2, N3). The regions further differentiate by the supplier who is less willing to collaborate or not willing to collaborate. Suppliers with aligned capabilities and power are more apt to collaborate than suppliers who lack this compatibility (for example a powerful yet technologically challenged supplier versus a small but very innovative supplier, in which case a transaction to grant the exclusive access to cost-reducing technology of the partner supplier to the focal supplier seems more appropriate). Figure 2 illustrates these regions for different values of B/A up to the maximum permissible at $1/4(\sqrt{3}-1) \cong 0.183$ for identical suppliers (that is, $p=1$ and $f=1/2$).

In Table 2 we list further properties of each of the regions. We also note that all integration cost bounds that form the collaboration regions C1, C2, and C3 always lead to non-negative effort levels in equilibrium.

Table 2 **Description of regions in Figure 2. The acronym LCS (stands for "least collaborating supplier") denotes the supplier with a marginal incentive to collaborate or a substantial incentive not to collaborate**

Region	**Boundaries**	**LCS**
$C1$	$p \in \left(\frac{1}{2}, 1\right) \cap B < \bar{B}_1(p,f)$	1
$N1$	$p \in \left[0, \frac{1}{2}\right] \cup \left(p \in \left(\frac{1}{2}, 1\right) \cap B \geq \bar{B}_1(p,f)\right)$	1
$C2$	$f \in \left[\frac{p}{p+1}, \frac{p}{2p-1}\right) \cap p \in [1,2) \cap B < \bar{B}_2(p,f))$	1
$N2$	$f \in \left[\frac{p}{2p-1}, 1\right] \cup \left(f \in \left[\frac{p}{p+1}, \frac{p}{2p-1}\right) \cap B \geq \bar{B}_2(p,f))\right) \cap p \in [1,2)$	1
$C3$	$f \in \left[\frac{1}{2}, \frac{p}{p+1}\right] \cap p \in [1,2) \cap B < \bar{B}_3(p,f)$	2
$N3$	$p \geq 2 \cup \left(f \in \left[\frac{1}{2}, \frac{p}{p+1}\right] \cap p \in [1,2) \cap B \geq \bar{B}_3(p,f)\right)$	2
Parameter	**Value**	
$\bar{B}_1(p,f)$	$A\frac{(p(-p^2-f^2(1+p)(-1+3p)+2f(-1+2p^2)+(f+p-fp)\sqrt{f^2-2(-3+f)fp+(1-3f)^2p^2}))}{(2(f+2fp+(1+f(-3+4f))p^2))}$	
$\bar{B}_2(p,f)$	$A\frac{-p^2+2fp^2-f^2(1+p)(-1+3p)+(f+p-fp)\sqrt{-2f(-1+p)p+p^2+f^2(1+p(-2+9p))}}{2(p+f(1+p(-2+4f+p)))}$	
$\bar{B}_3(p,f)$	$A\frac{f^2(-3+p)(1+p)-p(2+p)+f(2+4p)+(f+p-fp)\sqrt{(2+p)^2+f^2(9+(-2+p)p)-2f(6+p+p^2)}}{2(2+4f^2+p(2+p)-f(5+p(2+p)))}$	

Note: $\bar{B}_i(p,f)/A \leq \frac{Ap(1-f)}{2f-1}$ for region Ci, $i \in \{1,2,3\}$

The intuitions behind regions numbered 1 and 3 (that is, regions C1, C3, N1, N3) are straightforward. In regions N1 and N3, one supplier has sufficient capability to satisfy supply at a low

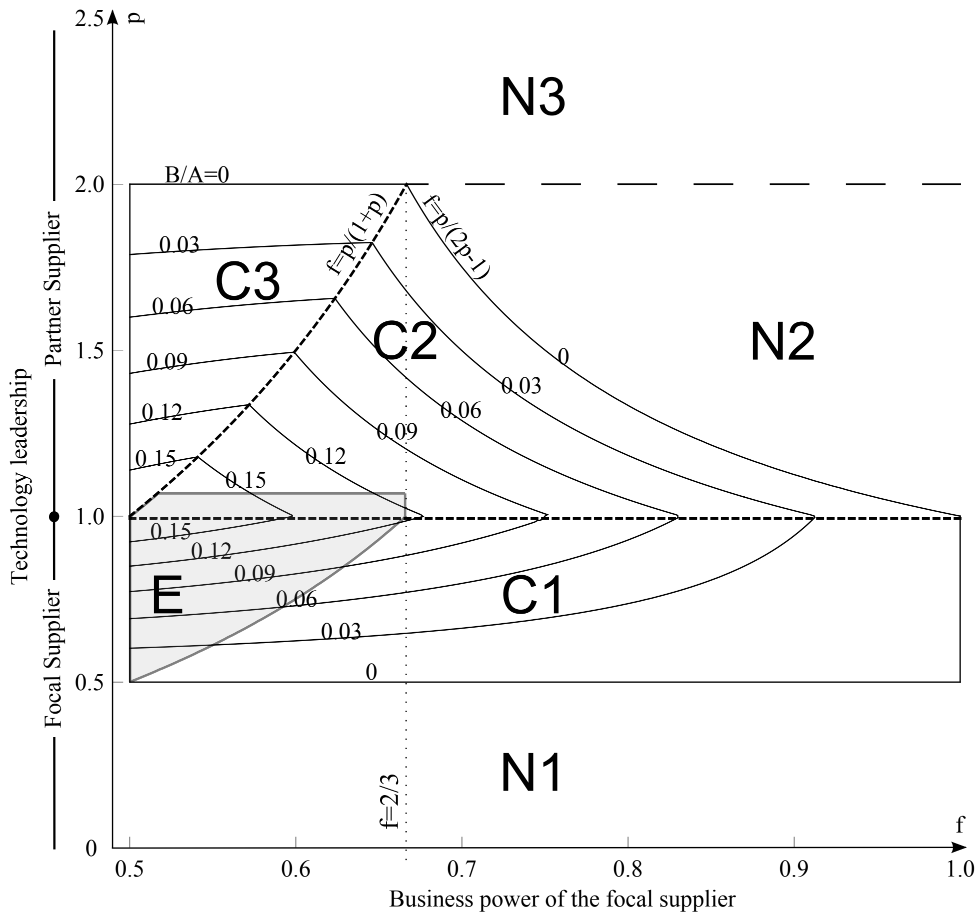

Figure 2 Six regions of the focal supplier's relative technology costs (p) and the focal supplier's relative business power (f), as a parameter of the normalized integration cost (B/A). The buyer induces collaboration in regions C1, C2, and C3 and opts for single sourcing in regions N1, N2, N3. As B/A increases, C* regions are replaced with their N* counterparts. The last point remaining for viable collaboration is the case of identical suppliers (that is, $p = 1$ and $f = 1/2$), in which suppliers collaborate at integration cost values up to $1/4(\sqrt{3} - 1) \cong 0.183$. Region E (§4.1) is shaded in gray.

price. Thus, involvement of the less efficient supplier creates an unnecessary inefficiency through the substantial difference between cost reduction technologies. In region C1, the powerful focal supplier who also has the technological lead is only marginally willing to collaborate. Likewise, in region C3, the disproportionately-capable-yet-almost-equally-powerful partner supplier, who is at a very suitable position to surpass the focal supplier, has little incentive to collaborate.

On the other hand, regions N2 and C2 bring a new insight. In N2, the disproportionately-powerful-yet-less-capable focal supplier does not want to collaborate, and in C2, the focal supplier has a marginal interest in forming a consortium. Such a focal supplier is dissuaded from meeting the competitively low price goal without either obtaining the ownership of the advantageous cost reduction capabilities, or a more generous allocation of the supply to justify independent production. Otherwise, the price savings promised by the partner supplier (and exploited by the buyer) pose a negative externality to the focal supplier given the focal supplier's own technological challenges. This may explain why empirical studies have consistently been reporting difficulties in consortium maintenance under such asymmetries in business power and technological capabilities (e.g., Hamel (1991), Alvarez and Barney (2001), Kalaignanam et al. (2007)) and why corporate takeovers continue to be the most prevalent mode of transaction among enterprises who possess business power and innovative enterprises who do not (Bleakley and Mullane 2013, Erwin 2014). From the perspective of the buyer, the buyer is also willing to be involved and provide the necessary leverage to the partner supplier who has an evident cost advantage incongruent with her lack of business power. Such an insight supports recent developments in the study of procurement trade-offs between an incumbent and an entrant supplier (e.g., Li (2013) and Tunca et al. (2013)).

Finally, as the buyer's pricing decision, as well as suppliers' participation decisions depend on the critical prices $\underline{\alpha}_{1N}$, $\underline{\alpha}_{2N}$, $\underline{\alpha}_{1C}$, and $\underline{\alpha}_{2C}$, we list some properties of these critical prices and briefly provide key insights.

Proposition 3. *The following holds for the critical prices:*

(i) *the critical prices for consortium formation* $\underline{\alpha}_{1C}$ *and* $\underline{\alpha}_{2C}$ *are concave increasing in* B.

(ii) *the critical prices for consortium formation* $\underline{\alpha}_{1C}$ *and* $\underline{\alpha}_{2C}$ *are increasing in* p.

(iii) *the consortium participation price for the focal supplier,* $\underline{\alpha}_{1C}$ *is increasing in* f *for* $p > 1$.

(iv) *the difference* $\underline{\alpha}_{1N}(x) - \underline{\alpha}_{1C}$ *is increasing in* p *for* $p \leq 1$ *and for* $x \geq f$.

Some of these results are expected. By Proposition 3(i), the buyer's potential benefit from consortium formation decreases with the integration cost. Proposition 3(iv) shows that a disproportionately powerful focal supplier will be less willing to collaborate. Interestingly, Lemma (i) also implies that marginal actions to reduce the integration cost bring little to the value of collaboration. We discuss this result further in §5.

The remaining Propositions 3(ii) and 3(iii) confirm the intuition that supplier consortium formation requires productivity from both suppliers and a harmony of business power and technological capabilities (e.g., Jarillo (1988), Singhal and Singhal (2002), Ireland and Webb (2007), Sears and Hoetker (2014)). In particular, both of the following reduces the value of collaboration for each supplier: lack of adequate business power of the technologically capable partner supplier and lack of technological capability of the focal supplier.

4.1 The Role of Buyer's Supply Allocation in Maintaining Supplier Consortia

We have stated in §3 that suppliers may have non-negative regrets of collaboration as the result of a large cost shock shortly following consortium formation. Up to this point, we have assumed that uncertainty in the supplier's integration cost cannot trigger reneging of the supplier or renegotiation between collaborating suppliers.

An extant stream of literature (such as Taylor and Plambeck (2007); Nagarajan and Sošić (2008) includes a fairly recent review) thoroughly discusses the effects and impacts of renegotiation and reneging both vertically and horizontally along the supply chain (for example when significant information asymmetries exist around suppliers' unit costs). In contrast, we focus on strategies to mitigate such incentives. A possible strategy is to minimize the maximum regret of collaboration with respect to independent participation across the two suppliers (or equivalently, maximizing the minimum benefit of collaboration between suppliers).

In this section, we demonstrate that the minimum benefit of collaboration can be maximized in the regions where suppliers can collaborate through the buyer's egalitarian commitment to allocate a larger (smaller) share of the supply to the partner supplier (focal supplier) if they fail to collaborate. We also show that this commitment is effective for almost all settings of business power (f), integration cost (B/A), and technological capability (p) in which suppliers collaborate. In effect, the buyer can drive supplier collaboration by particularly dissuading the independent focal supplier.

Two key results to establish our conclusion follow from the buyer's optimal strategy as stated in Proposition 2:

Lemma 1. *For* $(p, f, B/A) \in (C1 \cup C2 \cup C3)$*:*

(i) *The minimum benefit of collaboration across suppliers is concave in* x*.*

(ii) *The buyer can set* $x \in [0, 1]$ *in the regions C1, C2, and C3 without creating a positive incentive to leave the consortium.*

Therefore, the buyer has an alternative, and equally optimal sourcing strategy for the settings where suppliers choose to collaborate:

Lemma 2. *The buyer can attain identical profits as in Proposition 2 by committing to a price* $\alpha^* = \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\}$ *where he can choose to single source as follows:*

$$x^* = \begin{cases} 1 & p \leq 1 \cap N1, \\ 0 & (p > 1 \cap (N2 \cup N3), \\ \in [0, 1] & C1 \cup C2 \cup C3. \end{cases}$$

Thus, given an alternative optimal set of decisions available to the buyer in settings where suppliers decide to collaborate, we finally show that an egalitarian allocation of supply can maximize the minimum benefit of collaboration (vis-a-vis independent participation) in almost all of these settings and thus help to protect the suppliers against a degree of integration cost uncertainty.

PROPOSITION 4. *For every* $(p, f, B/A) \in (C1 \cup C2 \cup C3) \setminus E$*, the maximizer of minimum benefit of collaboration across suppliers is reached at some supply allocation* $\tilde{x}(p, f, B/A) < f$*, where* E *denotes the region* $\left((\frac{1}{2} \leq p \leq 1 \cap \frac{1}{2} \leq f \leq \frac{2p}{2p+1}) \cup (1 \leq p \leq \frac{15}{14} \cap \frac{p}{p+1} \leq f \leq \frac{2}{3}) \right)$.

Therefore, in settings where suppliers can form a collaboration (and in the presence of reasonable supplier asymmetry), the buyer can commit to egalitarian allocations in case they do not collaborate and combine it with a commitment to low prices to ensure participation to the collaboration and minimize the renegotiation risk at the same time.

The relationship is complicated in a small region E in the saddle of three regions (as illustrated in Figure 2) due to the close interplay of all the factors mentioned above combined with an almost evenly distributed supplier power in this region. Thus, our conclusion on egalitarian supply allocations necessitates a substantial degree of dissimilarity between the capabilities and the business power of the suppliers.

When this dissimilarity is established, the focal supplier is willing to work with the buyer, and prefers to be the buyer's sole supplier. When the focal supplier also has the technological lead, she becomes even harder to collaborate with, especially if the buyer allocates a more favorable share. By persistently inducing the focal supplier agree to collaborate with the partner supplier through allocations that provide for the partner supplier, the buyer effectively allows the partner supplier to take part in and anticipate a return from large development efforts.

Another interpretation of this observation can be that the buyer's commitment towards an equitable distribution of the supply reduces the opportunity costs of collaboration to both suppliers, which consequently ensures the financial health of both suppliers by allowing sizable returns to both the focal supplier and, more importantly, to the partner supplier. In this regard, our results agree with those of Usta et al. (2014a), who argue that the prominent buyer can sustain the financial health of his suppliers by committing to "equally strong financial resources." Here, we further claim that such a policy has the additional benefit of maintaining supplier collaboration. Our observations in Proposition 4 mimics the recent conclusion of Wan and Beil (2014) on procurement decisions of powerful buyers: to mitigate unexpected consequences within the supplier base, the price-controlling buyer should commit to diversify his supply.

5. Managerial Implications, Discussion, and Conclusions

We study how a powerful buyer in development-intensive industries can utilize and maintain the possibility of supplier collaboration. To model the intricacies of supplier collaboration, we formulate a stylized game-theoretic model of two suppliers incorporating scale benefits, uncertain coordination costs, and asymmetries along other operational dimensions such as technological capability and the share of business power within a consortium. Here, we summarize our results and discuss their managerial implications for the buyer, the suppliers, and the development-intensive supply chain.

Powerful Buyers Can Induce and Assure Collaborations Between Suppliers

Practitioners argue that the combined practice of "competitive, fixed price contracts" and "subcontracting" in the defense industry, particularly allowing for international partners, is helpful in fostering collaborations that are beneficial to the buyer (Hartley 1995, Bishop 2003, Kempf 2012). Empirical studies have taken notice of the positive impact of buyer's commitment to competitive cost targets on collaborative activity among the supplier base, including wafer size transitions in the semiconductor industry (Watanabe and Kramer 2006, Ku et al. 2007), and material transitions in the defense industry (McAdam et al. 2008).

Our analysis confirms the empirical and anecdotal evidence. We show that the buyer can optimize his profits by enacting supplier collaboration through competitively low wholesale prices (Proposition 2). Moreover, we demonstrate that the opportunity costs of such a collaboration on the supplier base can be reduced and renegotiation risk between the suppliers can be minimized given the buyer's commitment towards an equal distribution of the supply (Proposition 4). In this regard, the buyer can efficiently persuade the suppliers to collaborate, split their markets, and yet keep them concomitantly compelled to collaborate in a wide range of business power structures and profiles of technological capability. Thus, with the concerted efforts of the suppliers under collaboration, the buyer can achieve a high level of product development and product availability without the need to be involved with the development process himself.

In the defense and semiconductor industries, prominent buyers promote roadmaps and stringent supplier qualification procedures, which create a research environment with reduced uncertainty (Kostoff and Schaller 2001, Mowery 2012). We show that such an environment, especially when combined with the pricing strategies discussed above, enables and maintains a seamlessly collaborating supplier base. Thus, our results may explain the rising prevalence of horizontal collaborations in the defense and semiconductor industries.

Collaborations May Help Suppliers Sustain Their Businesses

As exemplified by the numerous arrangements across the semiconductor and defense industries (e.g., Global 450 Consortium, The Composites Consortium), competing suppliers—especially ones with similar capabilities, power, and complementary capabilities—cooperate to survive. Coined as the neologism "coopetition" (Brandenburger and Nalebuff 1998, p. 11-39), empirical researchers focusing on such collaboration have thoroughly studied strategic issues surrounding the concept (Gnyawali and Park 2011), while the operational aspects of supplier collaboration, or coopetition, is relatively understudied (Bonel and Rocco 2007).

Our stylized model involves an effort to effectively address various intricacies of supplier collaboration through an operations management perspective. In particular, our model of supplier collaboration captures the dynamics of consortium formation including synergies, difficulties of distributed development such as free-riding, and relationship risks. Through our analysis, we find that marginal actions to reduce such integration costs bring little to the value of collaboration (Proposition 3(i)). Therefore, suppliers are best-off either by forfeiting attempts to enhance cohesion or by a full-scale effort to achieve harmony. This finding may corroborate the observed schism between successful and failing consortia as expressed by Park and Ungson (2001) and Huxham and Vangen (2000). Accordingly, we confirm the well-established wisdom that supplier consortium formation requires productivity from both suppliers and a harmony of business power and technological capabilities. Both the lack of adequate business power of the partner supplier and the lack of technological capability of the focal supplier negatively impact consortium performance (Proposition 3(ii)-(iii)). Nonetheless, the buyer's commitment to egalitarian allocations can provide a more stable basis for collaborations once they are formed.

Supply Chains Benefit From Supplier Collaborations

Supplier collaborations, when they occur through the commitments of the buyer we prescribe, benefits all parties involved. The prominent buyer enjoys lower prices and sustained research activity dispersed throughout the supplier base. More importantly, the buyer can ensure availability and affordability of the supply without getting directly involved with the collaboration process. The partner supplier can take part in large development efforts and receive financial flows without a necessity to invest in providing a generous allocation of the supply. Finally, the focal supplier can access and complement the technological resources of the partner supplier without procuring or appropriating the partner supplier's assets.

Beyond Collaborations: When Supplier Collaborations Do Not Work

When suppliers have disproportionate business power or technological capability, supplier collaboration becomes hard to establish. In particular, the focal supplier has a greater incentive not to collaborate as her business power increases (Proposition 3(iv)). Such supplier bases (multi-national conglomerate divisions vs. academic start-ups as an extreme example) are prone to eventual appropriation and ensuing consolidation because the focal supplier gains productivity at parity with its business strength only through owning the efficient means of product development herself. The recent array of corporate takeovers among former collaborators Novellus Systems, Lam Research Corporation, and SpeedFarm-IPEC in the semiconductor industry (Grant 1997, Novellus 2013, Walker 2004, Lam Research 2013, LaPedus 2013); as well as the the latest consolidation of Orbital Sciences into Alliant Techsystems in the aerospace industry (Clark 2014, Orbital 2014, Jayakumar 2014) manifests the relevance and potential scale of this phenomenon.

The possibility of eventual exit of viable suppliers poses a considerable risk to the prominent buyer who needs to sustain a sizable supplier base to procure safely from meticulously qualified suppliers and avoid excessive supplier qualification in the longer run (Chaturvedi et al. 2014). Therefore, exploiting the value of collaborations may be limited in time by supplier health concerns even though supplier collaborations allow financial flows to each supplier and have a positive impact on the health of the suppliers. In this regard, the buyer should nevertheless be prepared to work more closely with his partner supplier (Yang et al. 2012, Usta et al. 2014a) and/or anticipate a future commitment to directly develop the supplier base (Lee and Li 2012, Usta et al. 2014b).

A. Proofs

Proof of Proposition 1.

(i) The profits of each supplier under $m = N$ can be expressed as $\pi_{1N}(x, r_1) = x(\alpha - \gamma + r_1) - \frac{pAr_1^2}{2}$ and $\pi_{2N}(x, r_2) = (1-x)(\alpha - \gamma + r_2) - \frac{pAr_2^2}{2}$, which have the negative second derivatives $-pA$ for the focal supplier and $-A$ for the partner supplier. Hence, the respective solution of the first-order conditions, $x - pAr_1 = 0$ and $(1-x) - Ar_2 = 0$ yields the desired unique maximizers, which yields the maxima $\pi^*_{1N}(x) = \frac{x^2}{2pA} + x(\alpha - \gamma)$ and $\pi^*_{2N}(x) = \frac{(1-x)^2}{2A} + (1-x)(\alpha - \gamma)$.

(ii) Because each supplier's payoff is an increasing function of the price set by the buyer, the profits of each supplier is greater than or equal to zero only if α is greater than or equal to $\underline{\alpha}_{1N}(x) := \gamma - \frac{x}{2Ap}$ for the focal supplier, and $\alpha \geq \underline{\alpha}_{2N}(x) := \gamma - \frac{(1-x)}{2A}$ for the partner supplier.

(iii) Because the buyer's profit is decreasing with the price he offers if at least one supplier or a consortium participates, the buyer can maximize his profits by setting the minimum price required to fulfill the supply, the minimum in x of $\min\{\underline{\alpha}_{1N}(x), \underline{\alpha}_{2N}(x)\}$. Since the price required for participation for each supplier, $\underline{\alpha}_{2N}(x)$ and $\underline{\alpha}_{1N}(x)$, is linear in x, the minimum of $\min\{\underline{\alpha}_{1N}(x), \underline{\alpha}_{2N}(x)\}$ in x is reached either at $x=0$ or $x=1$. In particular, $\underline{\alpha}_{1N}(1) = \gamma - \frac{1}{Ap}$ is the minimum in x if $p \leq 1$ and $\underline{\alpha}_{2N}(0) = \gamma - \frac{1}{A}$ is the minimum in x if $p > 1$. Therefore, the stated pricing and allocation maximizes the buyer's profits. ■

Proof of Proposition 2.

(i) Under collaboration, each supplier interacts with the other supplier and solves their best response to the other supplier's cost-reducing effort. The best-responses of each supplier are decreasing in the other supplier's effort because of the integration cost $K_{iC}(\cdot)$. Nevertheless, the best responses of each supplier can be easily shown to have a single intersection, giving a unique set of investments in equilibrium.

Profits of each supplier in a consortium can be expressed as $\pi_{1C}(r_1, r_2) = f(\alpha - \gamma + r_1 + r_2) - \frac{pAr_1^2}{2} - \frac{B(r_1+r_2)^2}{2} - \xi_1$ and $\pi_{2C}(r_1, r_2) = (1-f)(\alpha - \gamma + r_1 + r_2) - \frac{Ar_2^2}{2} - \frac{B(r_1+r_2)^2}{2} - \xi_2$. Further, for any given level of r_{i-}, the second derivative of the profits with respect to r_i are the negative quantities $-(Ap+B)$ for the focal supplier and $-(A+B)$ for the partner supplier. Hence, the best responses of each supplier in response to the other is characterized by the respective first-order conditions $r_{1C}^*(r_2) = \frac{f-Br_2}{Ap+B}$ and $r_{2C}^*(r_1) = \frac{1-f-Br_1}{A+B}$. The unique intersection of these conditions, which describes the anticipated cost-reducing efforts of each supplier, occur at the effort levels stated in the proposition.

To avoid the situation where the equilibrium efforts are non-positive, we henceforth assume $B \leq \min\{\frac{Ap(1-f)}{(2f-1)}, A\}$. We note further in §4 that this assumption is not restricting our analysis since it does not interfere with the supplier's collaboration decision.

(ii) The proof is of a similar nature of the proof of Proposition 1(ii). A consortium is formed only if both suppliers are willing to collaborate. Hence, the expected profits (in ξ_i) of a supplier i is greater than or equal to zero in at least one structure if either α allows positive expected profits to both suppliers, $\alpha \geq \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$, or α allows independent participation of the supplier, $\alpha \geq \underline{\alpha}_{iN}(x)$. The condition follows. The supplier chooses collaboration only when it gives greater profits in expectation.

(iii) The proof for the optimality of α^* is straightforward, since lowering α simply leads to supplier non-participation and raising α causes a loss of the buyer's profits. The statement also implies that the buyer cannot increase his profits by by setting $x \in (0,1)$ once the buyer sets $\alpha = \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\}$. In (ii) we have stated that the suppliers can participate if the buyer commits to a price greater than or equal to $\tilde{\alpha}_i := \min\{\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}, \underline{\alpha}_{iN}(x)\}$, where the minimum price for supplier collaboration, $\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$ does not depend on x. From Proposition 1(ii), $\underline{\alpha}_{1N}(x)$ and $\underline{\alpha}_{2N}(x)$ are linearly decreasing in x and $1-x$, respectively. Therefore, we can denote $[x_1, 1], x_1 \geq 0$ as the interval where $\underline{\alpha}_{1N}(x) \leq \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$ and $[0, x_2], x_2 \leq 1$ as the interval where $\underline{\alpha}_{2N}(x) \leq \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$. Suppose that the supplier can increase his profits by setting an $x \in (0,1)$. Given f, p and B, one and only one of the following cases may happen:

P1. Intervals $[x_1, 1]$ and $[0, x_2]$ do not exist

P2. Interval $[x_1, 1]$ exists but $[0, x_2]$ does not exist

P3. Interval $[0, x_2]$ exists but $[x_1, 1]$ does not exist

P4. Both intervals exist with $x_1 > x_2$

P5. Both intervals exist and $[x_1, x_2]$ also form an interval

In P1, the buyer can achieve maximum profits when a low enough price (that is not a function of x) is chosen so that both suppliers collaborate for any $x \in [0,1]$. Therefore, once the price is appropriately chosen, choosing a different x cannot further increase (nor decrease) his profits. In P2 (P3), the buyer can achieve better profits by setting $x = 1$ ($x = 0$), which allows him to pick the minimum α which maximizes his profits. In P4 and P5, the buyer can achieve better profits by setting either $x = 1$ or $x = 0$. In particular, $x = 1$ will be the optimal choice if $p < 1$ and $x = 0$ will be the optimal choice if $p > 1$. Therefore, setting $x \in (0,1)$ does not improve the buyer's profits. Finally, if $\alpha^* = \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$, $\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\} \leq \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0)\} \leq \min\{\underline{\alpha}_{1N}(x), \underline{\alpha}_{2N}(x)\}$ for every $x \in [0,1]$. Therefore, the suppliers either form a consortium or do not participate. On the other hand, if $\alpha^* = \underline{\alpha}_{1N}(1)$ ($\underline{\alpha}_{2N}(0)$), this implies that $\underline{\alpha}_{1N}(1) \leq \min\{\underline{\alpha}_{2N}(0), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\} \leq \min\{\underline{\alpha}_{2N}(1), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\}$ ($\underline{\alpha}_{2N}(0) \leq \min\{\underline{\alpha}_{1N}(1), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\} \leq \min\{\underline{\alpha}_{1N}(0), \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}\}$). The first inequality follows from the definition of α^* and the second inequality follows from Proposition 1(ii). Following Proposition 2(ii), only the focal (partner) supplier can participate at α^* and the buyer sources from the participating supplier. ■

Proof of Proposition 3.

(i) An increase in the integration costs decreases the incentive of each supplier to invest in cost-reducing effort. In turn, the collectively attainable cost of the supply increases, decreasing the profits of each supplier under collaboration. Formally speaking, the respective first derivatives of the focal and partner supplier profits under collaboration with respect to B, $\frac{A(-f-(1-f)p)(Ap(f+p+fp)+B(f+p+(-1+3f)p^2))}{2(B+(A+B)p)^3}$ and $\frac{A(-f-(1-f)p)(Ap(2-f+(1-f)p)+B(2+p(1+p)-f(3+p^2)))}{2(B+(A+B)p)^3}$ are negative for every $f \in [1/2, 1]$ and $p > 0$ given $B \leq \frac{Ap(1-f)}{2f-1}$. Therefore, $\underline{\alpha}_{1C}$ and $\underline{\alpha}_{2C}$ increases. Proof of concavity follows by inspecting the negative second derivatives of $\underline{\alpha}_{1C}$

and $\underline{\alpha}_{2C}$ with B, $\frac{(-f-(1-f)p)(Ap(f+p+3fp+2p^2)+B(1+p)(f+p+(-1+3f)p^2))}{f(B+(A+B)p)^4}$ for the focal supplier and $\frac{(-f-(1-f)p)(Ap(2+p(4+p-f(3+p)))+B(1+p)(2+p(1+p)-f(3+p^2)))}{(1-f)(B+(A+B)p)^4}$ for the partner supplier, for every $f \in [1/2, 1]$, $p > 0$, and $B \leq \frac{Ap(1-f)}{2f-1}$.

(ii) Similar to the proof of (i), an increase in p decreases the overall development capabilities of the suppliers (even though the focal supplier is willing to exert more cost-reducing effort in this case). Therefore, the collectively attainable cost of the supply increases, decreasing the profits of each supplier under collaboration. The respective first derivatives of the focal and partner supplier profits under collaboration with respect to p, $\frac{-(Af+B(-1+2f))^2(B(1-p)+Ap)}{2A(B+(A+B)p)^3)}$ (given $B \leq A$) and $\frac{-(A+B)(Af+B(2f-1))(A(1-f)p-B(2f-1))}{A(B+(A+B)p)^3)}$ (given $B \leq \frac{Ap(1-f)}{2f-1}$) are negative for every $f \in [1/2, 1]$ and $p > 0$. Therefore, $\underline{\alpha}_{1C}$ and $\underline{\alpha}_{2C}$ increases.

(iii) In the spirit of the proof of (ii), an increase in the profit allocation fraction of the technologically challenged focal supplier decreases the development incentive of the partner supplier having the technological lead. Overall, this increases the collectively attainable cost of the supply, and hurts the focal supplier collaborating with the partner. Therefore, $\underline{\alpha}_{1C}$ increases. In other words, the derivative of $\underline{\alpha}_{1C}$ with respect to f, $\frac{B^2(-1+4f^2)p+A^2f^2p(-1+2p)+AB(-p^2+f^2(1+p)(-1+3p))}{2Af^2(B+(A+B)p)^2}$ is positive for every $f \in [1/2, 1]$ and $p > 1$ given $B \leq A$.

(iv) An increase in the capabilities of the focal supplier who also has the technological lead (therefore a decrease in p in the region $p \leq 1$) increases both the consortium profits and the independent profits of the focal supplier. However, for any allocation that gives a larger fraction to the focal supplier than what he would get in a consortium, that is $x \in [f, 1]$, the independent profits of the focal supplier should increase more than her profits in a consortium where her cost reduction capabilities are not fully internalized. The derivative of $\underline{\alpha}_{1N}(x) - \underline{\alpha}_{1C}$ with respect to p, $\frac{-(Af+B(-1+2f))^2(B(1-p)+Ap)}{2Af(B+(A+B)p)^3} + \frac{x}{2Ap^2}$, is positive for every $f \in [1/2, 1]$ for any $x \geq f$. ■

Proof of Lemma 1.

(i) The (expected) benefit (or negative regret) of collaboration for each supplier at α^* (that is, the difference between expected profits under collaboration and profits with participation but without consortium formation) can be expressed for each of the two regions $R1 := (C1 \cup C2)$ and $R2 := C3$ which differ by their α^*. In particular, $\alpha^* = \underline{\alpha}_{1C}$ for the region $(C1 \cup C2)$ and $\alpha^* = \underline{\alpha}_{2C}$ for the region C3. In Table 3, we define the following benefit functions in x for each supplier and region.

Upon inspection, all of the benefit terms are quadratic in x with a negative coefficient, since all $\pi_N(x)$ terms (as expressed in the proof of Proposition 1) in the definitions of $B_{1,\cdot}(\cdot)$ and $B_{2,\cdot}(\cdot)$ are quadratic in x with a positive coefficient and the $E_{\xi_i}[\pi_{iC}]$ terms do not depend on x. Thus, all benefit terms are concave in x. Therefore, the minimum benefit of collaboration among suppliers,

Table 3 Description of benefit functions

Function	Definition	Evaluated at $\alpha = \alpha^*$
$B_{1,R1}(x)$	$E_{\xi_1}[\pi_{1C}] - \pi_{1N}(x)$	$\underline{\alpha}_{1C}$
$B_{2,R1}(x)$	$E_{\xi_2}[\pi_{2C}] - \pi_{2N}(x)$	$\underline{\alpha}_{1C}$
$B_{1,R2}(x)$	$E_{\xi_1}[\pi_{1C}] - \pi_{1N}(x)$	$\underline{\alpha}_{2C}$
$B_{2,R2}(x)$	$E_{\xi_2}[\pi_{2C}] - \pi_{2N}(x)$	$\underline{\alpha}_{2C}$

$\min\{B_{1,\cdot}(\cdot), B_{2,\cdot}(\cdot)\}$, is concave in x for both regions $R1$ and $R2$ because the minimum of two concave functions is also concave.

(ii) In $(p, f, B/A) \in (C1 \cup C2 \cup C3)$, $\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\} \le \min\{\underline{\alpha}_{1N}(1), \underline{\alpha}_{2N}(0)\} \le \min\{\underline{\alpha}_{1N}(x), \underline{\alpha}_{2N}(x)\}$ for every $x \in [0,1]$. As a result, the profit of consortium formation is non-negative for each supplier whereas the profit of each supplier without consortium formation is negative. Consequently, all benefit terms are positive for any $x \in [0,1]$ in the respective regions they are defined. ■

Proof of Lemma 2. The buyer's policy is identical to that outlined in Proposition 2 except for the region $(p, f, B/A) \in (C1 \cup C2 \cup C3)$. By Lemma 1$(ii)$, the suppliers continue to stay in the consortium for any $x \in [0,1]$ whenever $(p, f, B/A) \in (C1 \cup C2 \cup C3)$. Therefore, no interval of x in $[0,1]$ exists so that $\underline{\alpha}_{1N}(x) \le \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$ or $\underline{\alpha}_{2N}(x) \le \max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$. This corresponds to the case P1 as defined in the proof of Proposition 2(iii). In this case, the buyer achieves maximum profits at $\max\{\underline{\alpha}_{1C}, \underline{\alpha}_{2C}\}$, which is not a function of x. Therefore, once the price is appropriately chosen, choosing a different x cannot further increase nor decrease the profits of the buyer whenever $(p, f, B/A) \in (C1 \cup C2 \cup C3)$. ■

Proof of Proposition 4. As stated in Lemma 1(i), the minimum of benefit functions across two suppliers, as well as the individual benefit functions, are concave in x for both regions $R1$ and $R2$. The buyer can set any x in its entire range by Lemma 2. Therefore, showing that the minimum of benefit functions across two suppliers decreases with x at $x = f$ suffices to show that the minimum of benefit functions across two suppliers is maximized at some $x \le f$, an egalitarian allocation. Thus, we specifically show that the minimum of benefit functions across two suppliers decrease with x at $x = f$ for every $(p, f, B/A)$ combination in $(C1 \cup C2 \cup C3) \setminus E$. We divide the region $(C1 \cup C2 \cup C3) \setminus E$, $E = \Big((1/2 \le p \le 1 \cap 1/2 \le f \le \frac{2p}{2p+1}) \cup (1 \le p \le 15/14 \cap \frac{p}{p+1} \le f \le \frac{2}{3})\Big)$ into subregions and outline properties of each relevant benefit function at $x = f$ in Table 4.

For each region that collectively form $(C1 \cup C2 \cup C3) \setminus E$, the minimum of benefits across suppliers is decreasing in x at f. Since the minimum of benefits across suppliers is concave in x, the maximizer of the minimum of benefits can never be greater than f. ■

Table 4 **Description of comparative statics of relevant benefit functions as in Table 3 at $x = f$.**

Region	**Part of**	**Supplier with Minimum Benefit**	**Behavior with x at $x = f$**
$C1 \setminus E$	$R1$	1	↘
$C3 \setminus E$	$R2$	2	↘
$(C2 \setminus E) \cap (0 \leq B \leq \overline{\overline{B}}_2(p,f))$	$R1$	2	↘
$(C2 \setminus E) \cap (\overline{\overline{B}}_2(p,f)) < B < \bar{B}_2(p,f))$	$R1$	1	↘
Parameter	**Value**		
$\overline{\overline{B}}_2(p,f))$	$A\frac{p(-p+f(1-(-2+p)p)+f^2(-1+p^2)-(f+p-fp)\sqrt{1-2f(2+(-1+p)p)+f^2(3+p(-2+3p))})}{f^2(-1+p)^3-2fp(3+p^2)+p(2+p+p^2)}$		

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