Sourcing Innovation and Production

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ABSTRACT. We consider a buyer firm that sources the design and production of an innovative product from two suppliers. The value of a supplier's design depends on the supplier's effort, while the production cost is the supplier's private information. A supplier can potentially produce the design of another supplier, albeit at a switching cost added to the production cost. Hence, a sourcing mechanism of an innovative product should both motivate suppliers' innovation efforts to improve the design value and identify low-cost production solutions. We first investigate two sourcing mechanisms commonly observed in practice, under which the buyer commits to sourcing the design and the production *jointly* or *separately*. We then compare these two mechanisms with a *no-commitment* mechanism in which the buyer specifies the rules to select suppliers for design and production after receiving the designs submitted by suppliers. We also consider an *enhanced-commitment* mechanism in which the buyer commits to using the supplier who provides the best design for production. We compare the buyer's profit in each mechanism, and show that the mechanism of choice depends on the switching cost and the cost (effectiveness) of innovation investment to improve design values, because each mechanism has different capability to motivate innovation efforts and to achieve efficient design and production allocations. Our findings provide valuable managerial insights for practitioners and help explain why certain mechanisms are common in different industries.

Key words: innovation; sourcing; procurement mechanism; contest; commitment

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1. Introduction

Innovative products are the source of competitive advantage and engine of business growth in rapidly evolving industrial ecosystems (Loch and Kavadias 2008). Despite advantages, innovating takes time and resources. Thus, to reduce cycle time and lower costs, firms increasingly rely on suppliers to provide innovation (Eppinger and Chitkara 2006). For these firms, innovative-product sourcing involves two tasks: sourcing innovative solutions (product design and development), and sourcing the implementation or production of these solutions. Yet, the prior academic literature has focused on either sourcing innovation (see Ales et al. 2019 for a review) or purchasing already-developed products (see Beil 2011 and Elmaghraby 2000 for reviews). In this paper, we fill the void by studying how to source innovation and production.

Innovation sourcing and product purchasing have different objectives, hence, traditionally, different mechanisms are utilized to effectively manage each. Innovation sourcing aims to maximize the quality (value) of innovation solutions provided by suppliers. The nature of innovation makes it difficult for different parties to specify a process or an outcome of innovation to contract upon (Taylor 1995, Chen et al. 2021). Therefore, *innovation contests* have emerged as an effective tool to stimulate innovation effort in a competitive setup, in which the innovation supplier who submits the best design based on the buyer's subjective evaluation is rewarded a prize. Product purchasing is usually concerned with the cost of production (among other possible attributes) for a well-specified product. As suppliers' production costs are often private information, *procurement auctions* are common mechanisms for buyers to solicit supplier bids and award production contracts to the lowest bids. While innovation contests and procurement auctions are effective at managing each task, it is not clear how they perform when both innovation value and production costs are considered, and what alternative mechanisms might provide better overall performance.

Despite the differences, innovation sourcing and product purchasing are connected on two issues: technology transfer and innovation incentives. While suppliers are usually capable of both design and production, a supplier that provides the best design may or may not be the most efficient in production. Therefore, the buyer may use different suppliers for innovation and production, entailing a technology transfer of the design between suppliers. A supplier that provides the design usually comes with some advantage in the production know-how, often realized as a production efficiency gain, yet such an efficiency gain will be lost in the transfer. Therefore, whether to use the same supplier or different suppliers for innovation and production requires a consideration of suppliers' innovation values together with production costs as well as the friction of technology transfer. In addition, the supplier selection will affect suppliers' incentive to innovate, which depends on the expected return of innovation effort. This return may come directly from the prize of the innovation contest or indirectly from the potential compensation from follow-on production. Therefore, the connection between suppliers' innovation values and production contract awards will affect suppliers' upfront decisions of innovation effort.

Considering the differences and connections between innovation sourcing and product purchasing, different strategies are observed in the practice of innovative-product sourcing. In the public procurement domain, the European Commission (EC) supports innovative-product sourcing as a process in two phases: pre-commercial procurement for a buyer to select from alternative competing solutions, and public procurement of innovative solutions to purchase end products based on developed solutions from competing suppliers (EC n.d.). Recently introduced in the EC guidance is the Innovation Partnership procedure, in which innovation and production are sourced from a single supplier, with the innovator also providing production of the innovative solution (EC 2018).

In the U.S., the defense procurement has emphasized the use of competition to reduce costs. The Competition in Contracting Act of 1984 generally governs competition in federal procurement contracting, requiring contracts be entered into after "full and open competition" while limiting the use of noncompetitive contracts (Manuel 2011). As procurement of defense products typically involves multiple stages including R&D and production, the Department of Defense has the option to transfer technology from the developer to a second source, thereby enabling suppliers to compete for a production contract even without providing R&D (Riordan and Sappington 1989). Nevertheless, the National Defense Authorization Act for Fiscal Year 2016 (Section 815, Congress 2015) allows a production contract be awarded to the innovator for certain projects without the use of additional competitive procedures, provided that competitive procedures were used to select innovators.

In the automotive industry, shortened product life cycles has driven auto makers to accelerate innovation by increasingly leveraging suppliers for product design in addition to production. Depending on the competitive position, auto makers may use different strategies in the process of sourcing innovative products (Maurer et al. 2004). While supplier competition may be brought to the R&D stage, premium OEMs such as BMW and Porsche tend to continue working with the designer for series production. In contrast, volume players such as Ford and Volkswagen infuse more competition in the process. Not only they engage suppliers in competition for R&D contracts, they may replace the selected supplier with a low-cost supplier to take over the R&D results and bring the project into series production. The structure of OEMs remunerating suppliers' R&D expenses also differ (Maurer et al. 2004). Some explicitly compensate suppliers based on their R&D outputs with no binding elements regarding series production, whereas some others adopt production-cycle supply contracts, allowing suppliers to recoup R&D costs from a guaranteed production contract.

As the above examples demonstrate, sourcing strategies differ based on whether they choose to focus on the differences or on the connections between innovation and production. Focusing on the differences, a buyer may manage the two tasks separately, running an innovation contest to source the best design, and then, for production, giving the design to the most efficient supplier identified in a procurement auction. Such a *separate-sourcing mechanism* maximizes supplier competition in each task, allowing the flexibility to choose different suppliers for innovation and production, but it prohibits a joint consideration of both tasks in connection. An alternative is the *joint-sourcing mechanism*, in which the buyer commits to using a single supplier to provide both product design and production. The joint-sourcing mechanism avoids technology transfer between suppliers, allowing the convenience of considering suppliers' innovation values and production costs jointly in supplier selection. The commitment of awarding the production contract to the designer also enhances the incentive of supplier innovation. The drawback, however, is that the buyer loses the flexibility of using different suppliers, hence handicapping supplier competition, for the two tasks.

The above commonly-used sourcing mechanisms both require commitment to a certain sourcing structure before suppliers start their innovation process. Certainly, in a different mechanism, a buyer may still consider suppliers' innovation values and production costs simultaneously without committing to using a single supplier for both tasks. In other words, the buyer may choose the same or different suppliers for innovation and production, based on a consideration of innovation values and production costs provided by the suppliers. We call this strategy a *no-commitment mechanism*. In the construction industry such as home improvement, it is common that contractors provide an initial design along with a price quote in bidding for a project, and the client may adopt the idea of a contractor and use the same or a different contractor to build it based on the proposals received. On the other extreme, the buyer can make more commitment than the separate-sourcing mechanism by delegating production to the winner of the innovation contest (the supplier with the best design); we call this *enhanced-commitment mechanism*. This mechanism may also be interpreted as a simplified form of joint-sourcing mechanism as it commits to sourcing both design and production from a single supplier, yet selecting the supplier based only on innovation values. For instance, NATO allies recently organized a contest that solicited suppliers such as Boeing and Lockheed Martin to develop a next-generation military aircraft where the winner is promised a hefty supply contract (CRS 2020). Similarly, National Defense Authorization Act for Fiscal Year 2016 discussed above allows government agencies to employ enhanced-commitment mechanisms.

In this paper, we analyze and compare the performance of the above four mechanisms for innovative-product sourcing. We consider a buyer that sources an innovative product from two potential suppliers. Suppliers exert innovation effort in an innovation stage to improve their design values and then privately learn about their heterogeneous cost of production. A supplier has a cost advantage in implementing his own design due to the know-how built during the innovation stage, but a supplier can also produce another supplier's design by incurring an extra "switching cost." The buyer's profit consists of the value of the chosen innovative product net of all payments made to suppliers. Thus, the performance of a mechanism hinges on how effective it is in eliciting supplier effort to improve the design values (hereafter, "effort-incentive capability") and how effective it is in selecting suppliers for design and production to maximize the buyer's profit (hereafter, "allocation efficiency").

We start our analysis by comparing joint-sourcing and separate-sourcing mechanisms with respect to the buyer's profit. We show that which mechanism should be chosen hinges on how difficult it is to transfer the design of one supplier to another (i.e., switching cost) and how expensive the innovation investment is (or, in an alternative interpretation, how effective innovation investment is in increasing design values, i.e., "innovation-investment ratio"). We show that a separate-sourcing mechanism outperforms a joint-sourcing mechanism when both switching cost and innovation-investment ratio are large or when both of these values are small. In the former case, when the innovation cost is low (or innovation-investment ratio is large), suppliers have more incentive to exert effort in the innovation stage so suppliers' effort plays a bigger role in the buyer's profit. Thus, it is more beneficial for the buyer to focus on effort-incentive capability rather than allocation efficiency. When the switching cost is high, the winner of the innovation contest in the separate-sourcing mechanism gains a significant edge against the other supplier so winning the innovation contest becomes more critical. As a result, the separate-sourcing mechanism achieves a larger effort incentive than the joint-sourcing mechanism. In the other extreme where the innovation cost is high (or innovation-investment ratio is small), suppliers have less incentive to exert effort so allocation efficiency plays a critical role in the buyer's profit. In this case, when the switching cost is small, the separate-sourcing mechanism has high allocation efficiency because it has the flexibility to combine the best design with the most cost-efficient supplier whereas the joint-sourcing mechanism forgoes such flexibility by choosing a single supplier for both design and production.

Building on the strengths of the above mechanisms, we compare them to no-commitment and enhanced-commitment mechanisms. The no-commitment mechanism maximizes the allocation efficiency because depending on the innovation values, it can select the same supplier for both design and production and save from switching cost, or select different suppliers and bring together the best design with low production cost. But this comes at the expense of lower incentives for suppliers to exert effort. Thus, the no-commitment mechanism tends to dominate when the innovation cost is high (or innovation-investment ratio is small) so that allocation efficiency becomes more important than effort-incentive capability and also switching cost is small so that the no-commitment mechanism enjoys more flexibility in bringing together the best design with low production cost. The enhanced-commitment mechanism has the highest effort-incentive capability because the return of generating the best design is the largest in this mechanism. As a result, we show that the enhanced-commitment mechanism tends to dominate the other mechanisms when the innovation cost is low (or innovation-investment ratio is large) and hence effort-incentive capability plays a larger role in the buyer's profit than allocation efficiency.

The paper proceeds as follows. We first discuss the relevant streams of literature and how our work contributes to them in §2. Then, we present our model, detail separate-sourcing and joint-sourcing mechanisms, and compare them in §3, §4, and §5, respectively. We present no-commitment and enhanced-commitment mechanisms and compare them with the other mechanisms in §6 and §7, respectively. In §8, we summarize our key managerial insights and discuss their implications for different industries. In §9, we conclude our discussion.

2. Literature review

Our work combines the sourcing of innovation and production so it contributes to the innovation contest literature that focuses on sourcing innovation and the procurement literature that focuses on purchasing finished products.

We model the innovation stage in our paper building on the innovation-contest framework pioneered by Terwiesch and Xu (2008) who study how many participants to let in an innovation contest. Also called tournaments, such contest mechanisms award winners with pre-announced fixed prizes. Ales et al. (2017) study the optimal award scheme and show that a winner-take-all award scheme that awards only the best solution is optimal in a broad set of contests, and Mihm and Schlapp (2019) extend this framework to a multi-stage setting to analyze whether and how to provide feedback to participants. Follow-up work utilizes this framework to study different aspects of innovation contests such as whether to run contests internally or externally (Nittala and Krishnan 2016), how to run contests with multiple attributes (Hu and Wang 2020), how to set the duration of a contest (Korpeoglu et al. 2020), whether and when to allow open entry Ales et al. (2020), whether to allow teamwork (Candoğan et al. 2020), and the impact of running parallel contests (Körpeoğlu et al. 2021). Recently Chen et al. (2021) apply this framework to procurement settings to analyze how companies can utilize contests to procure complex innovations for products possibly consisting of multiple attributes. While these works give valuable insights on how a contest organizer can source the best innovation from a group of suppliers (also called solvers), they abstract away from how this innovation will be implemented or assume that the supplier with the best innovation will also perform the production (i.e., enhanced commitment). Thus, we contribute to this literature by considering the sourcing of innovation as well as its implementation or production. Indeed, our results show when it is without much loss to focus only on innovation value as in the above papers. Specifically, we show that enhanced commitment is justified when the innovation-investment ratio is large. Yet, this mechanism is not justified when the innovation-investment ratio is small. Instead, the buyer is better off making the decision of which supplier to choose for design and/or production after considering both the innovation values and production costs of suppliers.

Though fixed-prize innovation contests as shown in the above papers are common for sourcing innovation, a number of papers study the use of auctions in the contest mechanism. An auction allows suppliers to bid their prizes, and the buyer selects the winner based on the combination of suppliers' innovation values and prize bids. Fullerton and McAfee (1999) establishes that a first-price auction mechanism generally reduces the buyer's prize expenditure relative to a fixed-prize contest. Che and Gale (2003) analyze the optimal auction mechanism in a general form of menu prizes that can be reduced to a first-price auction or a fixed-prize contest, assuming deterministic innovation outcome. Considering a different type of innovation technology, Schöttner (2008) shows that a contest may or may not outperform a first-price auction depending on the distribution of suppliers' innovation values. While these three papers consider only the innovation task, Che et al. (2017) further incorporate suppliers' production costs, as in our paper. They assume the innovation values are verifiable and contractible, allowing the buyer to specify contract award rules based on the innovation values to realize, *before* suppliers choose their innovation efforts. However, when it comes to sourcing innovation, lack of technical knowledge by the buyer or the subjective nature of innovation value of a design makes it difficult to specify a certain metric for evaluation that can be verifiable in court (e.g., Taylor 1995, Chen et al. 2021). Thus, more consistent with innovation-sourcing practice, we consider the case where the innovation value is non-verifiable (though observable by the buyer), prohibiting the parties to write contracts contingent on the value. In this case, the buyer utilizes relative ranking of innovation values or a combination of innovation value and production cost to determine which suppliers to work with. This approach allows us to compare different practically-relevant mechanisms to source innovation and production, and generate valuable managerial insights about when to use each mechanism.

The procurement literature studies mechanisms for buyers to purchase from suppliers with unobservable characteristics (such as costs). These mechanisms typically use supplier competition or contract menus to reveal private information and extract surplus from suppliers (e.g., Laffont and Tirole 1987, Rogerson 2003, and Perry and Sákovics 2003). See Laffont and Tirole (1993) and Elmaghraby (2000) for reviews of procurement theories and sourcing mechanisms. In these papers, the supplier types, though unknown to the buyer, are given. The buyer designs a procurement mechanism to minimize expected costs. In our paper, the buyer faces a similar problem in the procurement stage after suppliers' design values and production costs are realized. However, we consider also the innovation stage preceding the procurement stage, in which suppliers invest in innovation that affects their design values, anticipating the payoff from the procurement stage.

A stream of papers in the procurement literature study suppliers' investment in cost reduction before they compete on costs. Piccione and Tan (1996) and Dasgupta (1990) analyze the equilibrium outcome of supplier investment in comparison to the first-best result, and investigate the impact of the number of suppliers on the outcome. Tan (1992) compare the performance of first-price and second-price procurement auctions, with suppliers investing in cost reduction before bidding in the auction. Bag (1997) shows that first-best results may be achieved with such auctions if the buyer commits to discriminating reservation prices in the auctions before suppliers invest. Li (2013) and Li and Wan (2017) study supply base design, considering the benefit of supplier competition in procurement and its impact on suppliers' cost reduction effort. Differing from these papers, we consider supplier investment in innovation that enhances the product value for the buyer, with exogenous and heterogeneous production costs. Therefore, the procurement mechanism must consider both the product values and production costs of suppliers. Though both a higher value and a lower cost improves a supplier's competitiveness, they impose different information and economic structures: the product value is observable by the buyer and the production cost is not. As the product value is specific to the buyer's market, it does not affect the supplier profit given the supply contract, whereas the production cost detracts from a supplier's profit.

While the above papers allow multiple suppliers to invest in cost reduction before they compete in the procurement auctions, a stream of papers considers the cost-reduction investment of a single incumbent supplier, who competes with entrant suppliers in a second-sourcing mechanism after the investment. By allowing the buyer to switch from the incumbent to an entrant supplier, a second-sourcing mechanism reduces the buyer's information rent while improving the allocation efficiency, but it hurts the incumbent's *ex-ante* incentive to invest in improvement. Considering this trade-off, Riordan and Sappington (1989) analyzes the overall benefit of second sourcing, Stole (1994) studies the optimal second-sourcing mechanism committed by the buyer before the incumbent's investment, and Rob (1986) focuses on the optimal quantity allocated for second sourcing as opposed to the quantity dedicated to the incumbent. In these papers, suppliers are asymmetric because only the incumbent invests in improvement (of production costs). In our case, the supplier competition is (ex ante) symmetric, causing a different incentive structure for suppliers' investment (in innovation value enhancement). Our study captures the potential innovation investment of suppliers as they compete to provide the innovative design, a feature that is common in the practice of innovative-product sourcing.

3. Model and Preliminaries

We build a parsimonious model that captures the main aspects of our problem while preserving tractability. A buyer (she) sources the design (innovation solution) and production of an innovative product from two symmetric risk-neutral suppliers (he) indexed $i \in \{1,2\}$ and $j = 3-i$.

We first describe the *innovation* model. We follow the setup that is common in the innovation contest literature (e.g., Mihm and Schlapp 2019, Hu and Wang 2020): Each supplier i exerts innovation effort e_i by incurring a cost $\psi(e_i) = ce_i^2$, where $c > 0$ determines the marginal cost of innovation effort. The value of a supplier's design is random, increasing stochastically in the effort. Specifically, given effort e_i, the value of a supplier's design is $v_i = m + e_i + \xi_i$, where m is a constant that represents the base value of innovation to the buyer and ξ_i is a random shock drawn from a uniform distribution on $[-d, +d]$. Therefore, with marginal cost parameter c, the effort brings expected return e_i in innovation value with marginal cost $2ce_i$. We call the return relative to cost the *innovation-investment ratio.* A higher cost parameter c is equivalent to a lower innovation-investment ratio. For innovation-driven industries such as aerospace, defense, and premier car makers, the return of innovation is high and so c may be considered low. For labor-intensive industries such as apparel and construction, the design process usually requires long labor hours (hence charged by hours), implying high c. Consistent with practice, the innovation value v_i depends on the subjective taste of the buyer, and a supplier's investment in innovation e_i involves complex activities that are difficult to specify in a contract. So neither a supplier's innovation effort nor the value generated with the effort is verifiable or contractible. As a result, the parties are prohibited from writing contracts contingent on efforts or innovation values to incentivize innovation efforts.

We next introduce the *production* model. Suppliers' production costs are uncertain, and are realized after the innovation stage. The uncertainty captures the variations in a supplier's internal and external environments (such as financial status, productivity, upstream suppliers, and logistics) that may occur over the time when the innovation effort takes place, affecting the supplier's cost efficiency. In our base model, we assume that the production costs are independent of the design quality (innovation value), considering designs focusing on product architecture that affects product performance and function but not production costs.[1] The production cost of supplier i, c_i, is a random draw from a uniform distribution $U(\underline{c}, \overline{c})$, with $\Delta \equiv \overline{c} - \underline{c}$. Hence the cumulative distribution function and density function of the production cost are $F(c_i) = (c_i - \underline{c})/\Delta$ and $f(c_i) = 1/\Delta$ (when $c_i \in [\underline{c}, \overline{c}]$), respectively. The prior distribution $U(\underline{c}, \overline{c})$ is common knowledge, while the realized costs c_i are private information held by each supplier i. Therefore, suppliers face the same ex-ante production costs, though their ex-post costs are different. To use in the procurement mechanism design, we define a supplier's virtual production cost as follows.

Definition 1. The virtual production cost is defined as $C(c_i) = c_i + \frac{F(c_i)}{f(c_i)} = 2c_i - \underline{c}$.

The buyer can potentially delegate a supplier's design to another supplier for production but there is a *switching cost* of $l > 0$ for a supplier to produce the design of another supplier. This switching cost can arise because the supplier who provides the design builds a know-how that makes it easier for him to implement his own design than any other supplier (see Stole 1994, Rob 1986, Riordan and Sappington 1989). Such a know-how advantage may manifest itself as knowledge of advanced technologies needed to produce an innovative design (as in the aerospace and defense industries) or as intangible details that cannot be fully specified in a design but requires a close collaboration between the designer and producer for implementation (as in apparel industry). Therefore, the actual production cost of supplier i becomes $c_i + l$ (the virtual production cost of supplier i becomes $C(c_i) + l$) if the design comes from another supplier. To ensure that there is

[1] In a general situation, a better design may require more expensive materials or special tools, leading to a higher production cost. Such a correlation can be incorporated by deducting the correlated part of production cost from the innovation value without changing the model. In §EC.3 of the Online Appendix, we model such correlation explicitly, and show the robustness of our main results.

a meaningful competition among suppliers when the buyer is procuring production, we make the following assumption:

ASSUMPTION 1. *$m - d - l > C(\bar{c})$.*

This assumption ensures that the innovation generates sufficient value for the buyer (i.e., $v > l + C(\bar{c})$ for any realization of v) so that neither supplier needs to be cut off from procurement, regardless of their production cost realization (see Li 2013). Assumption 1 is easily satisfied when the parameter m, which measures the expected base value of an innovation to the buyer, is sufficiently large.

We now describe the sourcing mechanisms. A mechanism proceeds in two stages. In the first *innovation* stage, each supplier i chooses an innovation effort e_i and develops a design (innovation solution), upon which the innovation value v_i and production cost c_i are realized. Then, in the second *procurement* stage, observing supplier's innovation values, the buyer selects the design and the supplier to produce the design, along with supplier payments. A mechanism differs in the rules adopted in the procurement stage. In a general form, the mechanism takes as inputs the suppliers' innovation values $\mathbf{v} \equiv (v_1, v_2)$. As suppliers' production costs $\mathbf{c} \equiv (c_1, c_2)$ are private information, in a direct mechanism, suppliers will be asked to report their costs, which, in an incentive compatible mechanism, will be truthful. Following the optimal mechanism design framework (Myerson 1981), it is without loss to restrict our attention to direct incentive compatible mechanisms that reveal suppliers' true production costs; so the mechanism uses the observed innovation values $\mathbf{v} \equiv (v_1, v_2)$ and the reported (but true) production costs $\mathbf{c} \equiv (c_1, c_2)$ in the allocation decisions. Specifically, an innovative-product sourcing mechanism consists of a design-selection rule $y_i(\mathbf{c}|\mathbf{v})$ (the probability that supplier i's design is selected), production-selection rule $x_i(\mathbf{c}|\mathbf{v})$ (the probability that supplier i is selected to provide production), and compensation rule $t_i(\mathbf{c}|\mathbf{v})$ (the payment to supplier i), which together compose a menu of contracts varying on $\mathbf{c}$ for given $\mathbf{v}$, for $i = 1, 2$.

In our main analysis, we focus on the two practically-relevant mechanisms in which the buyer sources design and production *jointly* by using a single supplier to provide both, or *separately* by adopting potentially different suppliers for each. Specifically, in the *separate-sourcing* mechanism, the buyer first chooses the best (highest value) design and then the best (lowest production cost) supplier to produce the design. Because the buyer decouples the procurement of design and production, this mechanism boils down to an *innovation contest* to source the best design, committing to $y_i(\mathbf{c}|\mathbf{v}) = 1(0)$ if and only if $v_i \geq (<) v_j$, followed by a *procurement auction* to source the production based on production costs. In the *joint-sourcing* mechanism, the buyer commits to $y_i(\mathbf{c}|\mathbf{v}) = x_i(\mathbf{c}|\mathbf{v})$, delegating the production to the supplier who provides the design. In this case, the buyer does not necessarily choose the best design, and may settle for a supplier with worse design if this supplier has a low production cost. Throughout the paper, we use subscripts S and J to denote the variables under separate-sourcing and joint-sourcing mechanisms, respectively.

In the following section, we provide details of the equilibrium analyses for the separate-sourcing and joint-sourcing mechanisms. Before we proceed, note that for given innovation values $\mathbf{v}$ and production costs $\mathbf{c}$ of suppliers, an *efficient allocation* of the design and production contracts would select the supplier(s) for design and production to maximize the innovation value net of the production cost (which includes the switching cost l if different suppliers provide design and production). Any deviation from this allocation causes inefficiency.

4. Mechanisms and Equilibria

4.1. Separate-Sourcing Mechanism

In a separate-sourcing mechanism, the buyer first announces the innovation contest prize $P \le \overline{P}$ that will be used to select the best design, where $\overline{P}$ is the buyer's budget for the prize. Then suppliers choose their efforts in the innovation stage. It is followed by the procurement stage, which is decoupled in two sequential steps, an innovation contest to source the design, and a procurement auction to source the production of the design. Therefore, this mechanism commits to a design selection rule $y_S(\mathbf{c}|\mathbf{v}) \equiv \{y_i(\mathbf{c}|\mathbf{v}), i = 1,2\}$, where $y_i(\mathbf{c}|\mathbf{v}) = 0$ if $v_i < v_j$ and $y_i(\mathbf{c}|\mathbf{v}) = 1$ otherwise, independent of suppliers' production costs. Let subscript 'W' ('L') represent the supplier who wins (loses) the innovation contest. Then, in the procurement auction, the buyer selects a supplier to produce the design of supplier W and determines the payment. Let the supplier-selection rule in the procurement auction be $\tilde{x}_i(\mathbf{c})$ and payment rule be $\tilde{t}_i(\mathbf{c})$, for $i = W, L$. Then, the separate-sourcing mechanism has the production-selection rule $x_S(\mathbf{c}|\mathbf{v}) \equiv \{x_i(\mathbf{c}|\mathbf{v}), i = 1,2\}$, for $x_i(\mathbf{c}|\mathbf{v}) = \tilde{x}_W(\mathbf{c})y_i(\mathbf{c}|\mathbf{v}) + \tilde{x}_L(\mathbf{c})(1 - y_i(\mathbf{c}|\mathbf{v}))$, and supplier-compensation rule $t_S(\mathbf{c}|\mathbf{v}) \equiv \{t_i(\mathbf{c}|\mathbf{v}), i = 1,2\}$, for $t_i(\mathbf{c}|\mathbf{v}) = (\tilde{t}_W(\mathbf{c}) + P)y_i(\mathbf{c}|\mathbf{v}) + \tilde{t}_L(\mathbf{c})(1 - y_i(\mathbf{c}|\mathbf{v}))$.

Next, using backward induction, we first analyze the procurement auction for production sourcing. Expecting this outcome along with the preceding innovation contest in the procurement stage, we then investigate the suppliers' effort decisions in the innovation stage for a given contest prize. This is followed by the analysis of the buyer's optimal contest prize, leading to the equilibrium outcome of the suppliers' effort and the buyer's profit.

Production Procurement. Recall that supplier W and L are identified in the innovation contest as the supplier who wins and loses the contest, respectively. The production-procurement mechanism specifies the supplier-selection rule $\tilde{x}_i(\mathbf{c})$ and payment rule $\tilde{t}_i(\mathbf{c})$, $i \in \{W, L\}$, for production of supplier W's design. By reporting cost $\hat{c}_W$, the winning supplier W with actual cost c_W receives expected utility $\hat{u}_W(\hat{c}_W, c_W) = \mathbb{E}_{c_L}[\tilde{t}_W(\hat{c}_W, c_L) - \tilde{x}_W(\hat{c}_W, c_L)\, c_W]$. Similarly, by reporting cost $\hat{c}_L$, the losing supplier L with actual cost c_L receives expected utility $\hat{u}_L(\hat{c}_L, c_L) = \mathbb{E}_{c_W}[\tilde{t}_L(c_W, \hat{c}_L) -$

$\tilde{x}_L(c_W, \hat{c}_L)(c_L + l)]$. Let $u_i(c_i) \equiv \hat{u}_i(c_i, c_i)$ be supplier i's ($i \in \{W, L\}$) expected utility from this mechanism when reporting true costs c_i. Based on the mechanism design theory (Myerson 1981), a feasible mechanism must satisfy incentive-compatibility (IC) constraints, which ensure that it is in the best interest of suppliers to report their true production costs:

$$u_i(c_i) \geq \hat{u}_i(\hat{c}_i, c_i), \quad i \in \{W, L\}. \tag{1}$$

In addition, a feasible mechanism must satisfy individual rationality (IR) constraints, which ensure that suppliers receive non-negative expected utility from participating in the mechanism:

$$u_i(c_i) \geq 0, \quad i \in \{W, L\}. \tag{2}$$

In the production procurement, the buyer aims to maximize her expected profit, which is the innovation value (v_W) net of the expected compensation to suppliers. Therefore, the buyer determines the production-procurement mechanism $(\tilde{x}_i(\mathbf{c}), \tilde{t}_i(\mathbf{c})), i \in \{W, L\}$, by solving the following mechanism design problem:

$$\begin{aligned} \max_{\tilde{x}_i(\mathbf{c}), \tilde{t}_i(\mathbf{c}), i \in \{W,L\}} \; & \mathbb{E}_{\mathbf{c}}\left[v_W - \sum_{i \in \{W,L\}} \tilde{t}_i(\mathbf{c})\right] \\ s.t. \quad & \sum_{i \in \{W,L\}} \tilde{x}_i(\mathbf{c}) \leq 1 \quad \text{and} \quad \tilde{x}_i(\mathbf{c}) \geq 0, \quad \forall \mathbf{c}, \\ & (1), (2). \end{aligned}$$

The following proposition characterizes the outcome of the procurement auction. All proofs are presented in the Online Appendix.

Proposition 1. *In the separate-sourcing mechanism, given suppliers' innovation values* $\mathbf{v}$, *an optimal procurement auction for production has the following results:*

(i) The optimal allocation rule for the winner of the innovation contest is:

$$\tilde{x}_W(\mathbf{c}) = \begin{cases} 1 & \text{if } C(c_W) \leq C(c_L) + l \\ 0 & \text{otherwise,} \end{cases}$$

and for the loser of the innovation contest is $\tilde{x}_L(\mathbf{c}) = 1 - \tilde{x}_W(\mathbf{c})$.

(ii) The suppliers who win and lose the innovation contest receive the following expected utility from the procurement auction, respectively:

$$\tilde{U}_W = \int_{\underline{c}}^{\overline{c}} F(c_W)\left(1 - F\left(c_W - \frac{l}{2}\right)\right) dc_W,$$

$$\tilde{U}_L = \int_{\underline{c}}^{\overline{c}} F(c_L)\left(1 - F\left(c_L + \frac{l}{2}\right)\right) dc_L.$$

We have $\tilde{U}_L \leq \tilde{U}_W$, *with* $\tilde{U}_L$ *decreasing while* $\tilde{U}_W$ *increasing in* l.

(iii) The expected utility of the buyer from the procurement auction is

$$U_S(\mathbf{v}) = v_W - \left[\int_{\underline{c}}^{\overline{c}} C(c_W)\left(1 - F\left(c_W - \frac{l}{2}\right)\right) f(c_W) dc_W + \int_{\underline{c}}^{\overline{c}} (C(c_L) + l)\left(1 - F\left(c_L + \frac{l}{2}\right)\right) f(c_L) dc_L\right]. \tag{3}$$

As characterized in Proposition 1(i), supplier L will win the production contract if and only if $C(c_L) \leq C(c_W) - l$; i.e., $c_L \leq c_W - l/2$ with the uniform production cost distribution. This is because supplier L incurs a switching cost l to implement the design of supplier W. Thus, the buyer will continue to select supplier W for production unless supplier L has a sufficiently large production-cost advantage, in which case the switching cost l will add to supplier L's effective production cost. In other words, even if $c_L < c_W$, the switching cost limits the buyer's ability to delegate the design to the supplier with a lower production cost, and increases the effective production cost when such delegation happens, both of which causing higher production-procurement costs for the buyer.

Proposition 1(ii) shows that the winner of the innovation contest expects a higher utility from the procurement auction than the loser, and the winner's utility increases and the loser's utility decreases with the switching cost l. This is because the switching cost will be incurred if the loser of the innovation contest is selected for production whereas it is avoided if the winner is selected. That is, the switching cost gives the winner an advantage over the loser in the procurement auction.

Proposition 1(iii) characterizes the buyer's expected utility from the procurement auction, which equals the innovation value v_W generated from the innovation contest, net of the expected payment to suppliers in production procurement. As discussed in part (i), if $c_L < c_W$, the switching cost will cause friction in production procurement. Thus, although the innovation contest allows the buyer to select the best-value design, this myopic selection might lead to higher costs in the later procurement auction if the design provider is disadvantageous in production efficiency, thereby causing *allocation inefficiency*. Specifically, when suppliers' innovation value difference $v_W - v_L > 0$ is small or the switching cost l is high, it might be beneficial for the buyer to take into consideration suppliers' production costs in the design allocation, selecting the supplier of a lower-value design to enjoy the lower production cost provided by the supplier without switching.

Innovation Effort Decisions for Given Prize P. In the innovation stage, given the innovation contest prize P and suppliers' expected utility $\tilde{U}_W$ and $\tilde{U}_L$ from the procurement auction, supplier $i \in \{1,2\}$ chooses his innovation effort to maximize his total expected profit by solving:

$$\max_{e_i} \pi_i(\mathbf{e}) = (\tilde{U}_W + P)\Pr(v_i > v_j|\mathbf{e}) + \tilde{U}_L(1 - \Pr(v_i > v_j|\mathbf{e})) - \psi(e_i). \tag{4}$$

Let $\epsilon = \xi_i - \xi_j$ with a cumulative distribution function H and a probability density function h. (The detailed characterization of H and h are shown in the proof of Lemma 3.) Then, the probability that supplier i wins the innovation contest is $\Pr(v_i > v_j|\mathbf{e}) = 1 - H(e_j - e_i)$ and the probability that supplier j wins is $\Pr(v_j > v_i|\mathbf{e}) = H(e_j - e_i)$.

Given the formulation in (4), we next derive the equilibrium of innovation effort between suppliers. As standard in the innovation-contest literature, we focus on a symmetric pure strategy Nash equilibrium among suppliers in the innovation stage. To ensure that such an equilibrium exists and the buyer's problem is well-defined, we make the following mild regulatory assumption.

Assumption 2. $0 < \overline{P} \leq 8cd^2 - \frac{\Delta}{3} - \frac{\min\{l,2\Delta\}^2}{8\Delta} + \frac{\min\{l,2\Delta\}^3}{24\Delta^2}$.

Assumption 2 is satisfied when the innovation uncertainty d is sufficiently high. Similar assumptions are common in the innovation-contest literature (e.g., Mihm and Schlapp 2019, Ales et al. 2020). Under this assumption, there exists a unique pure strategy Nash equilibrium, that can be proven symmetric; see the proof of Lemma 1 in the Online Appendix.

Lemma 1. *There exists a unique pure strategy Nash equilibrium in the separate-sourcing mechanism for given innovation contest prize P, where each supplier exerts the equilibrium effort*

$$e_S(P) = \begin{cases} \frac{2P+\Delta}{8cd} & l \geq 2\Delta \\ \frac{l(4\Delta-l)+8\Delta P}{32cd\Delta} & l < 2\Delta \end{cases} \tag{5}$$

that is increasing in P.

Unsurprisingly, the equilibrium effort $e_S(P)$ increases with the contest prize P, as a larger P increases the return of a supplier's effort on his expected compensation from the innovation contest, hence motivating more effort.

Optimal Contest Prize and Equilibrium Outcome. Given the buyer's expected utility from the procurement auction $U_S(\mathbf{v})$ (see (3)), her *ex-ante* expected profit is $\Pi_S(P) = \mathbb{E}_{\mathbf{v}}[U_S(\mathbf{v})|e_S(P)] - P$. As $e_S(P)$ increases with P, so does $\mathbf{v}$ and $U_S(\mathbf{v})$. Thus, the buyer chooses the contest prize $P \in [0, \overline{P}]$ to maximize $\Pi_S(P)$. Let P_S^* be the optimal prize, and $e_S^* \equiv e_S(P_S^*)$ the resulting supplier effort with buyer profit $\Pi_S^* \equiv \Pi_S(P_S^*)$. Lemma 2 characterizes P_S^*.

Lemma 2. *In the separating-sourcing mechanism, the optimal innovation-contest prize is*

$$P_S^* = \begin{cases} \overline{P} & \frac{1}{d} > 4c \\ 0 & \frac{1}{d} \leq 4c. \end{cases} \tag{6}$$

The optimal prize P_S^* is such that when the effort cost parameter c is small (i.e., $c < \frac{1}{4d}$), providing a monetary prize to suppliers in the innovation contest will benefit the buyer; whereas when the parameter c is large, the buyer should not give any prize to the contest winner. This is because when c is large, the benefit of prize P on motivating suppliers' innovation effort (see Lemma 1) cannot offset the prize P paid by the buyer; in this case, the contest winner's advantage in the procurement auction for production ($\tilde{U}_W > \tilde{U}_L$ as shown in Proposition 1(ii)) becomes the sole source of incentives for supplier innovation. Only when c is small enough, it becomes economically sensible to give a prize to reward the supplier with the best innovation value, and the best strategy is to set the prize as high as possible (i.e., at the prize budget $\overline{P}$). Such a binary structure for the optimal contest prize also appears in the innovation contest literature (see, e.g., Mihm and Schlapp 2019). It captures the common finding that the optimal prize decreases with the cost of effort (e.g., Korpeoglu et al. 2020) while preserving analytical tractability. (While the specific binary structure of the optimal prize stems from the quadratic cost function we use, we show the robustness of our findings in the case with a more general cost function in §EC.2 of the Online Appendix.)

With P_S^*, we obtain the following comparative statics of the supplier effort e_S^* and the buyer's expected profit Π_S^* with respect to the switching cost l.

COROLLARY 1. *In the separate-sourcing mechanism,*

(i) e_S^* *is increasing in the switching cost* l*.*

(ii) When $4cd \leq 1$*,* Π_S^* *is increasing in* l*; and when* $4cd > 1$*,* Π_S^* *is first decreasing and then increasing in* l*.*

As shown in Corollary 1(i), a higher switching cost l leads to a larger innovation effort for each supplier. This is because a higher l helps the supplier who wins the innovation contest receive a larger expected utility in the procurement auction (see Proposition 1(ii)) since the winning supplier carries to the auction an advantage of l in the expected production cost, which boosts his chances of producing his own design. However, as shown in Corollary 1(ii), the direction of how the switching cost l affects the buyer's expected profit Π_S^* is not monotone and it depends on the value of the effort cost parameter c. This is because l has two opposing effects on Π_S^*. On the one hand, a larger l aggravates allocation inefficiency of the myopic design-selection rule, causing higher production-procurement cost for the buyer. On the other hand, a large l induces suppliers to exert a larger equilibrium effort e_S^*, thereby improving the innovation value. When c is low, the supplier effort is sensitive to the switching cost l, so the benefit of larger l on the innovation value outweighs its harm on the production cost, whereas the opposite is true when c is high.

In summary, with a separate-sourcing mechanism, the innovation contest (even without an explicit prize) motivates suppliers to invest in innovation to gain an advantage in the procurement auction. The mechanism allows the buyer to select the best-value design in the innovation contest, and, given the design selection, to minimize the production cost in the the procurement auction. Nevertheless, the mechanism does not necessarily maximize the overall profit. This is because it selects the design myopically without considering the consequence on the production cost. Indeed, it might be better to select a lower-value design if its supplier has much lower production cost than the other supplier while the switching cost is high and the suppliers' innovation value difference is small. Thus, despite the effort incentive provided by the innovation contest, the separate-sourcing mechanism suffers from allocation inefficiency attributed to myopic design selection. While a larger switching cost l improves the effort incentive, it aggravates the allocation inefficiency.

4.2. Joint-Sourcing Mechanism

With a joint-sourcing mechanism, the buyer delegates design and production to the same supplier, committing to $y_i(\mathbf{c}|\mathbf{v}) = x_i(\mathbf{c}|\mathbf{v})$ before supplier innovation takes place. Anticipating this rule, suppliers exert innovation efforts e_i, $i=1,2$. Then, observing the innovation values $\mathbf{v}$, the buyer specifies the procurement mechanism (contract menus) including the supplier-selection rule $x_i(\mathbf{c}|\mathbf{v})$ and compensation rule $t_i(\mathbf{c}|\mathbf{v})$. Using backward induction, we first analyze the procurement mechanism for given $\mathbf{v}$, and then examine suppliers' innovation effort decisions that lead to $\mathbf{v}$. Let $y_J(\mathbf{c}|\mathbf{v}) \equiv \{y_i(\mathbf{c}|\mathbf{v}), i=1,2\}$, $x_J(\mathbf{c}|\mathbf{v}) \equiv \{x_i(\mathbf{c}|\mathbf{v}), i=1,2\}$, and $t_J(\mathbf{c}|\mathbf{v}) \equiv \{t_i(\mathbf{c}|\mathbf{v}), i=1,2\}$ be design-selection, production-selection, and supplier-compensation rules in the joint-sourcing mechanism.

Procurement Mechanism for Given v. By reporting cost $\hat{c}_i$, a supplier i with actual cost c_i would receive expected utility $\hat{u}_i(\hat{c}_i, c_i|\mathbf{v}) = \mathbb{E}_{c_j}[t_i(\hat{c}_i, c_j|\mathbf{v}) - x_i(\hat{c}_i, c_j|\mathbf{v})\, c_i]$. Let $u_i(c_i|\mathbf{v}) \equiv \hat{u}_i(c_i, c_i|\mathbf{v})$ be supplier i's *ex-ante* expected utility from the mechanism when reporting true cost c_i. Similar to the production-procurement mechanism in separate sourcing, a feasible mechanism $(x_i(\mathbf{c}|\mathbf{v}), t_i(\mathbf{c}|\mathbf{v}))$, $i=1,2$, must satisfy incentive-compatibility (IC) constraints, i.e.,

$$u_i(c_i|\mathbf{v}) \geq \hat{u}_i(\hat{c}_i, c_i|\mathbf{v}), \quad i \in \{1,2\}, \tag{7}$$

and individual rationality (IR) constraints, i.e.,

$$u_i(c_i|\mathbf{v}) \geq 0, \quad i \in \{1,2\}. \tag{8}$$

The buyer aims to maximize the expected innovation value $\mathbb{E}_{\mathbf{c}}[\sum_{i=1}^{2} v_i x_i(\mathbf{c}|\mathbf{v})]$ net of the expected compensation to the suppliers $\mathbb{E}_{\mathbf{c}}[\sum_{i=1}^{2} t_i(\mathbf{c}|\mathbf{v})]$. Therefore, the buyer can derive the optimal contract menu $(x_i(\mathbf{c}|\mathbf{v}), t_i(\mathbf{c}|\mathbf{v}))$ for each supplier i by solving the following mechanism design problem:

$$\begin{aligned} \max_{x_i(\mathbf{c}|\mathbf{v}), t_i(\mathbf{c}|\mathbf{v}), i=\{1,2\}} \; & \mathbb{E}_{\mathbf{c}}\left[\sum_{i=1}^{2} v_i x_i(\mathbf{c}|\mathbf{v}) - t_i(\mathbf{c}|\mathbf{v})\right] \\ s.t. \; & \sum_{i=1}^{2} x_i(\mathbf{c}|\mathbf{v}) \leq 1 \quad \text{and} \quad x_i(\mathbf{c}|\mathbf{v}) \geq 0, \quad \forall \mathbf{c}, \forall \mathbf{v}, \\ & (7), (8). \end{aligned} \tag{9}$$

The outcome of the optimal mechanism is characterized in Proposition 2.

PROPOSITION 2. *In an optimal joint-sourcing mechanism:*

(i) The buyer selects the winning supplier based on the following selection rule:

$$x_i(\mathbf{c}|\mathbf{v}) = \begin{cases} 1 & \text{if } v_i - C(c_i) \geq v_j - C(c_j) \\ 0 & \text{otherwise.} \end{cases}$$

(ii) Supplier i's expected utility, for given suppliers' innovation values $\mathbf{v}$*, is*

$$U_{iJ}(\mathbf{v}) = \int_{\underline{c}}^{\overline{c}} F(c_i) \left(1 - F\left(c_i - \frac{v_i - v_j}{2}\right)\right) dc_i. \tag{10}$$

Furthermore, $U_{iJ}(\mathbf{v})$ *is increasing in* v_i *and decreasing in* v_j*.*

(iii) The buyer's expected utility, for given suppliers' innovation values $\mathbf{v}$*, is*

$$U_J(\mathbf{v}) = \sum_{i=1}^{2} \int_{\underline{c}}^{\overline{c}} (v_i - C(c_i)) \left(1 - F\left(c_i - \frac{v_i - v_j}{2}\right)\right) f(c_i)\, dc_i. \tag{11}$$

Because the buyer cannot observe suppliers' production costs, she needs to pay each supplier an information rent to extract his private information about his cost. When viewed *ex-ante*, the buyer compensates a supplier based on his virtual production cost $C(c_i)$ (see Definition 1), which is greater than his true cost c_i. Thus, the buyer's profit margin from sourcing from supplier i, when viewed *ex-ante*, is $v_i - C(c_i)$. Therefore, as characterized in Proposition 2(i), it is *ex-ante* optimal for the buyer to select the supplier who yields the best profit margin based on the virtual cost. Recall that this allocation is based on the commitment of sourcing both design and production from a single supplier, thus not allowing supplier switching. However, given $\mathbf{v}$ and $\mathbf{c}$, it might generate higher profits for the buyer to use different suppliers for design and production despite the switching cost. Therefore, this allocation rule suffers from an efficiency loss from bundling design and production contracts with no switching allowed. Such loss is lower when the switching cost l is larger, as a larger l reduces the benefit of switching.

With the supplier selection rule characterized in Proposition 2(i), the probability that a supplier i is selected increases with the innovation value difference $v_i - v_j$. Thus, as shown in Proposition 2(ii), when a supplier's own innovation value v_i increases or the opponent's value v_j decreases, the supplier's expected utility from the procurement mechanism increases. This effect incentivizes suppliers to invest in innovation and improve their design values. By bundling design and production allocation, the buyer ensures that the supplier who provides the design (whose chance increases with the innovation value) is guaranteed a compensation from the production contract.

Finally, Proposition 2(iii) characterizes the buyer's expected utility. As discussed earlier, the buyer considers only the utility of sourcing both design and production from either supplier, $v_i - C(c_i)$, $i = 1, 2$, whereas allocating the two tasks to different suppliers might generate a higher utility. Thus, although bundling design and production in the joint-sourcing mechanism incentivizes supplier effort, it also contributes to allocation inefficiency.

Recall that the innovation values $\mathbf{v}$ are assessed subjectively by the buyer, so they are neither verifiable nor contractible. This raises the question of whether the buyer will truthfully reveal the innovation value of each supplier in the procurement stage. In §EC.1 of the Online Appendix, we show that the buyer does not have any incentive to manipulate suppliers' innovation values because the buyer uses innovation values only when selecting the winning supplier while compensating this supplier based only on his virtual production cost. Thus, even though innovation value is not verifiable, the buyer's mechanism is built on the real innovation values and is credible.

Innovation Effort Decisions. In the innovation stage, each supplier i chooses his innovation effort e_i to maximize his expected utility $\mathbb{E}_{\mathbf{v}}[U_{iJ}(\mathbf{v})]$ in the procurement stage, noting that his effort will stochastically improve the innovation value $v_i = m + e_i + \xi_i$. As in the separate-sourcing mechanism, we will focus on a symmetric pure strategy Nash equilibrium. Supplier i's equilibrium effort e^* is the effort e_i that solves the following optimization problem given the other supplier's effort $e_j = e^*$:

$$\max_{e_i} \mathbb{E}_{\mathbf{v}} \left[U_{iJ} \left(\mathbf{v} \right) | \mathbf{e} \right] - \psi(e_i). \tag{12}$$

The equilibrium effort level is characterized in Lemma 3. It is independent of the switching cost l because supplier switching will never occur in the joint-sourcing mechanism.

LEMMA 3. *There exists a unique symmetric pure strategy Nash equilibrium in the joint-sourcing mechanism, where each supplier exerts the equilibrium effort*

$$e_J^* = \begin{cases} \frac{(3d-\Delta)\Delta}{24cd^2} & d \geq \Delta \\ \frac{(3\Delta-d)}{24c\Delta} & d < \Delta \end{cases}, \tag{13}$$

which is independent of l.

Using the equilibrium effort in (13) and the buyer's expected utility (11) in the procurement stage, we can calculate the buyer's ex-ante expected profit in the joint-sourcing mechanism as $\Pi_J^* = \mathbb{E}_{\mathbf{v}} \left[U_J \left(\mathbf{v} \right) | e_J^* \right]$.

In summary, with a joint-sourcing mechanism, the buyer selects a single supplier for both design and production by jointly considering the innovation value and production cost. The bundling of design and production incentivizes suppliers to invest in innovation in order to win a contract that compensates for production. However, by committing to $y_J = x_J$, the buyer loses the flexibility of switching suppliers between design and production, thereby resulting in allocation inefficiency. A larger switching cost l reduces the benefit of switching suppliers, hence mitigates such allocation inefficiency.

5. Comparison results

In this section, we compare joint-sourcing and separate-sourcing mechanisms with respect to the suppliers' effort levels and the buyer's expected profit. The comparison of suppliers' effort levels is summarized in the following Proposition.

PROPOSITION 3. *The equilibrium effort in the separate-sourcing mechanism e_S^* and the one in the joint-sourcing mechanism e_J^* can be compared as follows:*

(i) $e_S^* - e_J^*$ is increasing in the switching cost l.

(ii) $e_S^* > e_J^*$ if and only if l is sufficiently high.

Proposition 3 follows the results that e_S^* is increasing in l (Corollary 1) while e_J^* is independent of l (Lemma 3). Therefore, the separate-sourcing mechanism provides a stronger effort incentive for suppliers than the joint-sourcing mechanism when the switching cost is sufficiently high.

Next, we compare the buyer's profits from the separate-sourcing and joint-sourcing mechanisms, Π_S^* and Π_J^*. Before formally presenting this comparison, we elaborate the key terms that determine the sign of $\Pi_S^* - \Pi_J^*$. We have

$$\Pi_S^* - \Pi_J^* = \underbrace{e_S^* - e_J^*}_{\text{Term 1}} + \underbrace{\frac{\min\{d,\Delta\}}{3} - \frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{l^2}{4\Delta} + \frac{\min\{d,\Delta\}^2(\min\{d,\Delta\} - 5\max\{d,\Delta\})}{30\max\{d,\Delta\}^2}}_{\text{Term 2}} - P_S^*. \qquad (14)$$

As (14) illustrates, the profit difference consists of three terms. The first term, which is the difference between the effort levels that each mechanism elicits, increases with the switching cost l as shown in Proposition 3(i). The second term of (14) is the profit difference induced by the value uncertainty d and the cost uncertainty Δ; it captures the difference in the allocation efficiency between the two mechanisms. This term is decreasing in the switching cost l because for given $\mathbf{v}$, the buyer's expected utility from the separate-sourcing mechanism (Equation 3) is decreasing in l while the one from the joint-sourcing mechanism (Equation 11) is independent of l. Since the switching cost l has opposite effects on the two terms, the structure of the profit comparison is non-trivial. The following proposition formally presents the comparison results.

Proposition 4. *Define thresholds* $C_1 \equiv \frac{5(d^2-3\Delta\min\{d,\Delta\}+3\Delta^2)\Delta}{4(-d^2\min\{d,\Delta\}+5d^2\max\{\Delta,d\}-10\Delta^2\min\{d,\Delta\}+10\Delta^3)\min\{d,\Delta\}}$ *and* $C_2 \equiv \frac{5(3\max\{\Delta,d\}-\min\{\Delta,d\})\Delta}{4(\min\{\Delta,d\}^2-5d\Delta+10\max\{\Delta,d\}^2)\min\{\Delta,d\}}$, *where* $C_1 < C_2$. *The buyer's expected profit in the separate-sourcing mechanism* Π_S^* *and that in the joint-sourcing mechanism* Π_J^* *can be compared as follows:*

(a) When $c > C_2$, *there exists a threshold* $\bar{l}$ *such that* $\Pi_S^* > \Pi_J^*$ *if and only if* $l < \bar{l}$;

(b) When $c \in [C_1, C_2]$, *we have* $\Pi_J^* > \Pi_S^*$;

(c) When $c < C_1$, *there exists a threshold* $\bar{l}$ *such that* $\Pi_S^* > \Pi_J^*$ *if and only if* $l > \bar{l}$;

where the threshold $\bar{l}$ *is defined by* $G(\bar{l}) = 0$, *with* $G(l) \equiv \frac{\min\{\Delta,d\}}{3} - \frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{\min\{\Delta,d\}^2(\min\{\Delta,d\}-5\max\{\Delta,d\})}{30\max\{\Delta,d\}^2} + \frac{l^2}{4\Delta} - \frac{(-\min\{\Delta,d\}+3\max\{\Delta,d\})\Delta}{24c\max\{\Delta,d\}^2} + \frac{l(-l+4\Delta)}{32cd\Delta} + (\frac{1}{4cd} - 1)P_S^*$.

Figure 1 plots the values of effort cost parameter c and switching cost l such that the separate-sourcing mechanism yields a larger profit than the joint-sourcing mechanism (i.e., $\Pi_S^* > \Pi_J^*$) and vice versa. We find that when c is small, the separate-sourcing mechanism is a better choice for the buyer if the switching cost l is large; however, when c is large, the result is exactly the opposite – it is beneficial for the buyer to select the separate-sourcing mechanism only when l is small. For moderate values of the effort cost parameter c, the joint-sourcing mechanism is always better.

This result occurs because of the mechanisms' strengths and weaknesses in stimulating supplier effort and achieving allocation efficiency. Recall that the separate-sourcing mechanism gains an advantage in eliciting supplier effort when the switching cost l is large, though its allocation inefficiency also gets worse with larger l. A smaller effort cost parameter c makes the supplier effort more sensitive to l, enhancing the effort advantage of the separate-sourcing mechanism generated with large l. Thus, when l is large and c is small, the separate-sourcing mechanism outperforms the

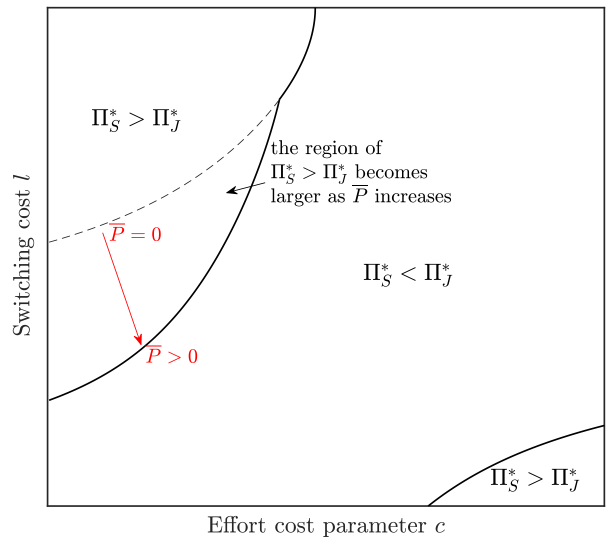

Figure 1 Profit comparison results associated with $\overline{P} = 0$ and $\overline{P} > 0$. Setting: $\Delta = 4, d = 6$.

joint-sourcing mechanism, for its advantage in eliciting *supplier effort* outweighs its disadvantage in achieving allocation efficiency. In the other extreme, when l is small, the allocation inefficiency of the separate-sourcing mechanism due to myopic design selection is low, whereas that of joint-sourcing mechanism due to no supplier switching is high. Meanwhile, when c is large, the difference in supplier effort between these mechanisms is small. Thus, when l is small and c is large, the separate-sourcing mechanism again outperforms the joint-sourcing mechanism due to a better *allocation efficiency*. The joint-sourcing mechanism prevails in other cases since the separate-sourcing mechanism has no strong advantage in either supplier effort or allocation efficiency.

6. No-Commitment Mechanism

In the above analysis, we have considered two mechanisms where the buyer commits to either selecting the best design and sourcing the production from potentially a different supplier, or delegating both design and production to the same supplier. As a third option, the buyer may refrain from committing to any structure of the mechanism before suppliers invest in innovation. In this *no-commitment* mechanism, the buyer does not constrain herself upfront, but only announces the procurement mechanism after suppliers submit their designs. Throughout this section, we use subscript N to denote the variables under no-commitment mechanisms.

With the no-commitment mechanism, suppliers first choose their innovation effort. Then, given the designs submitted by suppliers, the buyer announces the procurement mechanism. By submitting a design, each supplier i agrees to give the buyer the perpetual right to use his design in return for a chance to win the production contract.[2] Observing suppliers' design values $\mathbf{v}$, the buyer offers a menu of contracts $(x_i(\mathbf{c}|\mathbf{v}), y_i(\mathbf{c}|\mathbf{v}), t_i(\mathbf{c}|\mathbf{v}))$ for each supplier i, where $x_i(\mathbf{c}|\mathbf{v})$ is the production-selection rule (the probability of supplier i being selected for production given suppliers' reported costs $\mathbf{c}$), $y_i(\mathbf{c}|\mathbf{v})$ is the design-selection rule (the probability that design of supplier i will be chosen as a function of reported costs) and $t_i(\mathbf{c}|\mathbf{v})$ is the compensation rule that determines the payment to supplier i. Suppliers then report their costs, and the contracts are determined accordingly.

Similar to the analyses in §4.1 and §4.2, we first describe the buyer's mechanism in the procurement stage, and then discuss suppliers' effort decisions in the innovation stage.

Procurement Mechanism Design. Given the menu of contracts $(x_i(\mathbf{c}|\mathbf{v}), y_i(\mathbf{c}|\mathbf{v}), t_i(\mathbf{c}|\mathbf{v}))$, by reporting $\hat{c}_i$, a supplier i with actual cost c_i would receive expected utility $\hat{u}_i(\hat{c}_i, c_i|\mathbf{v}) = \mathbb{E}_{c_j}\left[t_i(\hat{c}_i, c_j|\mathbf{v}) - x_i(\hat{c}_i, c_j|\mathbf{v})(c_i + l(1 - y_i(\hat{c}_i, c_j|\mathbf{v})))\right]$. Supplier i's expected utility from reporting true cost is $u_i(c_i|\mathbf{v}) = \hat{u}_i(c_i, c_i|\mathbf{v})$. Thus, the IC constraints for the no-commitment mechanism are

$$u_i(c_i|\mathbf{v}) \geq \hat{u}_i(\hat{c}_i, c_i|\mathbf{v}), \quad i \in \{1,2\}, \tag{15}$$

and the IR constraints for the no-commitment mechanism are

$$u_i(c_i|\mathbf{v}) \geq 0, \quad i \in \{1,2\}. \tag{16}$$

The buyer's objective is to maximize her expected profit, which can be calculated as the expected total social surplus $\sum_{i=1}^{2} \mathbb{E}_{\mathbf{c}}\left[v_i y_i(\mathbf{c}|\mathbf{v}) - x_i(\mathbf{c}|\mathbf{v})(c_i + l(1 - y_i(\mathbf{c}|\mathbf{v})))\right]$ net of the suppliers' total expected utility $\sum_{i=1}^{2} \mathbb{E}_{c_i}[u_i(c_i|\mathbf{v})]$. Combining the above IC (15) and IR (16) constraints with the buyer's objective function, we have the buyer's optimization problem as:

$$\begin{aligned}
\max_{x_i(\mathbf{c}|\mathbf{v})), y_i(\mathbf{c}|\mathbf{v})), i \in \{1,2\}} \; & \sum_{i=1}^{2} \mathbb{E}_{\mathbf{c}}\left[v_i y_i(\mathbf{c}|\mathbf{v}) - x_i(\mathbf{c}|\mathbf{v})(c_i + l(1 - y_i(\mathbf{c}|\mathbf{v})))\right] - \sum_{i=1}^{2} \mathbb{E}_{c_i}[u_i(c_i|\mathbf{v})] \\
s.t. \; & \sum_{i=1}^{2} x_i(\mathbf{c}|\mathbf{v}) \leq 1 \quad \text{and} \quad x_i(\mathbf{c}|\mathbf{v}) \geq 0, \quad \forall \mathbf{c}, \forall \mathbf{v}, \\
& \sum_{i=1}^{2} y_i(\mathbf{c}|\mathbf{v}) \leq 1 \quad \text{and} \quad y_i(\mathbf{c}|\mathbf{v}) \geq 0, \quad \forall \mathbf{c}, \forall \mathbf{v}, \\
& \sum_{i=1}^{2} x_i(\mathbf{c}|\mathbf{v}) \leq \sum_{i=1}^{2} y_i(\mathbf{c}|\mathbf{v}), \\
& (15), (16).
\end{aligned} \tag{17}$$

The outcome of the optimal mechanism is characterized in Proposition 5.

PROPOSITION 5. *In an optimal no-commitment mechanism, the buyer offers the menu of contracts based on the joint-sourcing mechanism, $(x_J(\mathbf{c}|\mathbf{v}), y_J(\mathbf{c}|\mathbf{v}), t_J(\mathbf{c}|\mathbf{v}))$, when $|v_i - v_j| < l$, and the one based on the separate-sourcing mechanism, $(x_S(\mathbf{c}|\mathbf{v}), y_S(\mathbf{c}|\mathbf{v}), t_S(\mathbf{c}|\mathbf{v}))$, when $|v_i - v_j| \geq l$.*

[2] Such a policy, for instance, is not uncommon in ideation and design contests where the buyer commits to pay compensation to at least one supplier in exchange for the perpetual rights to use any submitted idea or design (cf. Ales et al. 2020). The no-commitment mechanism applies this policy in the procurement context.

Proposition 5 shows that the no-commitment allocation rule may follow the one in the separate-sourcing mechanism or in the joint-sourcing mechanism, depending on the difference in suppliers' innovation values. If this difference is larger than the switching cost l, then it is optimal to always select the best design and offer production to the supplier that minimizes the expected cost even with switching; in other words, decoupling design and production in the procurement is economically efficient. In contrast, if the innovation value difference is smaller than l, using different suppliers to provide design and production is never optimal because the gain in the innovation value from using the other supplier's design will never offset the switching cost; hence, in this case, no switching needs to be considered and the buyer can restrict to sourcing design and production jointly from a single supplier. Therefore, by not committing to either joint-sourcing or separate-sourcing, the buyer allows the *flexibility* of adopting either rule depending on the outcome of the innovation values, in a subgame perfect strategy, hence achieving better allocation efficiency.

Innovation Effort Decisions. From Proposition 5, we can deduce that (1) in the case of $|v_i - v_j| \geq l$, the no-commitment mechanism is akin to the separate-sourcing mechanism, yielding a supplier's expected utility $U_{iN}(\mathbf{v}) = \tilde{U}_W \cdot \mathbb{1}_{v_i > v_j} + \tilde{U}_L \cdot \mathbb{1}_{v_i \leq v_j}$ (see Proposition 1), and (2) in the case of $|v_i - v_j| < l$, the no-commitment mechanism is akin to the joint-sourcing mechanism, yielding a supplier's expected utility $U_{iN}(\mathbf{v}) = U_{iJ}(\mathbf{v})$ (see Proposition 2). Hence, based on the results from separate-sourcing and joint-sourcing mechanisms, we can derive suppliers' equilibrium effort by solving the optimization problem $\max_{e_i} \mathbb{E}_{\mathbf{v}}\left[U_{iN}(\mathbf{v})\,|\mathbf{e}\right] - \psi(e_i)$.

LEMMA 4. *In the no-commitment mechanism, each supplier exerts the equilibrium effort*

$$e_N^* = \begin{cases} e_J^* & \text{if } l > \min\{2d, 2\Delta\} \\ \frac{l(3d(4\Delta - l) - l(3\Delta - l))}{96cd^2\Delta} & \text{if } l \leq \min\{2d, 2\Delta\}, \end{cases} \tag{18}$$

that is increasing in l when $l \leq \min\{2d, 2\Delta\}$ and constant in l otherwise.

We finally calculate the buyer's expected profit at the start of the innovation stage. Given the equilibrium effort e_N^* shown in (18) and the allocation rule shown in Proposition 5, the buyer's expected utility in the procurement stage is $U_N(\mathbf{v}) = U_J(\mathbf{v})\mathbb{1}_{|v_i - v_j| < l} + U_S(\mathbf{v})\mathbb{1}_{|v_i - v_j| \geq l}$, where $U_S(\mathbf{v})$ and $U_J(\mathbf{v})$ are the buyer's expected utility functions characterized in Propositions 1 and 2 for separate-sourcing and joint-sourcing mechanisms, respectively. Taking expectation of $U_N(\mathbf{v})$ over $\mathbf{v}$ given suppliers' equilibrium effort e_N^* yields the buyer's expected profit $\Pi_N^* = \mathbb{E}_{\mathbf{v}}[U_N(\mathbf{v})|e_N^*]$.

LEMMA 5. *The buyer's expected profit from the no-commitment mechanism is*

$$\Pi_N(e_N^*) = \begin{cases} \Pi_J(e_J^*) & l > \min\{2d, 2\Delta\} \\ e_N^* + m - \underline{c} - \frac{2\Delta}{3} + \frac{5\Delta l^2\left(24d^2 - 16dl + 3l^2\right) + l^3\left(-20d^2 + 15dl - 3l^2\right) - 20\Delta^2(l - 2d)^3}{480d^2\Delta^2} & l \leq \min\{2d, 2\Delta\}. \end{cases} \tag{19}$$

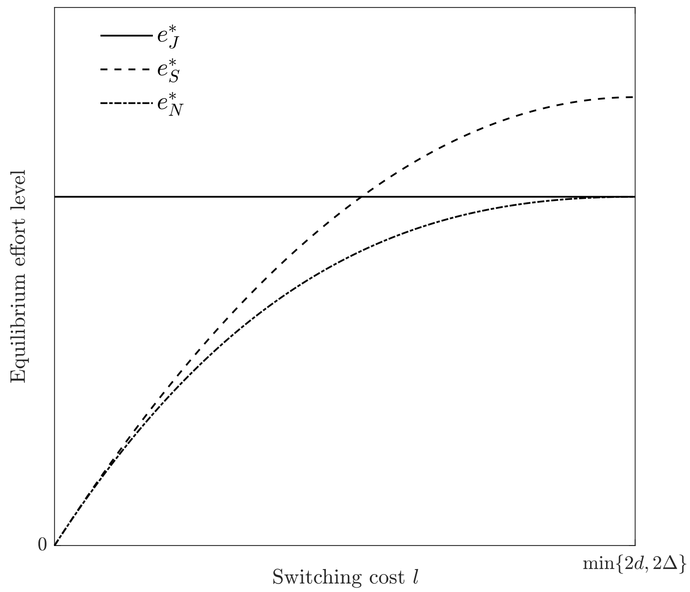

Figure 2 Equilibrium effort levels under the three mechanisms. The setting is the same as Figure 1 where $c = \frac{1}{20}$ and $\overline{P} = 0$.

Comparison Results. To derive the impact of the buyer's commitment, we compare the no-commitment mechanism with joint-sourcing and separate-sourcing mechanisms. We start by comparing these mechanisms in terms of suppliers' equilibrium effort characterized in (5), (13) and (18), followed by the main comparison in terms of the buyer's expected profit.

We compare suppliers' equilibrium effort in Proposition 6, and illustrate the equilibrium effort levels in the three mechanisms in Figure 2.

PROPOSITION 6. *The equilibrium efforts e_J^*, e_S^*, and e_N^* under joint-sourcing, separate-sourcing, and no-commitment mechanisms satisfy: 1) $e_J^* \geq e_N^*$; and 2) $e_S^* \geq e_N^*$.*

As shown in Proposition 6 and illustrated in Figure 2, the no-commitment mechanism yields less effort than the other two mechanisms. The reason is as follows. In the joint-sourcing mechanism, each supplier i can carry all of his innovation advantage $(v_i - v_j)$ into the procurement stage, and in the separate-sourcing mechanism, the supplier who has the best design has an advantage of l over his opponent. In the no-commitment mechanism, however, supplier i's advantage from achieving a better innovation is $\min\{v_i - v_j, l\}$. Hence, suppliers gain the least from achieving a better design and hence has the least incentive to exert innovation effort under the no-commitment mechanism. Therefore, even though the no-commitment mechanism improves the buyer's outcome from the procurement stage, this is at the expense of a worse outcome from the innovation stage.

We next compare the buyer's expected profit under the three mechanisms. In the remainder of the section, we let $\overline{P} = 0$ to see the isolated effect of the procurement mechanisms on the suppliers'

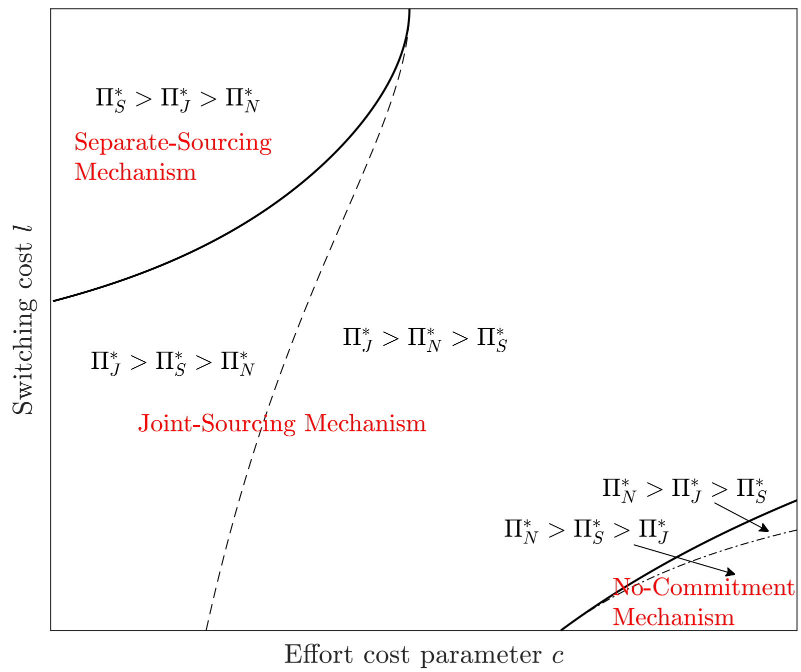

Figure 3 Profit comparison results for three mechanisms. The setting is the same as Figure 1 with $\overline{P} = 0$.

innovation incentives and the buyer's profit. At the end of the section, we discuss the impact of a positive $\overline{P}$. The result is characterized in Proposition 7.

PROPOSITION 7. *(i) There exist thresholds c_{SN}^L and c_{SN}^H such that the buyer's expected profits Π_N^* and Π_S^* under the no-commitment and the separate-sourcing mechanisms satisfy the following:*

1. *When $c \le c_{SN}^L$, $\Pi_S^* > \Pi_N^*$.*
2. *When $c_{SN}^L < c \le c_{SN}^H$, there exists a threshold $\tilde{l}_{SN}$ (where $\Pi_S^* - \Pi_N^* = 0$) such that $\Pi_S^* > \Pi_N^*$ if and only if $l > \tilde{l}_{SN}$.*
3. *When $c > c_{SN}^H$, $\Pi_S^* < \Pi_N^*$.*

(ii) There exists a threshold c_{JN} such that the buyer's expected profits Π_N^* and Π_J^* under the no-commitment and the joint-sourcing mechanisms satisfy the following:

1. *When $c \le c_{JN}$, $\Pi_J^* > \Pi_N^*$.*
2. *When $c > c_{JN}$, there exists a threshold $\tilde{l}_{JN}$ (where $\Pi_J^* - \Pi_N^* = 0$) such that $\Pi_J^* > \Pi_N^*$ if and only if $l > \tilde{l}_{JN}$.*

Figure 3 depicts the comparison of the buyer's profit from using each mechanisms under different values of effort cost parameter c and switching cost l. Proposition 7, as illustrated in Figure 3, shows that when the effort cost parameter c is small and the switching cost l is large, the separate-sourcing mechanism dominates, whereas when c is large and l is small, the no-commitment mechanism dominates, and in other cases, the joint-sourcing mechanism generates the highest profit for the buyer. This result occurs again due to the tradeoff between supplier effort and allocation efficiency. Recall that the no-commitment mechanism has the highest allocation efficiency since the buyer can choose the design and the producer after receiving the value and cost information. However, this efficiency comes at the expense of discouraging suppliers from exerting effort as shown in Proposition 6. Therefore, the no-commitment mechanism gains the most advantage when a large c reduces the effort difference among the mechanisms while a small l enhances allocation efficiency without commitment. As a result, the no-commitment mechanism outperforms the other mechanisms when c is large and l is small. Following the result in §5, it remains true that the the separate-sourcing mechanism dominates in the opposite situation when c is small and l is large for its strength in supplier effort, and the joint-sourcing mechanism prevails in other cases for its relative advantage in supplier effort and/or allocation efficiency in those cases.

The above comparison assumes $\overline{P}=0$, i.e., no prize is given in the innovation contest of the separate-sourcing mechanism. If $\overline{P}$ is positive, allowing a contest prize, the optimal prize will be zero when c is large (see Lemma 2). Therefore, a positive $\overline{P}$ has no impact on the region where the no-commitment mechanism dominates, in which c is large. The region where the separate-sourcing mechanism dominates will expand with $\overline{P}>0$ as shown in Figure 1, since in such cases, c is small and hence the buyer benefits from giving a positive prize in the separate-sourcing mechanism.

7. Enhanced-Commitment Mechanism

We have analyzed a separate-sourcing mechanism where the buyer commits to selecting the best design provided by suppliers while running an auction for production, and a joint-sourcing mechanism where the buyer commits to using a single supplier for both design and production. In this section, we analyze an enhanced-commitment mechanism where the buyer commits to allocate the production to the supplier who provides the best design. Specifically, the buyer runs an innovation contest to select the design and offers the winning supplier a production contract. Notice that the enhanced-commitment mechanism is a more restrictive version of both separate-sourcing and joint-sourcing mechanisms because it not only selects the best design (as in separate sourcing) but also allocates the production to the same supplier who provides the design (as in joint sourcing).

Let the contest winner be supplier W and loser be L. With no supplier competition for the production contract, the production-procurement mechanism reduces to $\tilde{x}_W=1$ with $\tilde{U}_W=\overline{c}-\mathbb{E}[c_W]$ and $\tilde{x}_L=0$ with $\tilde{U}_L=0$, that is, the buyer commits to selecting supplier W for production, and compensates this supplier based on the highest cost, $\overline{c}$, for production. We use subscript H to denote variables in the enhanced-commitment mechanism. As we can see, the enhanced-commitment mechanism achieves a worse allocation efficiency than the separate-sourcing mechanism by not allowing supplier switching, and than the joint-sourcing mechanism by selecting the supplier based only on the innovation value.

The equilibrium outcome follows the result of the separate-sourcing mechanism in the case of $l > 2\Delta$ where supplier switching will never occur and the design supplier will always be chosen as the production provider (see Proposition 1). This is characterized below.

PROPOSITION 8. *In the equilibrium outcome of the enhanced-commitment mechanism, suppliers will exert the equilibrium effort*

$$e_H^* = \frac{\Delta + 2P_H^*}{8cd}. \tag{20}$$

The optimal contest prize is

$$P_H^* = \begin{cases} \overline{P} & \frac{1}{d} > 4c \\ 0 & \frac{1}{d} \leq 4c, \end{cases} \tag{21}$$

and the buyer's expected profit is

$$\Pi_H^* = e_H^* + m - \underline{c} + \frac{d}{3} - \Delta - P_H^*. \tag{22}$$

In the following proposition, we compare the equilibrium effort under the enhanced-commitment mechanism with those in the other mechanisms.

PROPOSITION 9. *The equilibrium efforts under the enhanced-commitment, joint-sourcing, separate-sourcing, and no-commitment mechanisms satisfy* $e_H^* \geq \max\{e_J^*, e_S^*\} > e_N^*$.

Proposition 9 shows that suppliers exert the largest effort in the enhanced-commitment mechanism. This is because the enhanced-commitment mechanism provides all of the incentives the separate-sourcing and joint-sourcing mechanisms provide: the supplier with the highest innovation value will win the design, and the supplier who provides the design will win the production. This is reflected in the fact that the supplier with the best design is guaranteed a payment of $\overline{c}$ for production. Therefore, despite worse allocation efficiency, the enhanced-commitment mechanism enjoys superior effort-incentive capability over the other mechanisms.

In the following proposition, we compare the buyer's profit under the enhanced-commitment mechanism with those under joint-sourcing and separate-sourcing mechanisms.

PROPOSITION 10. *(i) The buyer's expected profit* Π_H^* *under the enhanced-commitment mechanism and expected profit* Π_S^* *under the separate-sourcing mechanism satisfy the following:*

1. *When* $c \leq \frac{3}{8d}$, $\Pi_S^* \leq \Pi_H^*$;
2. *When* $c > \frac{3}{8d}$, *there exist a threshold* $(2 - \frac{3}{4cd})\Delta$ *such that if and only if* $l > (2 - \frac{3}{4cd})\Delta$, $\Pi_H^* > \Pi_S^*$.

(ii) The buyer's expected profit Π_H^* *under the enhanced-commitment mechanism and expected profit* Π_J^* *under the joint-sourcing mechanism satisfy the following:*

1. *When* $c < C_1$, $\Pi_H^* > \Pi_J^*$;

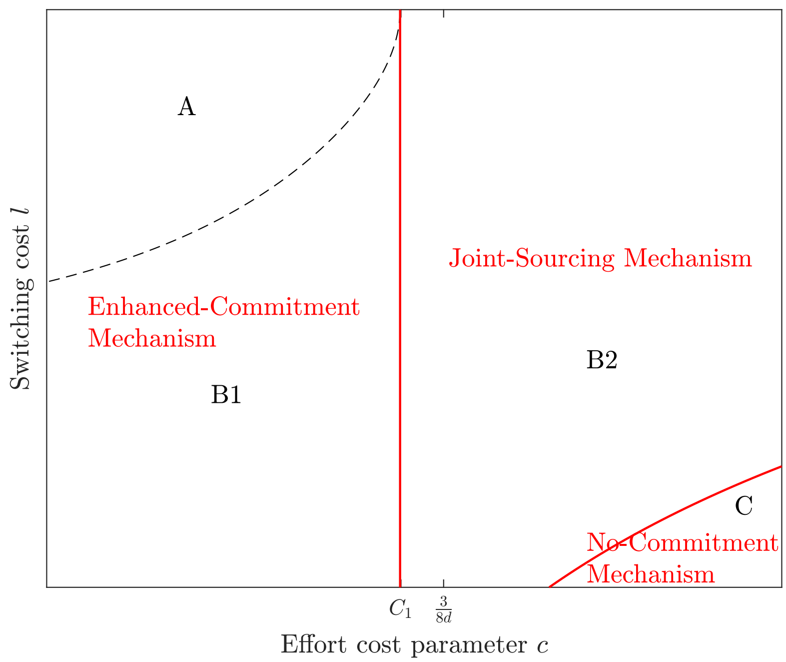

Figure 4 Profit comparison results for four mechanism. The setting is the same as Figure 1 with $\overline{P}=0$.

2. *When* $c \geq C_1$, $\Pi_H^* \leq \Pi_J^*$.

Combining Propositions 4, 7, and 10, we can draw the values of the effort cost parameter c and the switching cost l under which each mechanism dominates based on the buyer's expected profit, as depicted in Figure 4. Recall from Figure 3 that, before considering the enhanced-commitment mechanism, the separate-sourcing, joint-sourcing, and no-commitment mechanisms dominate in region A, regions B1 and B2, and region C, respectively. When considering the enhanced-commitment mechanism, it becomes the dominant mechanism in regions A and B1, where $c < C_1$ (as defined in Proposition 4). In this area, c is small, so the effort-incentive capability of the enhanced-commitment mechanism is large, enabling it to dominate all other mechanisms. However, when $c \geq C_1$ (regions B2 and C), its effort incentive is not significant enough to outweigh its weakness in allocation efficiency. As a result, the joint-sourcing mechanism remains optimal for region B2, and the no-commitment mechanism remains optimal for region C.

Our findings have interesting implications. Prior studies on innovation and procurement contests often implicitly or explicitly assume that winners of a contest receives a supply contract as in our enhanced-commitment mechanism (cf. Ales et al. 2020, Chen et al. 2021). Our result shows that this approach, although simple, is not necessarily a bad choice when the innovation-investment ratio is large (i.e., the cost parameter c is small). In this case, committing to a production contract for the innovation-contest winner outperforms a separate-sourcing mechanism which selects the best innovation but holds a procurement auction for selecting the producer. This result implies that although the separate-sourcing mechanism is utilized in practice, replacing it with a enhanced-commitment mechanism may be more effective. That being said, our results show that enhanced commitment is not a very good idea when the innovation-investment ratio is small, because the joint-sourcing mechanism or the no-commitment mechanism can provide better results in such cases due to their allocation efficiency. Thus, organizations should not blindly hand the production contract to the winner of an innovation contest but consider the type of problem they are posting, suppliers' cost for innovation, and the value to receive from suppliers' innovation investment.

8. Insights

In this section, we summarize our key insights. The strengths and weaknesses of the four mechanisms we consider, along with their suitable environments, are summarized in Table 1. As the table illustrates and we discuss in §1, these mechanisms have different capabilities for incentivizing suppliers to exert effort in the innovation stage (i.e., *effort-incentive capability*) and for achieving efficiency when selecting and compensating suppliers for design and production (i.e., *allocation efficiency*). How much effort-incentive capability and allocation efficiency affect the buyer's profit depends on how costly it is to switch the supplier when moving from design to production (i.e., switching cost) and how costly it is to achieve unit innovation, or equivalently, how effective innovation investment is in enhancing innovation value (i.e., innovation-investment ratio). Specifically, when the innovation-investment ratio is high (i.e., the innovation effort cost parameter c is small), a mechanism's relative performance in the buyer's profit is mainly determined by its effort-incentive capability whereas when the innovation-investment ratio is small, allocation efficiency becomes the leading factor. Accordingly, each mechanism becomes suitable in different environments as shown in Table 1.

Table 2 builds on Table 1, and demonstrates under which environments each mechanism should be used and offers plausible explanations for why different sourcing mechanism are utilized in different industries. We discuss these environments and some potentially suitable industries next.

- **High innovation-investment ratio and high switching cost.** In aerospace or defense industries, technology innovation plays a critical role that enables suppliers to generate significant value for the buyer as compared to the investment they make. Thus, the innovation-investment ratio seems to be high (i.e., c is low) and hence innovation effort plays a big role in the buyer's profit. Meanwhile, new advanced technologies adopted in product design endow the innovator with significant advantages in production know-how, implying a high switching cost. Therefore, in these industries, enhanced-commitment or separate-sourcing mechanisms could be good choices given their high innovation effort-incentive capability.
- **High innovation-investment ratio and low switching cost.** The automotive industry mostly uses matured production processes, making it relatively easier to switch suppliers from

Table 1 Summary of mechanisms.

Mechanism	Effort Incentive	Allocation Efficiency	Suitable Environment
Separate-Sourcing	The best design leads to an advantage in production procurement due to switching cost (in addition to the contest prize)	(+) Allowing supplier switching (-) Myopic selection of the best design	High switching cost and high innovation - investment ratio
Joint-Sourcing	A better design improves the chance of winning in the procurement mechanism for both design and production	(+) Joint consideration of design value and production cost (-) Not allowing supplier switching	High (resp., low) switching cost and low (resp., high) innovation - investment ratio
No- Commitment	(weakest) A better design improves the chance of winning in the procurement mechanism for design or production	(+) Allowing supplier switching (+) Joint consideration of design value and production cost	Low switching cost and low innovation - investment ratio
Enhanced-Commitment	(strongest) The best design receives a production contract (in addition to the contest prize)	(-) Myopic selection of the best design (-) Not allowing supplier switching	High innovation - investment ratio

design and production (hence l is low). Yet, the value associated with innovative design may be different depending on the market position of the auto maker. Product design is more important (return of innovation is higher, or effort cost c is lower) for the premier players such as BMW and Porsche than for volume players such as Ford and Volkswagen. Thus, enhanced-commitment or joint-sourcing mechanisms may be good options for the premier auto makers as these mechanisms provide good incentives for effort even under low switching cost.

- **Low innovation-investment ratio and high switching cost.** The design process in the apparel industry can be quite labor intensive, implying a low innovation-investment ratio (i.e., high innovation effort cost c). In addition, such design endeavors may involve intangible parts that are difficult to specify fully and require close collaboration with the production process to implement; in such cases, switching suppliers between design and production might cause significant efficiency loss, hence a high switching cost l. Therefore, in those industries, the joint-sourcing mechanism stands out as a good choice to achieve allocation efficiency.
- **Low innovation-investment ratio and low switching cost.** As discussed above, the volume players in the automotive industry such as Ford and Volkswagen have relatively low switching cost and low innovation-investment ratio (i.e., high c). These firms could consider not committing to any form of the sourcing mechanism at all before suppliers submit their designs, thereby adopting the no-commitment mechanism for the best allocation efficiency.

Table 2 Which mechanism to use in different situations.

	High Innovation-Investment Ratio	Low Innovation-Investment Ratio
High Switching Cost	Enhanced-commitment mechanism, or separate-sourcing mechanism as a close secondary choice (e.g., defense industry)	Joint-sourcing mechanism (e.g., apparel industry)
Low Switching Cost	Enhanced-commitment mechanism, or joint-sourcing mechanism as a close secondary choice (e.g., premium auto makers)	No-commitment mechanism or separate sourcing as a close secondary choice when the switching cost is very low (e.g., volume auto makers)

The separate-sourcing mechanism could be a close secondary alternative as it has decent allocation efficiency when the switching cost is low.

9. Conclusion

When sourcing innovative products, organizations need to source the design of an innovative solution and the production of this solution, so as to maximize the design value and minimize the production cost, respectively. Interconnected by supplier switching cost and innovation incentives, design and production may be sourced separately or jointly, giving rise to separate-sourcing and joint-sourcing mechanisms as often observed in practice. Whereas these two mechanisms impose certain commitment on the structure of the sourcing mechanisms *before* suppliers exert innovation effort, a firm may adopt a no-commitment mechanism that only specifies the allocation and payment rules *after* suppliers' innovation values are revealed. On the other extreme, a firm may employ an enhanced-commitment mechanism by committing to source the production from the supplier with the best design regardless of cost realizations. In this paper, we analyze and compare these innovative-product sourcing mechanisms that vary in the structure and level of commitment.

Our analysis reveals that these mechanisms differ in their capability to achieve supplier-effort incentive and allocation efficiency, as summarized in Table 1. Though more commitment provides better incentives that lead to greater innovation effort from suppliers, it also leads to lower efficiency in the allocation of design and production. Selecting the best-value design with no consideration of the production costs as in the separate-sourcing mechanism, and bundling design and production in the sourcing decision as in the joint-sourcing mechanism, both incentivize supplier effort while causing allocation inefficiency. The no-commitment mechanism eliminates allocation inefficiency (in the second-best solution) but suffers from low effort incentive and the enhanced-commitment mechanism provides the best effort incentive at the expense of lowest allocation efficiency. As a result, we find that each mechanism is suitable at a different environment as shown in Table 2. Our results not only provide valuable managerial insights for practitioners, but also help explain why certain mechanisms are widespread in different industries as discussed in §8.

This study contributes to both the innovation contest literature and the procurement literature. The innovation contest literature has focused on the contest prize and other tools (e.g., information disclosure, contest duration) as ways to provide innovation incentives. When sourcing innovative products for both design (innovative solution) and production, we show that the production procurement can also be used strategically to provide innovation incentives. A contest prize, therefore, is not necessary to motivate supplier innovation, but integrating production procurement with design sourcing, either directly through bundling (as in joint sourcing), or indirectly with the cost of switching (as in separate sourcing), provides effective innovation incentives in different environments. In the procurement literature, supplier switching cost hinders the competition between incumbent and entrant suppliers, causing higher purchasing costs for a buyer. However, in innovative-product sourcing, we show that the switching cost can benefit the buyer with its positive effect on suppliers' innovation effort. Therefore, despite causing *ex-post* friction in production efficiency, the supplier switching cost can be utilized strategically as an *ex-ante* driver for supplier innovation without the commitment of joint sourcing.

In the paper, we make several assumptions for tractability of the model. We show the robustness of our findings by considering two extensions in the Online Appendix. First, as several papers in the innovation contest literature (e.g., Nittala and Krishnan 2016, Mihm and Schlapp 2019), we assume that the innovation effort cost is a quadratic function of the effort. We consider a more general cost function in §EC.2 of the Online Appendix, and show that our main insights still hold with one exception: when the innovation-investment ratio is small (i.e., innovation cost is high) and the switching cost is very low, the separate-sourcing mechanism dominates all other mechanisms. Second, we assume that innovation value and production cost are independent. We relax this assumption in §EC.3, and show that all our main insights still hold. Finally, we assume that the buyer faces two potential suppliers to capture sharply the economic factors in supplier competition and switching. This setup is common in the procurement literature that consider supplier investment in improvement before competition (e.g., Stole 1994, Li 2013, Li and Wan 2017) and is also utilized by several papers in the contest literature (Bimpikis et al. 2019, Mihm and Schlapp 2019, Khorasani et al. 2021). Future work could examine a general number of suppliers and study the supply base size for different mechanisms.

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Online Appendix

EC.1. Would the Buyer Report Innovation Values Truthfully?

Take the joint-sourcing mechanism as an example and suppose that the buyer reports false innovation values $\hat{\mathbf{v}}$. To reveal suppliers' true cost information, the utility of a supplier with production cost c_i should be $u_i(c_i, \hat{\mathbf{v}}) = \int_{c_i}^{\overline{c}} \overline{x}_i(\theta, \hat{\mathbf{v}})\, d\theta$. Hence, the buyer's optimization problem at the procurement stage is:

$$\max_{x(\mathbf{c},\hat{\mathbf{v}})} U_J(\hat{\mathbf{v}}, \mathbf{v}) = \int_{\underline{c}}^{\overline{c}} \int_{\underline{c}}^{\overline{c}} \sum_{i=1}^{2} (v_i - C(c_i))\, x_i(\mathbf{c}, \hat{\mathbf{v}})\, f(c_1)\, f(c_2)\, dc_1 dc_2.$$

We find that whatever $\hat{\mathbf{v}}$ is, the optimal selection rule is:

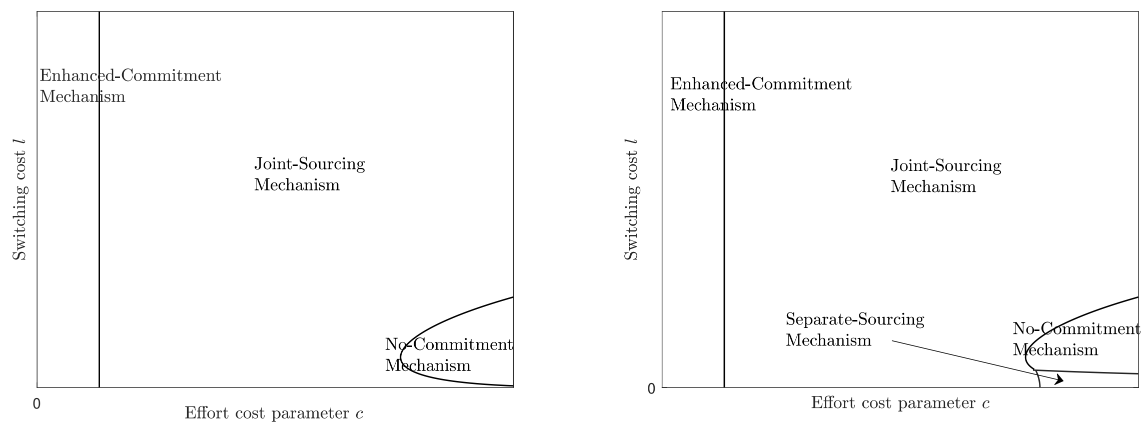
$$x_i(\mathbf{c}, \hat{\mathbf{v}}) = \begin{cases} 1 & \text{if } v_i - C(c_i) \geq \max(0, v_j - C(c_j)), \forall j \neq i \\ 0 & \text{otherwise.} \end{cases}$$

Note that the buyer's commitment power is key for the possibility of a direct mechanism implementation. If the buyer cannot commit to implementing the pre-announced mechanism after receiving suppliers' reported costs, then the revelation principle does not work. Hence, we conclude with a sufficient commitment power, the buyer does not misreport the value information.

EC.2. Robustness Check for Cost Function

In our base model, consistent with several papers in the innovation contest literature (e.g., Nittala and Krishnan 2016, Mihm and Schlapp 2019), we assume that the effort cost is quadratic in e_i. This assumption induces the buyer to choose a binary reward that equals either zero or all of her prize budget $\overline{P}$ in both separate-sourcing and enhanced-commitment mechanisms. In this section, we intend to relax the quadratic cost assumption by considering a more general cost structure $\psi(e_i) = ce_i^b$ where $b > 2$ to examine the impact of a smoother prize structure on how the buyer's profit compare in different sourcing mechanisms.

With a more general cost function $\psi(e_i) = ce_i^b$, we can derive a supplier's effort decision by applying a similar analysis as our base model. Let $\Lambda = \min\{l, 2\Delta\}$ and $\overline{P}_b$ be the solution of $\left(\frac{8\Delta^2(\Delta+3P)-\Lambda^3+3\Delta\Lambda^2}{96(b-1)bcd^2\Delta^2}\right)^{\frac{1}{b-2}} = \left(-\frac{-8\Delta P+\Lambda^2-4\Delta\Lambda}{16bcd\Delta}\right)^{\frac{1}{b-1}}$; and P_b^* be the solution of $2^{3-\frac{4}{b-1}}\left(\frac{8\Delta P-\Lambda^2+4\Delta\Lambda}{bcd\Delta}\right)^{\frac{1}{b-1}-1} = (b-1)bcd$. Note that $\overline{P}_b$ is akin to $\overline{P}$ in assumption 2, which ensures the existence of pure strategy Nash equilibrium, and P_b^* is an interior optimal solution to maximize the buyer's expected profit when the budget constraint does not bind. Lemma EC.1 summarizes the equilibrium efforts associated with all mechanisms under the more general cost function.



(a) $\overline{P}=0$. (b) $\overline{P}>0$.

Figure EC.1 Profit comparison results. Setting: $b=3, d=6$, and $\Delta=4$.

LEMMA EC.1. *When $\psi(e_i)=ce_i^b$, the equilibrium effort levels under joint-sourcing (J), separate-sourcing (S), no-commitment (N), and enhanced-commitment (H) mechanism are as follows:*

$$e_J^*=\begin{cases}\left(\frac{\Delta(3d-\Delta)}{12bcd^2}\right)^{\frac{1}{b-1}} & \text{if } d\le\Delta\\ \left(\frac{3\Delta-d}{12bc\Delta}\right)^{\frac{1}{b-1}} & \text{if } d<\Delta\end{cases};\qquad e_S^*=\begin{cases}\left(-\frac{-8\Delta P^{**}+s^2-4\Delta s}{16bcd\Delta}\right)^{\frac{1}{b-1}} & \text{if } l<2\Delta\\ \left(\frac{\Delta+2P^{**}}{4bcd}\right)^{\frac{1}{b-1}} & \text{if } l\ge2\Delta\end{cases}; \tag{EC.1}$$

$$e_N^*=\left(\frac{l(l(l-3\Delta)-3d(l-4\Delta))}{48bcd^2\Delta}\right)^{\frac{1}{b-1}};\qquad e_H^*=e_S^*|_{l=2\Delta}.$$

The optimal prizes in separate-sourcing and enhanced-commitment mechanisms, respectively, are:

$$P^{**}=\max\{\min\{\overline{P}_b,P_b^*\},0\}\ \text{and}\ P_H^{**}=\max\{\min\{\overline{P}_b,P_b^*\},0\}|_{l=2\Delta}. \tag{EC.2}$$

Although it is possible to characterize equilibrium effort levels, it is unfortunately analytically intractable to compare the buyer's profit under a more general cost function. Thus, plugging suppliers' effort e^* into the buyer's expected profit functions, we numerically compare each mechanism and show the regions where each mechanism dominates in Figures EC.1(a) and EC.1(b).

Figure EC.1(a) illustrates the dominance of each mechanism when the prize budget $\overline{P}=0$. Even with a zero prize for the selected design, the enhanced-commitment mechanism still provides the strongest effort incentive for suppliers. Knowing that when c is small, the effort plays a pivotal role in the buyer's profit, so the enhanced-commitment mechanism dominates other mechanisms. On the other hand, when c is large, the innovation efforts are small so they play a smaller part in the buyer's profit as compared to the procurement cost. Thus, the allocation efficiency becomes pivotal, so the no-commitment mechanism becomes dominant. In brief, when $\overline{P}=0$, the results derived from the base model (where $b=2$) continue to hold in the case with $b>2$.

When $\overline{P}>0$, in our base model, the optimal prize in the separate-sourcing mechanism is proved to be zero when $c>\frac{1}{4d}$. Hence, the effort-incentive capability of the separate-sourcing mechanism is dominated by the allocation efficiency of the no-commitment mechanism even with a positive prize budget. This result changes when considering a more general cost function. Specifically, when $b>2$, we observe that the optimal prize P^{**} in the separate sourcing mechanism (characterized in (EC.2)) is positive when c is large and l is small. This enlarges the effort gap between the separate-sourcing mechanism and the no-commitment mechanism. That is why in the right bottom corner of Figure EC.1(b), we observe that the separate-sourcing mechanism dominates other mechanisms.

To conclude, our main comparison results still hold in the case of $b>2$ with one exception: when c is sufficiently large and l is very small (in the right bottom corner of Figure EC.1(b)), the separate-sourcing mechanism dominates all other mechanisms.

EC.3. Robustness Check for the Correlation Between Innovation Value and Production Cost

In our base model, we assume that each supplier i's innovation value v_i and production cost c_i are independent. In this extension, we relax this assumption to check the robustness of our results to the correlation between v_i and c_i. To simplify our analysis, we let $c_i \sim U[\alpha v_i - \frac{\Delta}{2}, \alpha v_i + \frac{\Delta}{2}]$, where $\alpha \in [0,1]$ captures the correlation between innovation value and production cost. If supplier i is chosen to produce the design of supplier j (which is possible, for instance, under the separate-sourcing mechanism), then the production cost should be adjusted with a switch cost l such that $c_i \sim U[\alpha v_j - \frac{\Delta}{2} - l, \alpha v_j + \frac{\Delta}{2} - l]$. Given the cost distribution, similar to our base model, we can define the virtual production cost as $C_\alpha(c_i) = 2c_i - (\alpha v_i - \frac{\Delta}{2})$. Again similar to §3, we need the positive virtual valuation assumption to ensure each supplier is active in the procurement stage:

Assumption EC.1. $(1-\alpha)(m-d) - l > \frac{3\Delta}{2}$.

Applying the same analysis as our base model, we derive suppliers' optimal effort levels and the buyer's expected profits under the joint-sourcing as in the following proposition.

Proposition EC.1. *When the innovation value and product cost are correlated with a correlation parameter α, there exists a unique symmetric pure strategy Nash Equilibrium in the joint-sourcing mechanism, where each supplier exerts the equilibrium effort*

$$e_J^\alpha = \begin{cases} \frac{\Delta\left(3(\alpha+1)^3 d - (\alpha(7\alpha+4)+1)\Delta\right)}{24(\alpha+1)^3 c d^2} & (\alpha+1)d \geq \Delta \\ \frac{(1-\alpha)(3\Delta - d(1-\alpha))}{24c\Delta} & (\alpha+1)d < \Delta. \end{cases} \tag{EC.3}$$

e_J^α is increasing in Δ and decreasing in d and α. The buyer's expected profit is

$$\Pi_J^\alpha = \begin{cases} (1-\alpha)\left(e_J^\alpha + m\right) + \frac{1}{30}\left(-\frac{(\alpha-1)(\alpha(29\alpha+12)-1)\Delta^3}{(\alpha+1)^5 d^2} + \frac{5(\alpha(\alpha(9\alpha-1)-1)+1)\Delta^2}{(\alpha+1)^4 d} + 10d - 15\Delta\right) & (\alpha+1)d > \Delta \\ -\frac{(1-\alpha)^2 d^2((1-\alpha)d - 5\Delta)}{30\Delta^2} - \frac{\Delta}{6} + (1-\alpha)\left(e_J + m\right) & (\alpha+1)d < \Delta, \end{cases} \tag{EC.4}$$

which is decreasing in α.

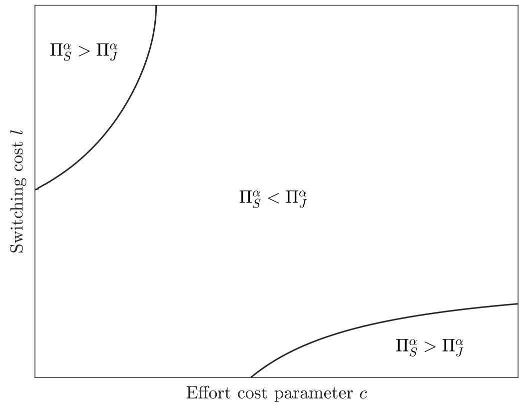


Figure EC.2 Profit comparison results. Setting: $d = 6, \Delta = 4, \alpha = \frac{1}{10}, \overline{P} = 0$.

It is easy to observe that as α approaches zero, the above result boils down to the one in our base model. In the presence of positive correlation between value and cost, the valuation advantage gained in the innovation stage will be partially counteracted by the potentially higher production cost. This is the reason why each supplier will exert less effort given a larger α. Furthermore, the created net value from the innovation, $v_i - c_i$, also decreases with α, and so does the buyer's expected profit. The following proposition repeats this analysis in the separate-sourcing mechanism.

PROPOSITION EC.2. *When the innovation value and product cost are correlated with a correlation parameter α, there exists a unique pure strategy Nash Equilibrium in the separate-sourcing mechanism, where each supplier exerts the equilibrium effort*

$$e_S^\alpha = \begin{cases} \frac{\Delta + 2P_S^*}{8cd} & l \geq 2\Delta \\ \frac{l(4\Delta - l) + 8\Delta P_S^*}{32cd\Delta} & l < 2\Delta, \end{cases} \tag{EC.5}$$

where the optimal prize is

$$P_S^* = \begin{cases} \overline{P}, & c \leq \frac{1-\alpha}{4d} \\ 0 & c > \frac{1-\alpha}{4d}. \end{cases} \tag{EC.6}$$

The buyer's expected profit is

$$\Pi_S^\alpha = \begin{cases} (1-\alpha)\left(\frac{d}{3} + e_S^\alpha + m\right) - \frac{\Delta}{2} - P_S^* & l \geq 2\Delta \\ (1-\alpha)\left(\frac{d}{3} + e_S^\alpha + m\right) - \frac{\Delta}{6} - \frac{l^3}{24\Delta^2} + \frac{l^2}{4\Delta} - \frac{l}{2} - P_S^* & l < 2\Delta. \end{cases} \tag{EC.7}$$

Comparing the buyer's expected profits associated with joint-sourcing and separate-sourcing mechanisms, we replicate the results in §4: the separate-sourcing mechanism dominates when the switching cost l is high (low) and the effort cost parameter c is low (high); see Figure EC.2.

EC.4. Proofs

Proof of Proposition 1. The proof is similar to Proposition 2. ■

Proof of Lemma 1. Expressing U_W and U_L in Proposition 1, we have

$$U_W = \begin{cases} \frac{\Delta}{2} & \text{if } l \geq 2\Delta \\ \frac{1}{48\Delta^2}(8\Delta^3 + 12\Delta^2 l - l^3) & \text{if } l < 2\Delta, \end{cases} \text{ and } U_L = \begin{cases} 0 & \text{if } l \geq 2\Delta \\ \frac{1}{48\Delta^2}(2\Delta - l)^3 & \text{if } l < 2\Delta. \end{cases}$$

We next derive supplies' equilibrium effort by considering the following two cases.

Case 1: $l \geq 2\Delta$. In this case, decoupling design and production is inefficient. Hence, the supplier with the best design will also be allocated the production contract. Thus, supplier i's optimization problem given supplier j's effort e_j, is as follows:

$$\max_{e_i} \pi_i(e_i|e_j) = \int_{e_j - e_i}^{2d} (P + \frac{\Delta}{2}) \frac{2d - \epsilon}{4d^2} d\epsilon - \psi(e_i).$$

Noting that $\pi_i'(e_i|e_j) = (P + \frac{\Delta}{2})\frac{2d+e_i-e_j}{4d^2} - 2ce_i$, we have $\pi_i''(e_i|e_j) = (P + \frac{\Delta}{2})\frac{1}{4d^2} - 2c \leq 0$ if and only if $P \leq 8cd^2 - \frac{\Delta}{2}$. Under this condition, supplier i's best-response effort decision should satisfy $\frac{(\Delta+2P)(2d+e_i-e_j)}{8d^2} - 2ce_i = 0$. We can similarly derive supplier j's best-response function. Solving these two best-response functions simultaneously, we obtain a unique and symmetric Nash equilibrium where both suppliers exert the equilibrium effort $e_S^* = \frac{2P+\Delta}{8cd}$.

Case 2: $l < 2\Delta$. In this case, the supplier with the best design may not be selected to produce his product and hence supplier i's optimization problem, given e_j, is as follows:

$$\max_{e_i} \pi_i(\mathbf{e}) = \int_{e_j - e_i}^{2d} (P + \frac{1}{48\triangle^2}(8\triangle^3 + 12\triangle^2 l - l^3)) \frac{2d - \epsilon}{4d^2} d\epsilon + \int_{-2d}^{e_j - e_i} \frac{1}{48\triangle^2}(2\triangle - l)^3 \frac{2d + \epsilon}{4d^2} d\epsilon - \psi(e_i).$$

Noting that $\pi_i''(e_i|e_j) = (P + \underbrace{\frac{\Delta}{3} + \frac{l^2}{8\Delta} - \frac{l^3}{24\Delta^2}}_{>0})\frac{1}{4d^2} - 2c \leq 0$ if and only if $P \leq 8cd^2 - \frac{\Delta}{3} - \frac{l^2}{8\Delta} + \frac{l^3}{24\Delta^2}$. Under this condition, supplier i's best-response effort should satisfy $-2ce_i + \frac{(2d+e_i-e_j)\left(8\Delta^2(\Delta+6P)-l^3+12\Delta^2 l\right)}{192d^2\Delta^2} + \frac{(l-2\Delta)^3(2d-e_i+e_j)}{192d^2\Delta^2} = 0$. We can derive supplier j's best-response function similarly. Solving these two best-response functions simultaneously, we derive a unique and symmetric Nash equilibrium where each supplier exerts the equilibrium effort $e_S^* = \frac{l(4\Delta-l)+8\Delta P}{32c\Delta d}$.

In both cases, it is easy to verify that the equilibrium effort e_S^* is increasing in P. ■

Proof of Lemma 2. To derive the optimal prize, we first need to calculate the buyer's expected profit in the separate-souring mechanism under the cases of $l < 2\Delta$ and $l \geq 2\Delta$.

If $l < 2\Delta$, the supplier who wins in the innovation stage cannot ensure that he will be selected to produce his own design. Hence, the expression of U_S is

$$U_S(\mathbf{v}) = \underbrace{\int_{\underline{c}+\frac{l}{2}}^{\overline{c}} (v_W - 2c_W + \underline{c})(1 - \frac{c_W - \frac{l}{2} - \underline{c}}{\Delta}) f(c_W) dc_W + \int_{\underline{c}}^{\underline{c}+\frac{l}{2}} (v_W - 2c_W + \underline{c}) f(c_W) dc_W}_{\text{Part (1)}}$$

$$+ \underbrace{\int_{\underline{c}}^{\overline{c}-\frac{l}{2}} (v_W - 2c_L + \underline{c} - l)(1 - \frac{c_j + \frac{l}{2} - \underline{c}}{\Delta}) f(c_L) dc_L}_{\text{Part (2)}}$$

$$= e_S^* + m + \max\{\xi_i, \xi_j\} - \underline{c} + \frac{l^2}{4\Delta} - \frac{l^3}{24\Delta^2} - \frac{l}{2} - \frac{2\Delta}{3}.$$

Taking expectation over ξ_i and ξ_j, buyer's *ex-ante* expected profit at the start of the innovation stage is:

$$\Pi_S(e_S^*) = \mathbb{E}[U_S(\mathbf{v}|e_S^*)] - P = e_S^* + m - \underline{c} + \frac{d}{3} + \frac{l^2}{4\Delta} - \frac{l^3}{24\Delta^2} - \frac{l}{2} - \frac{2\Delta}{3} - P.$$

If $l \geq 2\Delta$, the supplier who wins in the innovation stage will be the design producer. Accordingly, the expression of U_S is

$$U_S(\mathbf{v}) = \int_{\underline{c}}^{\overline{c}} (v_W - 2c_W + \underline{c}) f(c_W) dc_W = m + e_S^* + \max\{\xi_i, \xi_j\} - \underline{c} - \Delta.$$

Taking expectation over ξ_i and ξ_j, buyer's expected profit in the innovation stage is:

$$\Pi_S(e_S^*) = \mathbb{E}[U_S(\mathbf{v}|e_S^*)] - P = e_S^* + m - \underline{c} + \frac{d}{3} - \Delta - P.$$

Next, through solving the optimization problem $\max_P \Pi_S(e_S^*)$, we derive the optimal prize P_S^* as shown in Lemma 2. ■

Proof of Corollary 1. Taking derivative of $\Pi_S(e_S^*)$ on l, we have

$$\frac{\partial \Pi_S(e_S^*)}{\partial l} = \frac{(2\Delta - l)(2cd(l - 2\Delta) + \Delta)}{16cd\Delta^2}.$$

We observe that the sign of the above derivative is equivalent to the sign of $\Delta(1 - 4cd) + 2cdl$. Hence, we can easily get that when $1 - 4cd \geq 0$, the term $\Delta(1 - 4cd) + 2cdl$ is always positive. However, when $1 - 4cd < 0$, we have $\Delta(1 - 4cd) + 2cdl$ is positive only when $l > \frac{(4cd-1)2\Delta}{4cd}$; otherwise, it is negative. ■

Proof of Proposition 2. The logic of the proof is as follows. We first focus on determining the optimal joint-sourcing mechanism by ignoring the prize P as if $\overline{P} = 0$, and then prove that the prize budget $\overline{P}$ has no material impact on design of the joint-sourcing mechanism.

We can write the expected utility of supplier i who has true cost c_i and reports his cost as $\widehat{c}_i$ as:

$$u_i(\widehat{c}_i, c_i, \mathbf{v}) = \mathbb{E}_{c_j}[t_i(\widehat{c}_i, c_j|\mathbf{v}) - x_i(\widehat{c}_i, c_j|\mathbf{v})c_i].$$

Hence, $u_i(c_i, c_i, \mathbf{v})$ (presented as $u_i(c_i, \mathbf{v})$ for simplicity) is supplier i's expected utility when he chooses to report his cost information truthfully. The IC constraint requires that reporting true cost information generates the highest expected utility for each supplier i, i.e., $c_i = \arg\max_{\widehat{c}_i} u_i(\widehat{c}_i, c_i, \mathbf{v})$.

Based on the Envelope Theorem, we have:

$$\frac{\partial u_i(c_i,\mathbf{v})}{\partial c_i}=\frac{\partial u_i(\widehat{c}_i,c_i,\mathbf{v})}{\partial c_i}|_{\widehat{c}_i=c_i}=-E_{c_j}[x_i(c_i,c_j|\mathbf{v})]\Rightarrow u_i(c_i,\mathbf{v})=u_i(\underline{c})-\int_{\underline{c}}^{c_i}\overline{x}_i(\theta|\mathbf{v})d\theta, \qquad \text{(EC.8)}$$

where $\overline{x}_i(c_i|\mathbf{v})\equiv E_{\mathbf{c}\setminus c_i}[x_i(\mathbf{c}|\mathbf{v})]$. Because $u_i(c_i,\mathbf{v})$ is a decreasing function as implied by (EC.8) and based on the set of IR constraints, we have $u_i(\overline{c},\mathbf{v})=0$. Therefore, we can get $u_i(\underline{c})$ and $u_i(c_i,\mathbf{v})$ as follows:

$$\begin{aligned}u_i(\overline{c},\mathbf{v})=u_i(\underline{c})-\int_{\underline{c}}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})d\theta=0\Rightarrow u_i(\underline{c})&=\int_{\underline{c}}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})d\theta\\ \Rightarrow u_i(c_i,\mathbf{v})&=\int_{c_i}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})d\theta.\end{aligned}$$

Also, with $u_i(c_i,\mathbf{v})=\mathbb{E}_{c_j}[t_i(c_i,c_j|\mathbf{v})-x_i(c_i,c_j|\mathbf{v})c_i]=\int_{c_i}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})d\theta$, we have $\bar{t}_i(c_i|\mathbf{v})\equiv E_{\mathbf{c}\setminus c_i}[t_i(\mathbf{c}|\mathbf{v})]=\int_{c_i}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})d\theta+\overline{x}_i(c_i|\mathbf{v})c_i$. Hence, using IC and IR constraints, we obtain the expected utility of each supplier $i\in\{1,2\}$ with production cost c_i is

$$u_i(c_i,\mathbf{v})=\int_{c_i}^{\overline{c}}\overline{x}_i(\theta|\mathbf{v})\,d\theta, \qquad \text{(EC.9)}$$

where $\overline{x}_i(c_i|\mathbf{v})\equiv E_{\mathbf{c}\setminus c_i}[x_i(\mathbf{c}|\mathbf{v})]$ is the expected probability that supplier i wins the buyer's contract given the other supplier's cost. This indicates that the buyer's optimal compensations to suppliers are exactly determined by the optimal winning probabilities $(x_1^*(\mathbf{c}|\mathbf{v}),x_2^*(\mathbf{c}|\mathbf{v}))$. Thus, we shall focus on deriving the optimal selection rule $(x_1^*(\mathbf{c}|\mathbf{v}),x_2(\mathbf{c}|\mathbf{v}))$. Using (EC.9), we calculate supplier i's expected utility in the procurement stage as $U_{iJ}(\mathbf{v})=\int_{\underline{c}}^{\overline{c}}u_i(c_i,\mathbf{v})f(c_i)\,dc_i=\int_{\underline{c}}^{\overline{c}}F(c_i)\overline{x}_i(c_i,\mathbf{v})\,dc_i$. Therefore, the buyer's expected utility is

$$\begin{aligned}U_J(\mathbf{v})&=\mathbb{E}_{\mathbf{c}}\left[\sum_{i=1}^{2}v_ix_i(\mathbf{c}|\mathbf{v})-t_i(\mathbf{c}|\mathbf{v})\right]=\mathbb{E}_{\mathbf{c}}\left[\sum_{i=1}^{2}(v_i-c_i)x_i(\mathbf{c}|\mathbf{v})+\underbrace{c_ix_i(\mathbf{c}|\mathbf{v})-t_i(\mathbf{c}|\mathbf{v})}_{-u_i(c_i,\mathbf{v})}\right]\\&=\int_{\underline{c}}^{\overline{c}}\int_{\underline{c}}^{\overline{c}}\sum_{i=1}^{2}(v_i-c_i)\,x_i(\mathbf{c}|\mathbf{v})f(c_1)\,f(c_2)\,dc_1dc_2-\sum_{i=1}^{2}U_{iJ}(\mathbf{v})\\&=\int_{\underline{c}}^{\overline{c}}\int_{\underline{c}}^{\overline{c}}\sum_{i=1}^{2}(v_i-C(c_i))\,x_i(\mathbf{c}|\mathbf{v})\,f(c_1)\,f(c_2)\,dc_1dc_2,\end{aligned} \qquad \text{(EC.10)}$$

where $C(c_i)=c_i+\frac{F(c_i)}{f(c_i)}=2c_i-\underline{c}$ is the supplier's virtual cost as defined in Definition 1. Under Assumption 1, we know that $v_i-C(c_i)>0$ for all $i\in\{1,2\}$. Observing from (EC.10) that the buyer should maximize the realized value net of supplier's virtual cost, i.e., $\max\{v_i-C(c_i),v_j-C(c_j)\}$, we have the buyer's optimal selection rule as shown in Proposition 2(i).

Given the optimal selection rule, we can derive each supplier's expected utility in the procurement stage as follows:

$$U_{iJ}(\mathbf{v})=\int_{\underline{c}}^{\overline{c}}F(c_i)\left(1-F\left(c_i-\frac{v_i-v_j}{2}\right)\right)dc_i$$

$$= \begin{cases} \frac{\Delta}{2} & \text{if } v_i - v_j \geq 2\Delta \\ \frac{1}{48\triangle^2}(8\triangle^3 + 12\triangle^2(v_i - v_j) - (v_i - v_j)^3) & \text{if } 0 \leq v_i - v_j < 2\Delta \\ \frac{1}{48\triangle^2}(2\triangle + v_i - v_j)^3 & \text{if } -2\Delta \leq v_i - v_j < 0 \\ 0 & \text{if } v_i - v_j < -2\Delta. \end{cases}$$

Next, we prove that the prize P makes no material difference in the joint-sourcing mechanism. With prize P, supplier i's expected utility at the procurement stage when he has true cost c_i but reports his cost as $\widehat{c}_i$ is $u_i(\widehat{c}_i, c_i, \mathbf{v}) = \mathbb{E}_{c_j}[t_i(\widehat{c}_i, c_j|\mathbf{v}) - x_i(\widehat{c}_i, c_j|\mathbf{v})(c_i - P)]$. By the Envelope Theorem,

$$\frac{\partial u_i(c_i, \mathbf{v})}{\partial c_i} = \frac{\partial u_i(\widehat{c}_i, c_i, \mathbf{v})}{\partial c_i}|_{\widehat{c}_i = c_i} = -E_{c_j}[x_i(c_i, c_j|\mathbf{v})] \Rightarrow u_i(c_i, \mathbf{v}) = u_i(\underline{c}) - \int_{\underline{c}}^{c_i} \overline{x}_i(\theta|\mathbf{v}) d\theta.$$

Applying a similar analysis as the one above, we obtain $u_i(c_i, \mathbf{v}) = \int_{c_i}^{\overline{c}} \overline{x}_i(\theta|\mathbf{v}) d\theta$, which is identical to one in the case without prize P. Hence, we conclude that the prize P has no material impact on the joint-sourcing mechanism. ■

Proof of Lemma 3. Suppliers' expected utility in the procurement stage can be written as

$$U_{iJ}(\mathbf{v}) = \int_{\underline{c}}^{\overline{c}} F(c_i) \left(1 - F\left(c_i - \frac{v_i - v_j}{2}\right)\right) dc_i$$
$$= \begin{cases} \frac{\Delta}{2} & \text{if } v_i - v_j \geq 2\Delta \\ \frac{1}{48\triangle^2}(8\triangle^3 + 12\triangle^2(v_i - v_j) - (v_i - v_j)^3) & \text{if } 0 \leq v_i - v_j < 2\Delta \\ \frac{1}{48\triangle^2}(2\triangle + v_i - v_j)^3 & \text{if } -2\Delta \leq v_i - v_j < 0 \\ 0 & \text{if } v_i - v_j < -2\Delta. \end{cases}$$

We can derive the supplier's equilibrium effort by considering two cases: 1) $d \geq \Delta$ and 2) $d < \Delta$.

Case 1: $d \geq \Delta$. Given supplier j' effort e_j, supplier i's best-response effort is determined by solving the following problem:

$$\max_{e_i} \pi_i(\mathbf{e}) = \mathbb{E}_{\mathbf{v}}[U_{iJ}(\mathbf{v}|e_i, e_j)] - \psi(e_i) = \int_{-2\Delta + e_j - e_i}^{e_j - e_i} \frac{1}{48\triangle^2}(2\triangle + e_i - e_j + \epsilon)^3 \frac{2d + \epsilon}{4d^2} d\epsilon$$
$$+ \int_{e_j - e_i}^{2\Delta + e_j - e_i} \frac{1}{48\triangle^2}(8\triangle^3 + 12\triangle^2(e_i - e_j + \epsilon) - (e_i - e_j + \epsilon)^3) \frac{2d - \epsilon}{4d^2} d\epsilon + \int_{2\Delta + e_j - e_i}^{2d} \frac{\Delta}{2} \frac{2d - \epsilon}{4d^2} d\epsilon - \psi(e_i),$$

where $\epsilon = v_i - v_j = \xi_i - \xi_j$. Because $\xi_i \sim U[-d, +d]$, we can easily obtain the cumulative distribution function $H(\epsilon)$ and the probability density function $h(\epsilon)$ of ϵ as follows:

$$H(\epsilon) = \begin{cases} 1 & \text{if } 2d < \epsilon \\ \frac{(2d+\epsilon)^2 - 2\epsilon^2}{8d^2} & \text{if } 0 < \epsilon \leq 2d \\ \frac{(2d+\epsilon)^2}{8d^2} & \text{if } -2d \leq \epsilon \leq 0 \\ 0 & \text{if } \epsilon < -2d \end{cases} \text{ and } h(\epsilon) = \begin{cases} 0 & \text{if } 2d < \epsilon \\ \frac{2d-\epsilon}{4d^2} & \text{if } 0 < \epsilon \leq 2d \\ \frac{2d+\epsilon}{4d^2} & \text{if } -2d \leq \epsilon \leq 0 \\ 0 & \text{if } \epsilon < -2d. \end{cases} \quad \text{(EC.11)}$$

Taking derivative of supplier i's problem with respect to e_i, we have

$$\frac{\partial \pi_i(\mathbf{e})}{\partial e_i} = \frac{\Delta(6d - 2\Delta + 3e_i - 3e_j)}{24d^2} - 2ce_i.$$

Thus, supplier i's best-response function is $e_i(e_j) = \frac{6d\Delta - 2\Delta^2 - 3\Delta e_j}{3\left(16cd^2 - \Delta\right)}$. Similarly, we can derive supplier j's best-response function as $e_j(e_i) = \frac{6d\Delta - 2\Delta^2 - 3\Delta e_i}{3\left(16cd^2 - \Delta\right)}$. Solving these two best-response functions simultaneously, we derive the unique symmetric equilibrium in the joint-sourcing mechanism as

$$e_J^* = \frac{(3d-\Delta)\Delta}{24cd^2}.$$

Case 2: $d<\Delta$. Given supplier j's effort e_j, supplier i's best response should solve:

$$\max_{e_i} \pi_i(\mathbf{e}) = \mathbb{E}_{\mathbf{v}}[U_{iJ}(\mathbf{v}|e_i,e_j)] - \psi(e_i) = \int_{-2d}^{e_j-e_i} \left(\frac{1}{48\triangle^2}(2\triangle + e_i - e_j + \epsilon)^3\right)\frac{2d+\epsilon}{4d^2}d\epsilon$$
$$+\int_{e_j-e_i}^{2d}\left(\frac{1}{48\triangle^2}(8\triangle^3 + 12\triangle^2(e_i-e_j+\epsilon) - (e_i-e_j+\epsilon)^3)\right)\frac{2d-\epsilon}{4d^2}d\epsilon - \psi(e_i).$$

Taking derivative with respect to e_i, we have supplier i's best-response effort as characterized by

$$\frac{6\Delta^2\left(4d^2+(e_i-e_j)^2\right) - 2d(e_i-e_j)\left(4d^2+(e_i-e_j)^2\right) - \Delta(2d-e_i+e_j)^3 + 8\Delta^3(e_i-e_j)}{96d^2\Delta^2} - 2ce_i = 0.$$

We can similarly obtain supplier j's best-response function. Solving these two best-response functions simultaneously, we obtain the unique symmetric equilibrium as:

$$e_J^* = \frac{(3\Delta-d)}{24c\Delta}.$$

Next, we calculate buyer's expected utility in the procurement stage,

$$U_J(\mathbf{v}) = \sum_{i=1}^{2}\int_{\underline{c}}^{\overline{c}}(v_i - 2c_i + \underline{c})(1-F(c_i - \frac{v_i-v_j}{2}))f(c_i)dc_i$$
$$= \sum_{i=1}^{2}\int_{\underline{c}}^{\overline{c}}(m + e_J^* + \xi_i - 2c_i + \underline{c})(1-F(c_i-\frac{\epsilon}{2}))f(c_i)dc_i,$$

and we get that

$$U_J(\mathbf{v}) = \begin{cases} e_J^* + m + \xi_i - \Delta - \underline{c} & \text{if } \epsilon \geq 2\Delta \\ e_J^* + m + \xi_i - \frac{2\Delta}{3} - \underline{c} + \frac{\epsilon^2}{4\Delta} - \frac{\epsilon^3}{24\Delta^2} - \frac{\epsilon}{2} & \text{if } 0 \leq \epsilon < 2\Delta \\ e_J^* + m + \xi_i - \frac{2\Delta}{3} - \underline{c} + \frac{\epsilon^2}{4\Delta} + \frac{\epsilon^3}{24\Delta^2} - \frac{\epsilon}{2} & \text{if } -2\Delta \leq \epsilon < 0 \\ e_J^* + m + \xi_j - \Delta - \underline{c} & \text{if } \epsilon < 2\Delta. \end{cases}$$

Next, we need to consider the case of $d<\Delta$ and the case of $d\geq\Delta$, separately, when calculating the buyer's expected profit in the innovation stage.

Specifically, taking expectation over ξ_i, ξ_j (or ϵ), when $d<\Delta$, we have

$$\Pi_J(e^*) = E[(e_J^* + m + \xi_i - \frac{2\Delta}{3} - \underline{c} + \frac{\epsilon^2}{4\Delta} - \frac{\epsilon^3}{24\Delta^2} - \frac{\epsilon}{2})\cdot \mathbf{1}_{\epsilon\geq 0}]$$
$$+ E[(e_J^* + m + \xi_i - \frac{2\Delta}{3} - \underline{c} + \frac{\epsilon^2}{4\Delta} + \frac{\epsilon^3}{24\Delta^2} - \frac{\epsilon}{2})\cdot \mathbf{1}_{\epsilon<0}]$$
$$= E[e_J^* + m - \frac{2\Delta}{3} - \underline{c} + \frac{\epsilon^2}{4\Delta} - |\frac{\epsilon^3}{24\Delta^2}| - \frac{\epsilon}{2}] + E(\xi_i)$$
$$= e_J^* + m - \underline{c} - \frac{2\Delta}{3} - \frac{d^2(d-5\Delta)}{30\Delta^2};$$

and when $d \geq \Delta$, we have

$$\begin{aligned}\Pi_J(e_J^*) &= E[(e_J^*+m+\xi_i-\Delta-\underline{c})\cdot \mathbf{1}_{\epsilon\geq 2\Delta}]+E[(e_J^*+m+\xi_i-\frac{2\Delta}{3}-\underline{c}+\frac{\epsilon^2}{4\Delta}-\frac{\epsilon^3}{24\Delta^2}-\frac{\epsilon}{2})\cdot \mathbf{1}_{0\leq\epsilon<2\Delta}] \\ &+E[(e_J^*+m+\xi_i-\frac{2\Delta}{3}-\underline{c}+\frac{\epsilon^2}{4\Delta}+\frac{\epsilon^3}{24\Delta^2}-\frac{\epsilon}{2})\cdot \mathbf{1}_{-2\Delta\leq\epsilon<0}]+E[(e_J^*+m+\xi_j-\Delta-\underline{c})\cdot \mathbf{1}_{\epsilon<-2\Delta}] \\ &= e_J^*+m-\underline{c}-\Delta+\frac{d}{3}+\frac{\Delta^2}{6d}-\frac{\Delta^3}{30d^2}. \blacksquare\end{aligned}$$

Proof of Proposition 3. Let $l_1 = 2(\Delta - \sqrt{\frac{d^2-3d\Delta+3\Delta^2}{3}}), l_2 = 2(\Delta - \sqrt{\frac{\Delta^3}{3d}}), l_3 = \max\left\{2\left(\Delta-\frac{\sqrt{6\Delta\overline{P}+d^2-3d\Delta+3\Delta^2}}{\sqrt{3}}\right),0\right\}$, and $l_4 = \max\left\{2\Delta - \frac{2\sqrt{\Delta}\sqrt{6d\overline{P}+\Delta^2}}{\sqrt{3}\sqrt{d}},0\right\}$. Using Lemmas 1 and 3, we can compare the equilibrium effort levels e_J^* and e_S^* in the joint-sourcing and separate-sourcing mechanisms as follows:

1. When $l \geq 2\Delta$, $e_S^* > e_J^*$.
2. When $l < 2\Delta, \Delta \geq d$, the comparison results depend on both l, c and d. Specifically,
   (a) When $4cd \geq 1$, $e_S^* > e_J^*$ if and only if $l > l_1$.
   (b) When $4cd < 1$, $e_S^* > e_J^*$ if and only if $l > l_3$.
3. When $l < 2\Delta, \Delta < d$, the comparison results depend on both l, c and d.
   (a) When $4cd \geq 1$, $e_S^* > e_J^*$ if and only if $l > l_2$.
   (b) When $4cd < 1$, $e_S^* > e_J^*$ if and only if $l > l_4$.

Combining the above results, we conclude that when $l > l_{SJ}$, where

$$l_{SJ} = \begin{cases} l_1 & \Delta \geq d, 4cd \geq 1 \\ l_3 & \Delta \geq d, 4cd < 1 \\ l_2 & d > \Delta, 4cd \geq 1 \\ l_4 & d > \Delta, 4cd < 1, \end{cases}$$

the separate-sourcing mechanism generates a higher effort than the joint-sourcing mechanism. ■

Proof of Proposition 4. To formally compare the buyer's expected profits in separate-sourcing and joint-sourcing mechanisms, we need to consider two cases: (1) $d < \Delta$ and (2) $d \geq \Delta$.

Case 1: $d < \Delta$. The profit difference of the two mechanisms is

$$\begin{aligned}\Pi_S^* - \Pi_J^* &= \underbrace{e_S^* - e_J^*}_{\text{increasing in } l} + \underbrace{\frac{d}{3}-\frac{l}{2}-\frac{l^3}{24\Delta^2}+\frac{d^2(d-5\Delta)}{30\Delta^2}+\frac{l^2}{4\Delta}}_{\text{decreasing in } l} - P_S^* \\ &= \underbrace{(\frac{1}{4cd}-1)P_S^*}_{\geq 0} + G_1(l),\end{aligned}$$

where $G_1(l) = \frac{d}{3}-\frac{l}{2}-\frac{l^3}{24\Delta^2}+\frac{d^2(d-5\Delta)}{30\Delta^2}+\frac{l^2}{4\Delta}-\frac{-d+3\Delta}{24c\Delta}+\frac{l(-l+4\Delta)}{32cd\Delta}$. Differentiating $G_1(l)$, we obtain that when $4cd-1<0$, $G_1(l)$ is always increasing in l; and when $4cd-1>0$, $G_1(l)$ is first decreasing and then increasing in l with a turning point at $l = \Delta(2-\frac{1}{2cd})$. Next, we examine whether $G_1(l=0)$ and

$G_1(l=2\Delta)$ are positive or not. $G_1(l=0) = -\frac{1}{8c} + \frac{d}{3} + \frac{d^3}{30\Delta^2} + \frac{d}{24c\Delta} - \frac{d^2}{6\Delta} = \frac{5(d-3\Delta)\Delta+4cd(d^2-5d\Delta+10\Delta^2)}{120c\Delta^2}$. Hence, we have

$$G_1(l=0)\begin{cases} \geq 0 & \text{if } 4c \geq \frac{5(3\Delta-d)\Delta}{(d^2-5d\Delta+10\Delta^2)d} \\ < 0 & \text{if } 4c < \frac{5(3\Delta-d)\Delta}{(d^2-5d\Delta+10\Delta^2)d}. \end{cases}$$

$G_1(l=2\Delta) = \frac{5\Delta(d^2-3d\Delta+3\Delta^2)+4cd(d^3-5d^2\Delta+10d\Delta^2-10\Delta^3)}{120cd\Delta^2}$. Hence, we have

$$G_1(l=2\Delta)\begin{cases} \geq 0 & \text{if } 4c \leq \frac{5(d^2-3d\Delta+3\Delta^2)\Delta}{(-d^3+5d^2\Delta-10d\Delta^2+10\Delta^3)d} \\ < 0 & \text{if } 4c < \frac{5(d^2-3d\Delta+3\Delta^2)\Delta}{(-d^3+5d^2\Delta-10d\Delta^2+10\Delta^3)d}. \end{cases}$$

Comparing the above thresholds, we get that $\frac{1}{d} < \frac{5(d^2-3d\Delta+3\Delta^2)\Delta}{(-d^3+5d^2\Delta-10d\Delta^2+10\Delta^3)d} < \frac{5(3\Delta-d)\Delta}{(d^2-5d\Delta+10\Delta^2)d}$.

Case 2: $d \geq \Delta$. The profit difference between the two mechanisms is

$$\begin{aligned}\Pi_S^* - \Pi_J^* &= \underbrace{e_S^* - e_J^*}_{\text{increasing in } l} \underbrace{-\frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{l^2}{4\Delta} + \frac{\Delta}{3} - \frac{\Delta^2}{6d} + \frac{\Delta^3}{30d^2}}_{\text{decreasing in } l} - P_S^* \\ &= \underbrace{(\frac{1}{4cd} - 1)P_S^*}_{\geq 0} + G_2(l),\end{aligned}$$

where $G_2(l) = -\frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{l^2}{4\Delta} + \frac{\Delta}{3} - \frac{(3d-\Delta)\Delta}{24cd^2} - \frac{\Delta^2}{6d} + \frac{\Delta^3}{30d^2} + \frac{s(-s+4\Delta)}{32cd\Delta}$. Taking the derivative of $G_2(l)$, we get that when $4cd-1<0$, $G_2(l)$ is always increasing in l; and when $4cd-1>0$, $G_2(l)$ is first decreasing and then increasing in l with a turning point at $l = \Delta(2-\frac{1}{2cd})$. Next, we examine whether $G_2(l=0)$ and $G_2(l=2\Delta)$ are positive or not. $G_2(l=0) = \frac{\Delta(40cd^2-5d(3+4c\Delta)+\Delta(5+4c\Delta))}{120cd^2} = \frac{4c(10d^2+\Delta^2-5d\Delta)+5\Delta-15d}{120cd^2}$. Hence, we have

$$G_2(l=0)\begin{cases} \geq 0 & \text{if } 4c \geq \frac{15d-5\Delta}{10d^2-5d\Delta+\Delta^2} \\ < 0 & \text{if } 4c < \frac{15d-5\Delta}{10d^2-5d\Delta+\Delta^2}. \end{cases}$$

$G_2(l=2\Delta) = \frac{\Delta^2(5+4c(-5d+\Delta))}{120cd^2}$. Hence, we have

$$G_2(l=2\Delta)\begin{cases} \geq 0 & \text{if } 4c \leq \frac{5}{5d-\Delta} \\ < 0 & \text{if } 4c < \frac{5}{5d-\Delta}. \end{cases}$$

Comparing the above thresholds, we can easily get that $\frac{1}{d} < \frac{5}{5d-\Delta} < \frac{15d-5\Delta}{10d^2-5d\Delta+\Delta^2}$.

Combining the above two cases, we obtain the following comparison results about the buyer's ex-ante profits Π_S^* and Π_J^* in the separate-sourcing and joint-sourcing mechanisms:

1. When $d \leq \Delta$,
   (a) If $4c > \frac{5(3\Delta-d)\Delta}{(d^2-5d\Delta+10\Delta^2)d}$, there exists a threshold $\bar{l}$ (that solves $G_1(\bar{l})=0$) such that $\Pi_S^* > \Pi_J^*$ if and only if $l < \bar{l}$.
   (b) If $\frac{5(d^2-3d\Delta+3\Delta^2)\Delta}{(-d^3+5d^2\Delta-10d\Delta^2+10\Delta^3)d} \leq 4c \leq \frac{5(3\Delta-d)\Delta}{(d^2-5d\Delta+10\Delta^2)d}$, the joint-sourcing mechanism always generates a higher profit for the buyer, i.e., $\Pi_J^* > \Pi_S^*$.
   (c) If $\frac{1}{d} \leq 4c < \frac{5(d^2-3d\Delta+3\Delta^2)\Delta}{(-d^3+5d^2\Delta-10d\Delta^2+10\Delta^3)d}$, there exists a threshold $\bar{l}$ (where $G_1(\bar{l})=0$) such that when $l > \bar{l}$, the separate-sourcing mechanism generates a higher profit for the buyer (i.e., $\Pi_S^* > \Pi_J^*$), and vice versa.

(d) If $4c < \frac{1}{d}$, only when there exists a threshold $\bar{l}'$ such that $(\frac{1}{4cd}-1)P_S^* + G_1(\bar{l}') = 0$, the joint-sourcing mechanism generates a higher profit when $l < \bar{l}'$; otherwise, the separate-sourcing mechanism always generates a higher profit for the buyer.

2. When $d > \Delta$,

(a) If $4c > \frac{15d-5\Delta}{10d^2-5d\Delta+\Delta^2}$, there exists a threshold $\widehat{l}$ (where $G_2(\widehat{l}) = 0$) such that when $l < \widehat{l}$, the separate-sourcing mechanism generates a higher profit for the buyer (i.e., $\Pi_S^* > \Pi_J^*$), and vice versa.

(b) If $\frac{5}{5d-\Delta} \leq 4c \leq \frac{15d-5\Delta}{10d^2-5d\Delta+\Delta^2}$, the joint-sourcing mechanism always generates a higher profit for the buyer, i.e., $\Pi_J^* > \Pi_S^*$.

(c) If $\frac{1}{d} \leq 4c < \frac{5}{5d-\Delta}$, there exists a threshold $\widehat{l}$ (where $G_2(\widehat{l}) = 0$) such that when $l > \widehat{l}$, the separate-sourcing mechanism generates a higher profit for the buyer (i.e., $\Pi_S^* > \Pi_J^*$), and vice versa.

(d) If $4c < \frac{1}{d}$, only when there exists a threshold $\widehat{l}'$ such that $(\frac{1}{4cd}-1)P_S^* + G_2(\widehat{l}') = 0$, the joint-sourcing mechanism generates a higher profit when $l < \widehat{l}'$; otherwise, the separate-sourcing mechanism always generates a higher profit for the buyer.

Here $G_1(l) = \frac{d}{3} - \frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{d^2(d-5\Delta)}{30\Delta^2} + \frac{l^2}{4\Delta} - \frac{-d+3\Delta}{24c\Delta} + \frac{s(-s+4\Delta)}{32cd\Delta}$ and $G_2(l) = -\frac{l}{2} - \frac{l^3}{24\Delta^2} + \frac{l^2}{4\Delta} + \frac{\Delta}{3} - \frac{(3d-\Delta)\Delta}{24cd^2} - \frac{\Delta^2}{6d} + \frac{\Delta^3}{30d^2} + \frac{s(-s+4\Delta)}{32cd\Delta}$. ■

Proof of Proposition 5. The buyer's optimization problem in the no-commitment mechanism is:

$$\begin{aligned}\max_{x(\mathbf{c}|\mathbf{v}),y(\mathbf{c}|\mathbf{v}),t(\mathbf{c}|\mathbf{v})} \mathbb{E}_{\mathbf{c}}\left[\sum_{i=1}^{2}(v_i-c_i)y_i(\mathbf{c}|\mathbf{v})x_i(\mathbf{c}|\mathbf{v}) + \sum_{i=1}^{2}(v_i-c_j-l)y_i(\mathbf{c}|\mathbf{v})x_j(\mathbf{c}|\mathbf{v})\right] - \sum_{i=1}^{2}E_{c_i}[u_i(c_i,\mathbf{v})] \\ s.t. \quad \sum_{i=1}^{2}x_i(\mathbf{c}|\mathbf{v}) \leq 1 \quad \text{and} \quad x_i \geq 0, \quad \forall \mathbf{c}, \forall \mathbf{v}, \\ (IC), (IR).\end{aligned} \tag{EC.12}$$

Following the analysis of the joint-sourcing mechanism, we have $E_{c_i}[u_i(c_i,\mathbf{v})] = \int_{\underline{c}}^{\bar{c}}\int_{\underline{c}}^{\bar{c}} F(c_i)x_i(\mathbf{c}|\mathbf{v})f(c_j)dc_jdc_i$, so the buyer's optimization problem becomes:

$$\max_{x(\mathbf{c}|\mathbf{v}),y(\mathbf{c}|\mathbf{v})} \int_{\underline{c}}^{\bar{c}}\int_{\underline{c}}^{\bar{c}}\sum_{i=1}^{2}\left[(v_i-c_i)y_i(\mathbf{c}|\mathbf{v}) + (v_j-c_i-l)y_j(\mathbf{c}|\mathbf{v}) - \frac{F(c_i)}{f(c_i)}\right]x_i(\mathbf{c}|\mathbf{v})f(c_i)f(c_j)dc_idc_j.$$

Then we can derive the optimal design selection and production selection rule by solving the pointwise optimization problem given $\mathbf{c}, \mathbf{v}$, i.e.,

$$\max_{x(\mathbf{c}|\mathbf{v}),y(\mathbf{c}|\mathbf{v})} \sum_{i=1}^{2}\left[(v_i-c_i)y_i(\mathbf{c}|\mathbf{v}) + (v_j-c_i-l)y_j(\mathbf{c}|\mathbf{v}) - \frac{F(c_i)}{f(c_i)}\right]x_i(\mathbf{c}|\mathbf{v}).$$

There exist four possible solutions for the above pointwise optimization problem:

1. $y_i(\mathbf{c}|\mathbf{v}) = 1, x_i(\mathbf{c}|\mathbf{v}) = 1$, then buyer's ex-post profit is $v_i - C(c_i)$;
2. $y_i(\mathbf{c}|\mathbf{v}) = 1, x_i(\mathbf{c}|\mathbf{v}) = 0$, then buyer's ex-post profit is $v_i - C(c_j) - l$;

3. $y_i(\mathbf{c}|\mathbf{v}) = 0, x_i(\mathbf{c}|\mathbf{v}) = 1$, then buyer's ex-post profit is $v_j - C(c_i) - l$;
4. $y_i(\mathbf{c}|\mathbf{v}) = 0, x_i(\mathbf{c}|\mathbf{v}) = 0$, then buyer's ex-post profit is $v_j - C(c_j)$.

Proposition 5 follows from comparing the buyer's profit in the above four solutions given $\mathbf{c}, \mathbf{v}$. ■

Proof of Lemma 4. Given supplier j's effort e_j, the first-order condition of solver i's optimization problem $\max_{e_i} \pi_i(\mathbf{e}) = E_{\mathbf{v}}\left[U_{iN}\left(\mathbf{v}|\,\mathbf{e}\right)\right] - \psi(e_i)$ is:

$$\frac{\partial}{\partial e_i}\Bigg(-ce_i^2 + \int_{-e_i+e_j+l}^{2d} \frac{8\Delta^3 - l^3 + 12\Delta^2 l}{48\Delta^2}\frac{2d-\epsilon}{4d^2}d\epsilon + \int_{-2d}^{-e_i+e_j-l}\frac{(2\Delta-l)^3}{(48\Delta^2)}\frac{2d+\epsilon}{4d^2}d\epsilon$$
$$+\int_{-e_i+e_j-l}^{e_j-e_i}\frac{(2d+\epsilon)(2\Delta+e_i-e_j+\epsilon)^3}{(4d^2)\,(48\Delta^2)}\,d\epsilon + \int_{e_j-e_i}^{-e_i+e_j+l}\frac{8\Delta^3+12\Delta^2(e_i-e_j+\epsilon)-(e_i-e_j+\epsilon)^3}{48\Delta^2}\frac{2d-\epsilon}{4d^2}d\epsilon\Bigg)$$
$$= \frac{1}{96d^2\Delta^2}\left(-6\Delta^2\left(32cd^2e_i - 4dl + l^2\right) + \Delta l^2(-6d+3e_i-3e_j+2l) + 8\Delta^3(e_i-e_j) + l^3(e_j-e_i)\right).$$

Because $\frac{\partial \pi_i(\mathbf{e})}{\partial e_i}|_{e_i=e_j=e^*} = 0$, we have

$$e_N^* = \frac{l(l(l-3\Delta)-3d(l-4\Delta))}{96cd^2\Delta}. \blacksquare$$

Proof of Lemma 5. To derive the buyer's expected profit Π_N^* in the innovation stage, we should calculate $U_N(\mathbf{v})$ first by considering the following four cases.

Case 1: $\epsilon = \xi_i - \xi_j > l$**.** The buyer's expected utility in the procurement stage is: $U_N(\xi_i, \xi_j|e_i = e_j = e_N^*) = \int_{\underline{c}+\frac{l}{2}}^{\bar{c}}\left(1 - \frac{-\underline{c}+c_i-\frac{l}{2}}{\Delta}\right)(\underline{c} - 2c_i + e_N^* + m + \epsilon + \xi_j)\frac{1}{\Delta}dc_i + \int_{\underline{c}}^{\underline{c}+\frac{l}{2}}(\underline{c} - 2c_i + e_N^* + m + \epsilon + \xi_j)\frac{1}{\Delta}dc_i + \int_{\underline{c}}^{\bar{c}-\frac{l}{2}}\frac{\left(1-\frac{-\underline{c}+c_j+\frac{l}{2}}{\Delta}\right)\left(\underline{c}-2c_j+e_N^*+m-l+\xi_i\right)}{\Delta}dc_j = -\underline{c} + e_N^* + m - \frac{2\Delta}{3} - \frac{l^3-6\Delta l^2+12\Delta^2 l}{24\Delta^2} + \xi_i$.

Case 2: $0 < \epsilon \leq l$**.** The buyer's expected utility in the procurement stage is: $U_N(\xi_i, \xi_j|e_i = e_j = e_N^*) = \int_{\underline{c}+\frac{z}{2}}^{\bar{c}}\left(1 - \frac{-\underline{c}+c_i-\frac{z}{2}}{\Delta}\right)(\underline{c} - 2c_i + e_N^* + m + z + \xi_j)\frac{1}{\Delta}dc_i + \int_{\underline{c}}^{\underline{c}+\frac{\epsilon}{2}}(\underline{c} - 2c_i + e_N^* + m + \epsilon + \xi_j)\frac{1}{\Delta}dc_i + \int_{\underline{c}}^{\bar{c}-\frac{\epsilon}{2}}\left(1 - \frac{-\underline{c}+c_j+\frac{\epsilon}{2}}{\Delta}\right)(\underline{c} - 2c_j + e_N^* + m - \epsilon + \xi_i)\frac{1}{\Delta}dc_j = -\underline{c} - \frac{2\Delta}{3} + e_N^* + m - \frac{\epsilon^3}{24\Delta^2} + \frac{\epsilon^2}{4\Delta} + \frac{\xi_i+\xi_j}{2}$.

Similarly to the above cases, we can derive U_N in the case of $-l < \epsilon \leq 0$ and $\epsilon \leq -l$. We summarize the buyer's expected utility in each case in the following equation:

$$U_N(\xi_i, \xi_j|e_i = e_j = e_N^*) = \begin{cases} e_N^* + m - \underline{c} - \frac{2\Delta}{3} - \frac{l^3-6\Delta l^2+12\Delta^2 l}{24\Delta^2} + \xi_i & \epsilon > l \\ e_N^* + m - \underline{c} - \frac{2\Delta}{3} - \frac{\epsilon^3}{24\Delta^2} + \frac{\epsilon^2}{4\Delta} + \frac{\xi_i+\xi_j}{2} & 0 < \epsilon \leq l \\ e_N^* + m - \underline{c} - \frac{2\Delta}{3} + \frac{\epsilon^3}{24\Delta^2} + \frac{\epsilon^2}{4\Delta} + \frac{\xi_i+\xi_j}{2} & -l < \epsilon \leq 0 \\ e_N^* + m - \underline{c} - \frac{2\Delta}{3} - \frac{l^3-6\Delta l^2+12\Delta^2 l}{24\Delta^2} + \xi_j & \epsilon \leq -l. \end{cases} \quad \text{(EC.13)}$$

Taking expectation of U_N over ξ_i and ξ_j, we have

$$\Pi_N^* = e^* + m - \underline{c} - \frac{2\Delta}{3}$$
$$+ \int_{-d}^{d-l}\left(\int_{s+\xi_j}^{d}(\xi_i - \frac{-6\Delta l^2 + l^3 + 12\Delta^2 l}{24\Delta^2})\frac{1}{4d^2}d\xi_i\right)d\xi_j + \int_{s-d}^{d}\left(\int_{-d}^{\xi_j - l}(\xi_j - \frac{-6\Delta l^2 + l^3 + 12\Delta^2 l}{24\Delta^2})\frac{1}{4d^2}d\xi_i\right)d\xi_j$$
$$+ \int_{-d}^{s-d}\left(\int_{-d}^{\xi_j}\frac{\frac{(\xi_i-\xi_j)^3}{24\Delta^2} + \frac{(\xi_i-\xi_j)^2}{4\Delta} + \frac{\xi_i+\xi_j}{2}}{4d^2}d\xi_i\right)d\xi_j + \int_{s-d}^{d}\left(\int_{\xi_j-l}^{\xi_j}\frac{\frac{(\xi_i-\xi_j)^3}{24\Delta^2} + \frac{(\xi_i-\xi_j)^2}{4\Delta} + \frac{\xi_i+\xi_j}{2}}{4d^2}d\xi_i\right)d\xi_j$$

$$+\int_{d-l}^{d}\left(\int_{\xi_j}^{d}\frac{-\frac{(\xi_i-\xi_j)^3}{24\Delta^2}+\frac{(\xi_i-\xi_j)^2}{4\Delta}+\frac{\xi_i+\xi_j}{2}}{4d^2}d\xi_i\right)d\xi_j+\int_{-d}^{d-l}\left(\int_{\xi_j}^{s+\xi_j}\frac{-\frac{(\xi_i-\xi_j)^3}{24\Delta^2}+\frac{(\xi_i-\xi_j)^2}{4\Delta}+\frac{\xi_i+\xi_j}{2}}{4d^2}d\xi_i\right)d\xi_j.$$

Thus, $\Pi_N(e_N^*)=e_N^*+m-\underline{c}-\frac{2\Delta}{3}+\frac{5\Delta l^2\left(24d^2-16dl+3l^2\right)+l^3\left(-20d^2+15dl-3l^2\right)-20\Delta^2(l-2d)^3}{480d^2\Delta^2}$. ■

Proof of Proposition 6. Knowing that e_N^* is increasing in l and $e_N^*|_{l=\min\{2d,2\Delta\}}=e_J^*$, we can easily obtain that $e_J^*\geq e_N^*$. Also, we have

$$e_N^*=\frac{l(4\Delta-l)}{32cd\Delta}-\underbrace{\frac{l^2(3\Delta-l)}{96cd^2\Delta}}_{\leq 0}\leq\frac{l(4\Delta-l)+8\Delta P_S^*}{32cd\Delta}=e_S^*. ■$$

Proof of Proposition 7. (i) Comparing the buyer's expected profits in separate-sourcing and non-commitment mechanisms, we obtain

$$\Pi_S^*-\Pi_N^*=\underbrace{\frac{P^*(1-4cd)}{4cd}}_{\geq 0}+\underbrace{\frac{15\Delta^2l^2(1-8cd)-5\Delta l^3(-16cd+3cl+1)+3cl^4(l-5d)+20c\Delta^2l^3}{480cd^2\Delta^2}}_{D_1(l)}.$$

To fairly compare the no-commitment mechanism and separate-sourcing mechanism, we let $\overline{P}=0$. Now we only need to analyze the function $D_1(l)$. The-first order condition yields:

$$\frac{\partial D_1(l)}{\partial l}=\frac{s(l-2\Delta)(-c(4d-l)(l-2\Delta)-\Delta)}{32cd^2\Delta^2}.$$

Thus, we obtain that:

1. When $\Delta>d$,
   (a) when $c\leq\frac{1}{8d}$, $\Pi_S^*-\Pi_N^*$ is increasing in $l\in[0,\min\{2d,2\Delta\}]$;
   (b) When $\frac{1}{8d}<c\leq\frac{\Delta}{4d(\Delta-d)}$, $\Pi_S^*-\Pi_N^*$ is first decreasing and then increasing in l and the minimum value is achieved at $l=2d+\Delta-\sqrt{\frac{\Delta+c(\Delta-2d)^2}{c}}$;
   (c) When $c>\frac{\Delta}{4d(\Delta-d)}$, $\Pi_S^*-\Pi_N^*$ is decreasing in l.
2. when $\Delta\leq d$,
   (a) when $c\leq\frac{1}{8d}$, $\Pi_S^*-\Pi_N^*$ is increasing in $l\in[0,\min\{2d,2\Delta\}]$;
   (b) When $\frac{1}{8d}<c$, $\Pi_S^*-\Pi_N^*$ is first decreasing and then increasing in l and the minimum value is achieved at $l=2d+\Delta-\sqrt{\frac{\Delta+c(\Delta-2d)^2}{c}}$.

Because $D_1(l=0)=0$, by considering signs of $D_1(l=2d)$ and $D_1(l=2\Delta)$, we obtain part (i) of the proposition, where $c_{SN}^L=\frac{1}{8d}$, $c_{SN}^H=\frac{5}{4(5d-\Delta)}$ when $\Delta\leq d$ and $c_{SN}^H=\frac{5\Delta(3\Delta-2d)}{4d(9d^2-25d\Delta+20\Delta^2)}$ when $\Delta>d$.
(ii) To compare the buyer's profits in joint-sourcing and enhanced-commitment mechanisms, we need to consider two cases: 1)$\Delta>d$ and 2) $\Delta\leq d$.

When $\Delta>d$, we have

$$\Pi_J^*-\Pi_N^*=\underbrace{-\frac{(l-2d)^2\left(c(2d-l)\left(2d^2-5\Delta(2d+3l)+3ds+20\Delta^2+3l^2\right)+5\Delta(d-3\Delta+l)\right)}{480cd^2\Delta^2}}_{D_2(l)}.$$

Analyzing the first-order condition,

$$\frac{\partial D_2(l)}{\partial l} = \frac{(2d-l)(l-2\Delta)(c(2d-l)(l-2\Delta)+\Delta)}{32cd^2\Delta^2},$$

we obtain that:

1. When $c \leq \frac{1}{4d}$, $\Pi_J^* - \Pi_N^*$ is decreasing in $l \in [0, 2d]$;
2. When $c > \frac{1}{4d}$, $\Pi_J^* - \Pi_N^*$ is first increasing and then decreasing in $l \in [0, 2d]$. The maximal value is achieved at $l = (d + \Delta - \sqrt{(d-\Delta)^2 + \frac{\Delta}{c}})$.

Because $D_2(l = 2d) = 0$, we only need to check the sign of $D_2(l = 0)$. Applying a similar analysis for the case where $\Delta \leq d$, we obtain part (ii) of the proposition where

$$c_{JN} = \begin{cases} \frac{15d-5\Delta}{40d^2-20d\Delta+4\Delta^2} & \Delta \leq d \\ \frac{15\Delta^2-5d\Delta}{4d^3-20d^2\Delta+40d\Delta^2} & \Delta > d \end{cases}. \blacksquare$$

Proof of Proposition 8. Noting that the equilibrium in the enhanced-commitment mechanism is the same as that under the separate-sourcing mechanism when $l > 2\Delta$, the result follows from the proofs of Proposition 1 and Lemmas 1 and 2. ■

Proof of Proposition 9. Follows from Proposition 6 and by comparing the equilibrium efforts characterized for joint-sourcing, separate-sourcing, and enhanced-commitment mechanisms. ■

Proof of Proposition 10. (i) First, we compare the buyer's expected profits in separate-sourcing and enhanced-commitment mechanisms. Since $\frac{\partial \Pi_S^* - \Pi_H^*}{\partial l} = -\frac{(l-2\Delta)(2cd(l-2\Delta)+\Delta)}{16cd\Delta^2}$, when $1 - 4cd \geq 0$, $\frac{\partial \Pi_S^* - \Pi_H^*}{\partial l} > 0$; and when $1 - 4cd < 0$, $\Pi_S^* - \Pi_H^*$ is first decreasing and then increasing. Noting that $\Pi_S^*|_{l=2\Delta} = \Pi_H^*$ and $\Pi_S^*|_{l=0} - \Pi_H^* = \frac{1}{24}(8 - \frac{3}{cd})\Delta$ (which is negative when $c < \frac{3}{8d}$), we conclude that 1) when $1 - 4cd \geq 0$, or when $1 - 4cd < 0$ and $c \leq \frac{3}{8d}$, $\Pi_H^* \geq \Pi_S^*$; and 2) when $1 - 4cd < 0$ and $c > \frac{3}{8d}$, there exists a threshold $(2 - \frac{3}{4cd})\Delta$ such that $\Pi_H^* > \Pi_S^*$ if and only if $l > (2 - \frac{3}{4cd})\Delta$.

(ii) Next, we compare the enhanced-commitment mechanism with the joint-sourcing mechanism by considering cases of $d \geq \Delta$ and $d < \Delta$.

Case 1: $d \geq \Delta$. Since $\frac{\partial \Pi_J^* - \Pi_H^*}{\partial c} > 0$, there exists a threshold $\frac{5\left(6dP_H^* + \Delta^2\right)}{4\left(30d^2P_H^* + 5d\Delta^2 - \Delta^3\right)}$ such that $\Pi_J^* > \Pi_H^*$ if and only if $c > \frac{5\left(6dP_H^* + \Delta^2\right)}{4\left(30d^2P_H^* + 5d\Delta^2 - \Delta^3\right)}$. Since the threshold $\frac{5\left(6dP_H^* + \Delta^2\right)}{4\left(30d^2P_H^* + 5d\Delta^2 - \Delta^3\right)} > \frac{1}{4d}$, we have $P_H^* = 0$ and the threshold becomes $\frac{5}{4(5d-\Delta)}$.

Case 2: $d < \Delta$. Applying similar analysis as case 1, we have that $\Pi_J^* > \Pi_H^*$ if and only if $c > \frac{5\Delta\left(d^2 - 3d\Delta + 3\Delta^2\right)}{4d\left(-d^3 + 5d^2\Delta - 10d\Delta^2 + 10\Delta^3\right)}$.

Combining cases 1 and 2, we find that the threshold is exactly C_1 shown in Proposition 4. ■

Proof of Proposition EC.1. To derive suppliers' equilibrium effort and the buyer's expected profit, we apply the following four steps.

Step 1: Calculate the allocation rule. Applying a similar analysis as our base model, we get the optimal allocation rule as

$$x_i(\mathbf{c}|\mathbf{v}) = \begin{cases} 1 & \text{if } v_i - v_j < \frac{2}{1+\alpha}(c_i - c_j) \\ 0 & \text{otherwise.} \end{cases}$$

Step 2: Calculate supplier's expected profit in the procurement stage. With the optimal selection rule, we can derive each supplier's expected utility in the procurement stage:

$$\begin{aligned} U_i(\mathbf{v}) &= \int_{\alpha v_i - \frac{\Delta}{2}}^{\alpha v_i + \frac{\Delta}{2}} \frac{c - \left(\alpha v_i - \frac{\Delta}{2}\right)}{\Delta} \Pr(c_j > c_i - \frac{(1+\alpha)(v_i - v_j)}{2}) dc_i \\ &= \begin{cases} \frac{\Delta}{2} & v_i - v_j \geq \frac{2}{1+\alpha}\Delta \\ \frac{8\Delta^3 + 12(1-\alpha)\Delta^2\left(v_i - v_j\right) - (1-\alpha)^3\left(v_i - v_j\right)^3}{48\Delta^2} & 0 \leq v_i - v_j < \frac{2}{1+\alpha}\Delta \\ \frac{\left(2\Delta + (1-\alpha)(v_i - v_j)\right)^3}{48\Delta^2} & -\frac{2}{1+\alpha}\Delta < v_i - v_j < 0 \\ 0 & v_i - v_j \leq -\frac{2}{1+\alpha}\Delta. \end{cases} \end{aligned}$$

Step 3: Derive and analyze the equilibrium effort. To calculate suppliers' equilibrium effort in the joint-sourcing mechanism, we need to consider two cases: 1) $(1+\alpha)d \geq \Delta$ and 2) $(1+\alpha)d < \Delta$.

Take case 1 as an example. Given supplier j's effort e_j, supplier i's best-response effort e_i is determined by the following condition

$$\begin{aligned} &\frac{\partial}{\partial e_i}(-ce_i^2 + \int_{-\frac{2\Delta}{\alpha+1} - e_i + e_j}^{e_j - e_i} \frac{(2d+z)(2\Delta + (1-\alpha)(e_i - e_j + z))^3}{(4d^2)\,(48\Delta^2)} dz \\ &\quad + \int_{e_j - e_i}^{\frac{2\Delta}{\alpha+1} - e_i + e_j} \frac{(2d-z)\,(8\Delta^3 + 12(1-\alpha)\Delta^2(e_i - e_j + z) + (1-\alpha)^3\,(-(e_i - e_j + z)^3))}{(4d^2)\,(48\Delta^2)} dz \\ &\quad + \int_{\frac{2\Delta}{\alpha+1} - e_i + e_j}^{2d} \frac{\Delta(2d-z)}{2\,(4d^2)} dz) = 0. \end{aligned}$$

Similarly, we can derive the best response e_j given e_i. Solving these two best-response function simultaneously, we get a pure strategy symmetric equilibrium, which is $e_J^\alpha = \frac{\Delta\left(3(\alpha+1)^3 d - (\alpha(7\alpha+4)+1)\Delta\right)}{24(\alpha+1)^3 cd^2}$.

Taking derivative of the equilibrium effort on α, we have

$$\frac{\partial\left(-\frac{(\alpha-1)(\alpha d - d + 3\Delta)}{24c\Delta}\right)}{\partial\alpha} = -\frac{2(\alpha-1)d + 3\Delta}{24c\Delta} < 0,$$

and

$$\frac{\partial \frac{\Delta\left(3(\alpha+1)^3 d - (\alpha(7\alpha+4)+1)\Delta\right)}{24(\alpha+1)^3 cd^2}}{\partial\alpha} = \frac{(\alpha-1)(7\alpha+1)\Delta^2}{24(\alpha+1)^4 cd^2} < 0.$$

Hence, the equilibrium effort is decreasing in α.

Step 4: Calculate the buyer's expected profit in the joint-sourcing mechanism. The buyer's expected profit in the procurement stage is:

$$U_b(\mathbf{v}) = \int_{\alpha v_i - \frac{\Delta}{2}}^{\alpha v_i + \frac{\Delta}{2}} (v_i - C_\alpha(c_i)) \Pr(c_j > c_i - \frac{(1+\alpha)(v_i - v_j)}{2}) dc_i + \int_{\alpha v_j - \frac{\Delta}{2}}^{\alpha v_j + \frac{\Delta}{2}} (v_j - C_\alpha(c_j)) \Pr(c_i > c_j - \frac{(1+\alpha)(v_j - v_i)}{2}) dc_j.$$

Taking expected over ξ_i and ξ_j, we can get the buyer's expected profit.

We now use the case of $(1+\alpha)d > \Delta$ as an example to show that buyer's expected profit is decreasing in α. Taking derivative of Π_J^α on α, we know that the sign of $\frac{\Pi_J^\alpha}{\partial \alpha}$ is determined by the sign of $\frac{(1-\alpha)e_J^\alpha}{\partial \alpha}$ and the sign of $\frac{\partial\left(\frac{5(\alpha(\alpha(9\alpha-1)-1)+1)\Delta^2}{(\alpha+1)^4 d}-\frac{(\alpha-1)(\alpha(29\alpha+12)-1)\Delta^3}{(\alpha+1)^5 d^2}\right)}{\partial \alpha}$. Since $sgn\{\frac{(1-\alpha)e_J^\alpha}{\partial \alpha}\} < 0$ and

$$
\begin{aligned}
& sgn\left\{\frac{\partial\left(\frac{5(\alpha(\alpha(9\alpha-1)-1)+1)\Delta^2}{(\alpha+1)^4 d}-\frac{(\alpha-1)(\alpha(29\alpha+12)-1)\Delta^3}{(\alpha+1)^5 d^2}\right)}{\partial \alpha}\right\} \\
&= sgn\{2(\alpha(\alpha(29\alpha-69)-9)+9)\Delta-5(\alpha+1)(\alpha(\alpha(9\alpha-29)-1)+5)d\} \\
&= sgn\{(\alpha-1)(\alpha+1)(13\alpha+7)\} < 0,
\end{aligned}
$$

we conclude that Π_J^α is decreasing in α. ■