Optimal Procurement Mechanisms for Assembly

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This paper investigates mechanisms by which a powerful OEM procures multiple inputs for assembly from suppliers with privately informed costs, either simultaneously or sequentially. The optimal mechanisms always lead to matching purchase quantities of the inputs. Thus, quantity-payment contracts that implement the optimal mechanisms are contingent across suppliers (i.e., each supplier's contract terms contain other suppliers' private costs as variables), making the implementation impractical. To address this issue, we propose alternative implementations of the optimal mechanisms by menus of two-part tariff contracts that are non-contingent. In addition, optimal simultaneous and sequential procurement mechanisms for assembly are shown to be revenue-equivalent for all parties, despite their differing asymmetric information structures. Our findings suggest that procurement managers need not strategize contracting sequences for assembly, but should rather focus on achieving the best pricing with each supplier and coordinating purchase quantities.

Key words: mechanism design, screening, two-part tariff, contracting timing, informed principal

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1. Introduction

Manufacturing firms are increasingly specializing in their core competencies and depending on suppliers for other value-added processes. Major original equipment manufacturers (OEMs), such as Apple and Boeing, regularly procure inputs worth billions of dollars from suppliers. Such OEMs possess dominant market power and can extract most profits from suppliers (Greene 2012). Nevertheless, suppliers typically have more accurate information regarding their own costs than do OEMs, preventing the latter from extracting all profits despite their market power. The classic model for a powerful OEM contracting with a privately informed supplier is the principal-agent model (Ha 2001, Corbett et al. 2004), in which the OEM's optimal procurement mechanism is to offer a menu of quantity-payment contracts (each consisting of a purchase quantity and a corresponding payment) from which the supplier chooses one that maximizes its profit. In this mechanism, the OEM forfeits information rents to the supplier in exchange for the latter to reveal its private cost information—a strategy known as *screening*. Practical evidence of screening includes, for instance, an interview reported by Lovejoy (2010) of a supply chain manager who was willing to pay more to a supplier in exchange for its "opening the book" and revealing its cost.

The above model describes a buyer procuring a single input from a supplier. In practice, however, OEMs often procure multiple inputs from different suppliers to assemble the final products: Apple procures processors from Samsung and LCD screens from Japan Display for the iPhone 6 (IHS 2014); Boeing procures engines from Rolls-Royce (Clark 2012) and nacelles from Goodrich Corp (Bigelow 2007) for the 787 Dreamliner. While specific types of procurement contracts for assembly have been studied (e.g., Fang et al. 2014 study independent quantity-payment contracts), the general optimal mechanism is yet to be thoroughly investigated. Our first research question thus follows: *what is the general optimal procurement mechanism for assembly?*

The quest does not end at identifying the general optimal procurement mechanism for assembly. Optimal mechanisms in complex settings tend to be rather complicated, presenting to practitioners the tradeoff of theoretical performance and practical implementability. The ideal solution to the dilemma would be to find a simple, practical implementation of the optimal mechanism (Duenyas et al. 2013, Bolandifar et al. 2016a). Accordingly, our second research question is: *what is a practical implementation of the general optimal procurement mechanism for assembly?*

Lastly, an OEM contracting with multiple suppliers for assembly naturally faces the issue of timing: the contracting can be *simultaneous* or *sequential*. We note that contracting timing impacts the asymmetric information structure. Under simultaneous contracting, all suppliers' costs are unknown to the OEM during the contracting process. In contrast, under sequential contracting, the OEM learns the first supplier's private cost information through screening before contracting with other suppliers, making it an *informed principal* in the latter process. It may be tempting to assume that the OEM would prefer sequential contracting because of the additional information it could acquire, yet the comparison has not been formally established. To provide a definitive answer, our third research question is: *how do the optimal simultaneous and sequential mechanisms differ, and what are the OEM's and suppliers' preferences between them?*

We extend the single-input principal-agent model to consider a powerful OEM contracting with two suppliers privately informed of their costs for assembly. We derive the OEM's optimal mechanisms under simultaneous and sequential contracting, adopting the theory of contracting with externalities (Segal 1999), the theory of optimal mechanism design (Myerson 1981), and the theory of mechanism design by an informed principal (Maskin and Tirole 1992). We find that the optimal mechanisms coordinate purchase quantities of different inputs (i.e., lead to matching purchase quantities). As a result, the quantity-payment contracts that implement the optimal mechanisms are contingent across suppliers (i.e., each supplier's contract terms contain other suppliers' private costs as variables).

Such optimal mechanisms based on contingent quantity-payment contracts are complicated and impractical. It would be practically valuable if there were non-contingent implementations. We note that for procuring a single input, the optimal mechanism has an equivalent implementation where the OEM offers a menu of two-part tariff contracts (each consisting of a wholesale price and a fixed payment) to the supplier and determines the purchase quantity once the supplier has chosen a contract from the menu (Laffont and Martimort 2002, p. 375). We show that menus of two-part tariff contracts can similarly implement the optimal procurement mechanisms for assembly. More importantly, the contracts therein are non-contingent (i.e., each supplier's contract terms do not contain other suppliers' unknown private costs as variables), thus this implementation is more practical. Non-contingent two-part tariff contracts can implement the optimal mechanisms because such contracts inherently allow the OEM to coordinate purchase quantities after contracting on pricing with all suppliers.

We then compare optimal simultaneous and sequential procurement mechanisms for assembly and find that they actually yield equal expected profits for the OEM as well as for each supplier. Recall the optimal mechanism insight that the suppliers' incentives are provided by information rents, and the OEM's total marginal sourcing cost determines the purchase quantities. A definitive feature of assembly systems is that the OEM's total marginal sourcing cost is a sum of all suppliers' marginal costs without externalities (i.e., one supplier's cost does not affect another supplier's contribution to the OEM's total marginal sourcing cost.) Consequently, the knowledge of a supplier's cost is irrelevant in the OEM's screening of other suppliers, leading to the same expected profits under simultaneous and sequential contracting, despite their differing asymmetric information structures.

In what follows, we review the literature in Section 2 before introducing our base model in Section 3. We then respectively analyze simultaneous and sequential contracting in Sections 4 and 5, and show their revenue equivalence in Section 6. Section 7 extends all results to general convex costs before Section 8 concludes the paper. The Appendix contains all proofs.

2. Literature review

This paper belongs to the literature on procurement and contracting under asymmetric information. One stream of research in this literature focuses on how to overcome information asymmetry through contracting. Topics include private cost and/or capacity information (Ha 2001, Corbett et al. 2004, Chu and Sappington 2015), forecast information sharing (Özer and Wei 2006, Babich et al. 2012, Kong et al. 2013), competing suppliers (Özer and Raz 2011, Li et al. 2015), private supply disruption information (Yang et al. 2009, Gümüs et al. 2012), and private effort (Zhang et al. 2017). The other stream focuses on how to overcome information asymmetry through bidder competition in auctions. Topics include quantity auction (Dasgupta and Spulber 1990), supplier qualification (Wan and Beil 2009, Wan et al. 2012, Chen et al. 2016), double auction (Chu and Shen 2006, 2008), supply risk (Chaturvedi and Martínez-de Albéniz 2011), supplier retention with split award auction (Chaturvedi et al. 2014), implementation of optimal procurement mechanism (Chen 2007, Duenyas et al. 2013), and procurement under capacity and business rule constraints (Gupta et al. 2015). All papers mentioned concern procuring a single input. Our study, however, focuses on the optimal procurement of multiple inputs for assembly.

There are two prominent papers on procurement mechanisms for assembly under information asymmetry. Fang et al. (2014) consider a manufacturer procuring multiple inputs for assembly using menus of independent quantity-payment contracts. While they focus on a specific contract type, we study general optimal mechanisms among all possible contract types. We also investigate contracting timing, an issue not discussed in their paper. Kalkanci and Erhun (2012) also consider procurement mechanisms for assembly. They model powerful suppliers proposing contracts to a privately informed OEM and find that either the simultaneous or sequential mechanism may be better for the suppliers and the OEM, whereas we model a powerful OEM proposing contracts to privately informed suppliers. Thus, our work complements Kalkanci and Erhun (2012) to provide a comprehensive understanding of procurement mechanisms for assembly under information asymmetry. Procurement for assembly has also been studied from perspectives other than managing information asymmetry. Jiang and Wang (2010) and Jiang (2015) study the impact of supplier competition on procurement for assembly, and the latter finds that sequential procurement may be better than simultaneous procurement in this setting. Gerchak and Wang (2004) and Zhang (2006) derive coordinating contracts in procurement for assembly.

One of our key findings is that optimal simultaneous and sequential procurement mechanisms for assembly are revenue-equivalent. Generally, when a principal contracts with multiple agents, optimal simultaneous and sequential mechanisms do *not* yield the same payoffs. For example, the optimal simultaneous mechanism to motivate workers to exert complementary efforts derived by Winter (2004) is more costly than the optimal sequential mechanism derived by Winter (2006). This result is because in the sequential setting, one worker's effort is credibly observed by other workers, whereas in the simultaneous setting, the principal needs to shape the beliefs of all agents. When the workers' efforts are substitutes, Winter (2010) shows that the optimal simultaneous mechanism is less costly than the optimal sequential mechanism. Gerardi and Yariv (2008) consider the optimal mechanisms to form an expert committee, and show that either a sequential mechanism or not forming the committee is better than a simultaneous mechanism. Hu and Wang (2017) compare the optimal sequential and simultaneous mechanisms in crowdsourcing contests and show that either mechanism may be better. Gal-Or et al. (2007) compare the optimal simultaneous and sequential mechanisms to select a supplier where the buyer has private information about the fitness of each supplier and decides whether to share the information with the suppliers. They show that the simultaneous mechanism with information sharing is better than the sequential mechanism under certain parameters. In summary, timing generally matters for a principal contracting with multiple agents, in contrast with our revenue equivalence result.

Another related stream of literature in operations management considers contracting in a three-tier supply chain, where an OEM procures a component from a contractor, which in turn procures a sub-component from a subcontractor to produce the component. The central question is whether the OEM should *control* the procurement of the sub-component or *delegate* the procurement of the sub-component to the contractor. Kayis et al. (2013) identify conditions under which delegation outperforms control for a class of simple contracts. Chen et al. (2012) consider a large OEM's delegation versus control decision when the contractor also supplies to a small competing OEM and the contractor's cost information is private. Bolandifar et al. (2016b) consider two competing OEMs' delegation-versus-control decisions. Wang et al. (2014) derives an OEM and a contractor's preferences between delegation and control under push and pull contracts. The delegation-versus-control problem's main connection to our problem is that, in its control scenario, an OEM simultaneously contracts with a contractor and a subcontractor, resembling simultaneous contracting for assembly; see Section 4.1. Nevertheless, the research problems are distinct. Rather than *delegation versus control*, we compare optimal simultaneous and sequential contracting mechanisms *while the OEM retains control*; see Section 6 for a more in-depth discussion.

3. Base model

We model an OEM that sources two inputs from two suppliers (respectively indexed 1 and 2) to assemble a final product. Without loss of generality we assume that the OEM needs one unit of each input to make one unit of the final product, and the assembly cost is normalized to zero.[1] Modeled after powerful manufacturers such as Apple and Boeing, we assume that the OEM has the power to offer take-it-or-leave-it contracts to the suppliers that are better informed of their own costs to provide the inputs than the OEM. We assume that the two suppliers have independent unit costs c_1 and c_2.[2] The exact unit cost of Supplier i is its private information, but it is common knowledge that the cost has the prior cumulative distribution function G_i and the probability density function g_i over support $[L_i, H_i]$. We assume that Supplier i has reservation profit $V_i \geq 0$ which captures its alternative options. This model extends the optimal procurement model for a single input (e.g., Corbett et al. 2004) to assembly settings. We make an additional assumption regarding the suppliers' cost priors. This assumption is common in mechanism design and satisfied by many important distributions (Chen 2007).

Assumption 1. *Each Supplier i's virtual cost $\phi_i(c_i) \doteq c_i + G_i(c_i)/g_i(c_i)$ is increasing in c_i.*

Our goal is to find general optimal procurement mechanisms, namely ones that yield the highest expected profit for the OEM among all possible mechanisms. Following the revelation principle, it suffices to consider direct-revelation mechanisms (Laffont and Martimort 2002, p. 49), namely mechanisms that require that the suppliers report their unit costs and map the reported costs to purchase quantities and payments, while providing incentives for the suppliers to report costs truthfully. Any such mechanisms can be described by the quadruple of mappings $\{Q_1(c_1,c_2), Q_2(c_1,c_2), P_1(c_1,c_2), P_2(c_1,c_2)\}$, which specify that given reported costs c_1 and c_2, the OEM will pay $P_i(c_1,c_2)$ to Supplier i for the delivery of $Q_i(c_1,c_2)$ units of input i. The contracting process will be elaborated in Sections 4 and 5.

After purchasing inputs, the OEM assembles final products to output in the market, where the output quantity is constrained by both inputs' purchase quantities. When the OEM outputs Q units, we assume that the OEM earns revenue $R(Q)$ which is increasing and concave in the output quantity Q, and define $r(Q) \doteq R'(Q)$ which is accordingly positive, decreasing, and invertible. We require $R(0) = 0$ and $r(0)$ sufficiently large to ensure a positive output quantity. A special case of the concave revenue model is the linear inverse demand model, where the market-clearing price for output Q is $a - Q$ and the OEM's revenue $Q(a-Q)$ is concave and increasing for $Q \leq a/2$. Another special case is a risk-neutral OEM producing-to-stock for a random demand as a newsvendor à la Fang et al. (2014), because a newsvendor's expected revenue is known to be concave in its stock

[1] The extensions to more than two inputs and suppliers and ratios of needed inputs other than 1:1 are straightforward.

[2] This implies that suppliers' costs are linear in production quantities. Section 7 extends all results to general convex costs.

level. We next prove that the purchasing quantities of the two inputs being different from each other or more than the output quantity is never optimal. All proofs are relegated to the Appendix.

LEMMA 1. *An optimal procurement mechanism for assembly must have* $Q_1(c_1, c_2) \equiv Q_2(c_1, c_2)$ *equal to the output quantity* $Q(c_1, c_2)$.

The lemma's intuition is that purchasing different quantities of inputs than what is needed is inefficient. It implies that mechanisms based on menus of independent quantity-payment contracts (Fang et al. 2014) cannot be generally optimal, as they may result in the OEM purchasing mismatched quantities of different inputs. Following this lemma, we restrict attention to mechanisms where the output quantity $Q \equiv Q_1 \equiv Q_2$ without loss of optimality.

We note that timing issues naturally arise in the contracting process. The OEM may contract with two suppliers simultaneously or sequentially; in the latter case the contracting sequence may matter as well. Contracting timing impacts the asymmetric information structure: under simultaneous contracting both suppliers' costs are unknown to the OEM during the contracting process, whereas under sequential contracting the OEM would have learned the first supplier's cost before contracting with the second one. We next analyze simultaneous and sequential contracting, respectively, in Sections 4 and 5, and compare them in Section 6.

4. Simultaneous contracting

4.1. Optimal direct-revelation mechanism

Under simultaneous contracting, the OEM contracts with both suppliers at the same time. Following Lemma 1, it suffices to consider mechanisms characterized by the trio of mappings $\{Q(c_1, c_2), P_1(c_1, c_2), P_2(c_1, c_2)\}$ satisfying the following constraints: (1) a supplier of any cost can expect to earn at least the reservation profit V_i (individual rationality or IR); and (2) a supplier of any cost finds it weakly optimal to report its true cost (incentive compatibility or IC). In practice, OEMs usually contract for procurement in secrecy and with non-disclosure agreements. We accordingly assume that the OEM only reveals (Q, P_i) to Supplier i, and the three parties play a game with incomplete information. A fitting framework to analyze such a game is the optimal mechanism design framework nested within the theory of contracting with externalities (Segal 1999, Section IV, private offers). A perfect Bayesian equilibrium of the game requires that (1) given the OEM's mechanism, once each supplier receives its own offer, the supplier forms a belief on the other supplier's offer; (2) given the OEM's mechanism and the belief, each supplier chooses the contract that maximizes its expected profit; and (3) anticipating all suppliers' beliefs and chosen contracts, the OEM designs the mechanism to maximize its expected profit. A solution satisfying the three interlocked requirements is provided by Segal (1999), who shows that assuming *passive beliefs* (a common assumption that each party maintains the equilibrium belief off the equilibrium path), each supplier can form correct beliefs about the other suppliers' offers in a perfect Bayesian equilibrium, which is determined by the OEM maximizing its expected profit subject to each supplier's unilateral IR and IC constraints under correct beliefs about the other suppliers' offers. We adopt this solution to formulate our problem as follows:

$$\max_{Q,P_1,P_2} \int_{L_1}^{H_1}\int_{L_2}^{H_2}[R(Q(c_1,c_2)) - P_1(c_1,c_2) - P_2(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1)$$

$$\text{s.t.} \int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1Q(c_1,c_2)]\,\mathrm{d}G_2(c_2) \geq V_1, \quad \forall c_1 \qquad \text{(IR1)}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2Q(c_1,c_2)]\,\mathrm{d}G_1(c_1) \geq V_2, \quad \forall c_2 \qquad \text{(IR2)}$$

$$\int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1Q(c_1,c_2)]\,\mathrm{d}G_2(c_2) \geq \int_{L_2}^{H_2}[P_1(c_1',c_2) - c_1Q(c_1',c_2)]\,\mathrm{d}G_2(c_2), \quad \forall c_1, c_1' \qquad \text{(IC1)}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2Q(c_1,c_2)]\,\mathrm{d}G_1(c_1) \geq \int_{L_1}^{H_1}[P_2(c_1,c_2') - c_2Q(c_1,c_2')]\,\mathrm{d}G_1(c_1), \quad \forall c_2, c_2' \qquad \text{(IC2)}$$

This formulation can be further simplified. First, our model satisfies the Spence-Mirrlees condition, namely Supplier i's profit function $P_i - c_iQ$'s marginal rates of substitution between Q and P_i is decreasing in c_i. In this case, the full IR and IC constraints can be replaced by the IR constraint for the lowest type (highest cost) supplier, and local downward IC constraints (a supplier of any cost does not report a slightly higher cost.) Furthermore, these constraints will be binding in an optimal mechanism if the mechanism satisfies the monotonicity (MN) constraints, namely lower costs lead to higher purchase quantities. Below is the resulting simplified formulation:[3]

$$\max_{Q,P_1,P_2} \int_{L_1}^{H_1}\int_{L_2}^{H_2}[R(Q(c_1,c_2)) - P_1(c_1,c_2) - P_2(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1)$$

$$\text{s.t.} \int_{L_2}^{H_2}[P_1(H_1,c_2) - H_1Q(H_1,c_2)]\,\mathrm{d}G_2(c_2) = V_1 \qquad \text{(IR1)}$$

$$\int_{L_1}^{H_1}[P_2(c_1,H_2) - H_2Q(c_1,H_2)]\,\mathrm{d}G_1(c_1) = V_2 \qquad \text{(IR2)}$$

$$\int_{L_2}^{H_2}\left[\frac{\partial P_1(c_1,c_2)}{\partial c_1} - c_1\frac{\partial Q(c_1,c_2)}{\partial c_1}\right]\mathrm{d}G_2(c_2) = 0, \quad \forall c_1 \qquad \text{(IC1)}$$

$$\int_{L_1}^{H_1}\left[\frac{\partial P_2(c_1,c_2)}{\partial c_2} - c_2\frac{\partial Q(c_1,c_2)}{\partial c_2}\right]\mathrm{d}G_1(c_1) = 0, \quad \forall c_2 \qquad \text{(IC2)}$$

$$\frac{\partial Q(c_1,c_2)}{\partial c_i} \leq 0, \quad i = 1,2 \qquad \text{(MN)}$$

The problem can be solved following the standard mechanism design approach.

[3] Functions P and Q are almost everywhere differentiable following standard arguments; see Laffont and Martimort (2002), p. 135.

Proposition 1. *The optimal direct-revelation simultaneous contracting mechanism is*

$$Q^*(c_1,c_2) = r^{-1}(\phi_1(c_1)+\phi_2(c_2)),$$

$$P_1^*(c_1,c_2) = V_1 + c_1 Q^*(c_1,c_2) + \int_{c_1}^{H_1} Q^*(s_1,c_2)\,\mathrm{d}s_1, \quad P_2^*(c_1,c_2) = V_2 + c_2 Q^*(c_1,c_2) + \int_{c_2}^{H_2} Q^*(c_1,s_2)\,\mathrm{d}s_2,$$

which yields the expected profit for the OEM

$$\int_{L_1}^{H_1}\int_{L_2}^{H_2} [R(Q^*(c_1,c_2)) - (\phi_1(c_1)+\phi_2(c_2))Q^*(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1) - V_1 - V_2$$

and respective expected profits for Suppliers 1 and 2

$$V_1 + \int_{L_2}^{H_2}\int_{c_1}^{H_1} Q^*(s_1,c_2)\,\mathrm{d}s_1\,\mathrm{d}G_2(c_2), \quad V_2 + \int_{L_1}^{H_1}\int_{c_2}^{H_2} Q^*(c_1,s_2)\,\mathrm{d}s_2\,\mathrm{d}G_1(c_1).$$

We note that the optimal simultaneous assembly formulation and the resulting mechanism are technically equivalent to those in the control scenario (where simultaneous contracting is implied) of the classic delegation literature; see Lemma 1 of Melumad et al. (1995). The mechanism of Proposition 1 is a generalization of the classic optimal procurement mechanism for a single input (Laffont and Martimort 2002, p. 139), which involves an OEM screening a supplier of its private cost information with a menu of quantity-payment contracts. In our mechanism, the OEM screens the two suppliers' cost information by offering each a menu of *contingent* quantity-payment contracts (i.e., the contracts' terms contain the other supplier's private cost as a variable). The contingency arises from the OEM's need to coordinate purchase quantities of two inputs. Despite the complication, the high level mechanism-design insight remains the same: in exchange for each Supplier i to report its true cost, the OEM grants the supplier an information rent, which inflates its cost c_i to the virtual cost $\phi_i(c_i)$ and results in the OEM purchasing lower-than-first-best quantities.

4.2. Implementation of optimal mechanism by two-part tariff contracts

The optimal direct-revelation mechanism of Proposition 1 based on contingent quantity-payment contracts is significantly more complicated than its single-input counterpart. It would be practically valuable if a simpler and non-contingent implementation of the optimal mechanism were to exist. We note that for optimal procurement of a single input, there exists an alternative implementation based on two-part tariff contracts (Laffont and Martimort 2002, p. 375). A two-part tariff contract (w,f) specifies the OEM's payment to the supplier in two parts—a wholesale price w, and a fixed payment f, while granting the OEM the right to purchase any quantity. Under a two-part tariff contract (w,f), the OEM purchasing Q units is obliged to pay the supplier $P(Q) = wQ + f$. Whereas the optimal direct-revelation mechanism screens a supplier of its cost by eliciting its preference within a menu of quantity-payment contracts, this alternative implementation does so by eliciting its preference within a menu of two-part tariff contracts. A feature of this implementation is that the OEM contracts with the supplier on pricing before choosing its purchase quantity. This feature may be valuable in assembly settings, as it would naturally allow an OEM to purchase matching quantities of inputs. Therefore, in this section, we investigate implementing the mechanism of Proposition 1 by two-part tariff contracts.

Consider the following mechanism. The OEM simultaneously offers a menu of two-part tariff contracts $\{(w_i(c_i), f_i(c_i))\}$ to each Supplier i, with contract $(w_i(c_i), f_i(c_i))$ intended for Supplier i of unit cost c_i. After each supplier chooses a contract (w_i, f_i), the OEM (whose profit equals $R(Q) - (w_1 + w_2)Q - f_1 - f_2$) purchases $Q^* = r^{-1}(w_1 + w_2)$ units of each input i and accordingly pays $w_i r^{-1}(w_1 + w_2) + f_i$ to Supplier i. Define $q(c_1, c_2) \doteq r^{-1}(w_1(c_1) + w_2(c_2))$ as the corresponding output quantity. Following similar arguments as in Section 4.1, we obtain the following simplified formulation and show that the optimal mechanism of Proposition 1 can indeed be implemented by two-part tariff contracts:

$$
\begin{aligned}
\max_{w_i, f_i} \; & \int_{L_2}^{H_2} \int_{L_1}^{H_1} [R(q(c_1, c_2)) - (w_1(c_1) + w_2(c_2))q(c_1, c_2) - f_1(c_1) - f_2(c_2)] \, \mathrm{d}G_1(c_1) \, \mathrm{d}G_2(c_2) \\
\text{s.t. } & (w_1(H_1) - H_1) \int_{L_2}^{H_2} q(H_1, c_2) \, \mathrm{d}G_2(c_2) + f_1(H_1) = V_1 && \text{(IR1)} \\
& (w_2(H_2) - H_2) \int_{L_1}^{H_1} q(c_1, H_2) \, \mathrm{d}G_1(c_1) + f_2(H_2) = V_2 && \text{(IR2)} \\
& \int_{L_2}^{H_2} \left[w_1'(c_1) q(c_1, c_2) + (w_1(c_1) - c_1) \frac{\partial q(c_1, c_2)}{\partial c_1} \right] \mathrm{d}G_2(c_2) + f_1'(c_1) = 0, \quad \forall c_1 && \text{(IC1)} \\
& \int_{L_1}^{H_1} \left[w_2'(c_2) q(c_1, c_2) + (w_2(c_2) - c_2) \frac{\partial q(c_1, c_2)}{\partial c_2} \right] \mathrm{d}G_1(c_1) + f_2'(c_2) = 0, \quad \forall c_2 && \text{(IC2)} \\
& w_i'(c_i) \geq 0, \quad i = 1, 2 && \text{(MN)}
\end{aligned}
$$

PROPOSITION 2. *The following revenue-equivalent two-part tariff mechanisms implement the optimal direct-revelation simultaneous contracting mechanism in Proposition 1, where* Δ *is any real number and* $q^*(c_1, c_2) \doteq r^{-1}(\phi_1(c_1) + \phi_2(c_2))$*:*

$$
\begin{aligned}
& w_1^*(c_1) = \phi_1(c_1) + \Delta, \quad w_2^*(c_2) = \phi_2(c_2) - \Delta, \\
& f_1^*(c_1) = V_1 + (c_1 - w_1^*(c_1)) \int_{L_2}^{H_2} q^*(c_1, c_2) \, \mathrm{d}G_2(c_2) + \int_{L_2}^{H_2} \int_{c_1}^{H_1} q^*(s_1, c_2) \, \mathrm{d}s_1 \, \mathrm{d}G_2(c_2), \\
& f_2^*(c_2) = V_2 + (c_2 - w_2^*(c_2)) \int_{L_1}^{H_1} q^*(c_1, c_2) \, \mathrm{d}G_1(c_1) + \int_{L_1}^{H_1} \int_{c_2}^{H_2} q^*(c_1, s_2) \, \mathrm{d}s_2 \, \mathrm{d}G_1(c_1).
\end{aligned}
$$

These mechanisms all yield expected profit for the OEM

$$
\int_{L_1}^{H_1} \int_{L_2}^{H_2} [R(q^*(c_1, c_2)) - (\phi_1(c_1) + \phi_2(c_2)) q^*(c_1, c_2)] \, \mathrm{d}G_2(c_2) \, \mathrm{d}G_1(c_1) - V_1 - V_2
$$

and respective expected profits for Suppliers 1 and 2

$$V_1 + \int_{L_2}^{H_2} \int_{c_1}^{H_1} q^*(s_1, c_2)\, \mathrm{d}s_1\, \mathrm{d}G_2(c_2), \quad V_2 + \int_{L_1}^{H_1} \int_{c_2}^{H_2} q^*(c_1, s_2)\, \mathrm{d}s_2\, \mathrm{d}G_1(c_1).$$

The first observation about Proposition 2 is that a system of revenue-equivalent two-part tariff mechanisms all implement the optimal direct-revelation mechanism in Proposition 1. Intuitively, the OEM is only concerned about the total marginal input cost $w_1 + w_2$ being equal to the total virtual cost $\phi_1(c_1) + \phi_2(c_2)$, which leads to the optimal purchase quantity $q^*(c_1, c_2) = Q^*(c_1, c_2) = r^{-1}(\phi_1(c_1) + \phi_2(c_2))$ as in Proposition 1, regardless of its allocation between the two inputs. The suppliers are indifferent about the allocation because any resulting profit changes are offset by the fixed payments.

The most notable merit of the mechanisms in Proposition 2, in contrast with the optimal direct-revelation mechanism in Proposition 1, is the *lack of contingency*, namely that contracts offered to each supplier do *not* contain the other supplier's private cost as a variable. In practice, a supplier signing a contract whose terms are contingent upon other suppliers' actions or information is improbable. The non-contingent two-part tariff mechanism thus offers a much more practical implementation of the optimal mechanism. This merit of two-part tariff implementations over quantity-payment implementations is unique in assembly settings, as quantity coordination is irrelevant for procuring a single input.

In addition, observe that when each Supplier i's reservation profit V_i is sufficiently large, the fixed payment $f_i^*(\cdot) > 0$. Under such a contract, the OEM's average unit price for component i, $(w_i^* Q + f_i^*)/Q$, is decreasing in the purchase quantity Q. In other words, when all suppliers' reservation profits are sufficiently large, the mechanism of Proposition 2 can be seen as the OEM screening each supplier with a menu of *quantity-discount* contracts. Quantity-discount contracts are commonly used in industry, for example, for sharing volume risks (Lovejoy 2010). Proposition 2 shows that quantity-discount contracts may also be used to coordinate purchase quantities of different inputs for assembly. This use is confirmed in our interview with a sourcing executive at a leading consumer healthcare company.

5. Sequential contracting

Under sequential contracting, we consider the OEM first contracting with Supplier 1 and then with Supplier 2 (the contracting sequence may matter in general.) Contracting timing impacts the asymmetric information structure. Consider the two stages of this process. In Stage 1 the OEM offers a menu of contracts to Supplier 1, which chooses one and in the meantime reveals its private cost information to the OEM. As a result, before designing Supplier 2's menu in Stage 2, the OEM has already learned Supplier 1's cost, which is unknown to Supplier 2. This process makes the OEM an *informed principal* in Stage 2. Mechanism design by an informed principal (Maskin and Tirole 1992) is more complicated than that by an uninformed principal. The informed principal cannot assume its private information is unknown to the agent in designing the mechanism, because the proposed mechanism itself may signal the information. Nor can the principal simply reveal its private information to the agent, because such revelations may not be credible (i.e., the principal of another type may have an incentive to mimic this one).

We briefly summarize the relevant results of Maskin and Tirole (1992). First, the *Rothschild-Stiglitz-Wilson (RSW)* solution exists, where the principal of each type maximizes its profit subject to its own incentive compatibility and the agent's incentive constraints, assuming that the principal is able to signal its type to the agent. Furthermore, if the RSW solution is *interim efficient relative to the prior belief* (i.e., the solution is Pareto efficient for the principal of all types among all incentive-compatible solutions that do not reduce the agent's expected profit under the prior belief), then it is the unique perfect Bayesian equilibrium. Contrary to popular belief that having more information should be better, this theory implies that a principal is generally *hurt* by its private information because of the potential cost to signal such information to the agent. This means that sequential contracting, which grants private information to the OEM, should generally yield *lower* profits than simultaneous contracting for the OEM.

To solve the sequential contracting problem, we nest the optimal mechanism design framework and the framework of Maskin and Tirole (1992) within that of Segal (1999), thus ensuring that each supplier forms a correct belief about the other supplier's offer as in Section 4.1. In Stage 1, the OEM designs an optimal mechanism for Supplier 1. In Stage 2, the OEM designs an optimal mechanism as an informed principal for Supplier 2. We could formulate the general optimal sequential mechanism design problem similarly to Section 4.1; however, directly solving this problem is difficult. Inspired by the two-part tariff implementation in Section 4.2 of the optimal simultaneous procurement mechanism, below we first find the optimal sequential two-part tariff mechanism, and then prove its general optimality.

5.1. Stage 2

We restrict our attention to two-part tariff mechanisms. In Stage 2, the OEM has learned Supplier 1's cost c_1 (henceforth also referred to as the OEM's type) through screening, and Supplier 2 has formed a correct belief about $w_1(c_1)$ and $f_1(c_1)$ offered to Supplier 1 during Stage 1, but does not know c_1. We first solve for the RSW solution, namely the mechanism to maximize the profit of the

OEM of each type (c_1) while signaling its type to Supplier 2. We use $w_2(c_2;c_1)$ and $f_2(c_2;c_1)$ to denote the wholesale price and fixed payment intended for Supplier 2 of cost c_2 given its belief of Supplier 1's cost c_1, and define $\bar{q}(c_1,c_2;c_1') \doteq r^{-1}(w_1(c_1)+w_2(c_2;c_1'))$ as the corresponding output quantity. Where $c_1'=c_1$, we use $\bar{q}(c_1,c_2) \doteq r^{-1}(w_1(c_1)+w_2(c_2;c_1))$ for ease of exposition. Following standard mechanism design simplifications as in Section 4, the reduced RSW formulation is

$$\max_{w_2,f_2} \int_{L_2}^{H_2} [R(\bar{q}(c_1,c_2)) - (w_1(c_1)+w_2(c_2;c_1))\bar{q}(c_1,c_2) - f_1(c_1) - f_2(c_2;c_1)]\,\mathrm{d}G_2(c_2), \quad \forall c_1$$

$$\text{s.t. } (w_2(H_2;c_1)-H_2)\bar{q}(c_1,H_2) + f_2(H_2;c_1) = V_2, \quad \forall c_1 \tag{IR2}$$

$$w_2'(c_2;c_1)\bar{q}(c_1,c_2) + [w_2(c_2;c_1)-c_2]\frac{\partial \bar{q}(c_1,c_2)}{\partial c_2} + f_2'(c_2;c_1) = 0, \quad \forall c_1,c_2 \tag{IC2}$$

$$\begin{aligned}&\int_{L_2}^{H_2} [R(\bar{q}(c_1,c_2)) - (w_1(c_1)+w_2(c_2;c_1))\bar{q}(c_1,c_2) - f_1(c_1) - f_2(c_2;c_1)]\,\mathrm{d}G_2(c_2)\\ \geq &\int_{L_2}^{H_2} [R(\bar{q}(c_1,c_2;c_1')) - (w_1(c_1)+w_2(c_2;c_1'))\bar{q}(c_1,c_2;c_1') - f_1(c_1) - f_2(c_2;c_1')]\,\mathrm{d}G_2(c_2), \forall c_1,c_1'\end{aligned} \tag{MIC}$$

$$\frac{\mathrm{d}w_2(c_2;c_1)}{\mathrm{d}c_2} \geq 0, \quad \forall c_1 \tag{MN}$$

The RSW formulation is a system of optimizations (one for each possible value of c_1) under respective IR and IC constraints. Note the OEM's incentive compatibility constraints MIC (that require that the OEM of each type c_1 have no incentive to mimic any other type c_1') are absent under simultaneous contracting. These MIC constraints are an important technical feature of sequential contracting, and play a key role in understanding the optimal sequential mechanism and the simultaneous-sequential contracting comparison. The following lemma describes the solution to the above RSW formulation.

Lemma 2. *The RSW solution of Stage 2 of the sequential contracting problem is as follows, where* $\bar{q}^\dagger(c_1,c_2) \doteq r^{-1}(w_1(c_1)+w_2^\dagger(c_2;c_1))$*:*

$$w_2^\dagger(c_2;c_1) = \phi_2(c_2), \quad f_2^\dagger(c_2;c_1) = V_2 + \left(c_2 - w_2^\dagger(c_2;c_1)\right)\bar{q}^\dagger(c_1,c_2) + \int_{c_2}^{H_2} \bar{q}^\dagger(c_1,s_2)\,\mathrm{d}s_2$$

which implies the MIC constraints. In addition, the RSW solution is interim efficient for the prior belief, and thus a unique perfect Bayesian equilibrium in Stage 2.

A notable observation is that the OEM's incentive compatibility constraints are implied by the RSW solution. That is, the relaxed solution ignoring the MIC constraints always satisfies the constraints, and thus is the RSW solution. Intuitively, the RSW solution is a separating mechanism where the principal signals its type to the agent. Signaling is generally costly and lowers the principal's profit compared to when the type is known to the agent, and the MIC constraints capture the signaling cost. The fact that in our problem the MIC constraints are implied means that the knowledge of c_1 is irrelevant for the OEM's screening of Supplier 2, and can be signaled *cost-free*. As a result, the privately informed OEM in Stage 2 of sequential contracting earns the same profit as when such information is public. These observations are in stark contrast with the general theory of mechanism design by an informed principal, and indicate the uniqueness of optimal sequential contracting for assembly. We relegate the reasoning behind these observations to Section 6, and move onto solving the Stage 1 problem.

5.2. Stage 1

Substituting the Stage 2 solution into the Stage 1 problem yields the following reduced mechanism design formulation:

$$\max_{w_1, f_1} \int_{L_1}^{H_1} \int_{L_2}^{H_2} [R(\bar{q}^\dagger(c_1,c_2)) - (w_1(c_1) + w_2^\dagger(c_2;c_1))\bar{q}^\dagger(c_1,c_2) - f_1(c_1) - f_2^\dagger(c_2;c_1)] \, \mathrm{d}G_2(c_2) \, \mathrm{d}G_1(c_1)$$

$$\text{s.t. } (w_1(H_1) - H_1) \int_{L_2}^{H_2} \bar{q}^\dagger(H_1,c_2) \, \mathrm{d}G_2(c_2) + f_1(H_1) = V_1 \quad \text{(IR1)}$$

$$w_1'(c_1) \int_{L_2}^{H_2} \bar{q}^\dagger(c_1,c_2) \, \mathrm{d}G_2(c_2) + [w_1(c_1) - c_1] \int_{L_2}^{H_2} \frac{\partial \bar{q}^\dagger(c_1,c_2)}{\partial c_1} \mathrm{d}G_2(c_2) + f_1'(c_1) = 0, \quad \forall c_1 \quad \text{(IC1)}$$

$$w_1'(c_1) \geq 0 \quad \text{(MN)}$$

This problem can be solved similarly to Proposition 1, which yields the optimal sequential two-part tariff mechanism. We then show that it indeed implements the general optimal sequential contracting mechanism. These results are formalized below. Recall that $q^*(c_1,c_2) \doteq r^{-1}(\phi_1(c_1) + \phi_2(c_2))$.

Proposition 3. *The optimal sequential contracting mechanism can be implemented as the following two-part tariff mechanism: in Stage 1, the OEM offers to Supplier 1*

$$w_1^\dagger(c_1) = \phi_1(c_1), \quad f_1^\dagger(c_1) = V_1 + (c_1 - w_1^\dagger(c_1)) \int_{L_2}^{H_2} q^*(c_1,c_2) \, \mathrm{d}G_2(c_2) + \int_{L_2}^{H_2} \int_{c_1}^{H_1} q^*(s_1,c_2) \, \mathrm{d}s_1 \, \mathrm{d}G_2(c_2),$$

After Supplier 1 chooses a contract which reveals c_1, in Stage 2 the OEM offers to Supplier 2

$$w_2^\dagger(c_2;c_1) = \phi_2(c_2), \quad f_2^\dagger(c_2;c_1) = V_2 + \left(c_2 - w_2^\dagger(c_2;c_1)\right) q^*(c_1,c_2) + \int_{c_2}^{H_2} q^*(c_1,s_2) \, \mathrm{d}s_2.$$

This mechanism yields expected profit for the OEM

$$\int_{L_1}^{H_1} \int_{L_2}^{H_2} [R(q^*(c_1,c_2)) - (\phi_1(c_1) + \phi_2(c_2))q^*(c_1,c_2)] \, \mathrm{d}G_2(c_2) \, \mathrm{d}G_1(c_1) - V_1 - V_2$$

and respective expected profits for Suppliers 1 and 2

$$V_1 + \int_{L_2}^{H_2} \int_{c_1}^{H_1} q^*(s_1,c_2) \, \mathrm{d}s_1 \, \mathrm{d}G_2(c_2), \quad V_2 + \int_{L_1}^{H_1} \int_{c_2}^{H_2} q^*(c_1,s_2) \, \mathrm{d}s_2 \, \mathrm{d}G_1(c_1).$$

Note that the OEM's and the two suppliers' profit expressions are symmetric between indices 1 and 2, thus yielding the following corollary:

COROLLARY 1. *The OEM and both suppliers are indifferent regarding the contracting sequence under optimal sequential contracting.*

Thus far we have solved the sequential contracting problem and shown that the optimal sequential mechanism can be implemented by two-part tariff contracts. Similar to under simultaneous contracting, the two-part tariff implementation of the optimal sequential mechanism is also non-contingent,[4] making it more practical than the quantity-payment implementation.

6. Revenue equivalence of optimal simultaneous and sequential mechanisms

By comparing the OEM's and the suppliers' expected profits from Propositions 2 and 3, we can make the following observation:

PROPOSITION 4. *The optimal simultaneous and sequential procurement mechanisms for assembly yield equal expected profits for the OEM as well as each supplier.*

The revenue equivalence of optimal simultaneous and sequential mechanisms is non-straightforward: the two contracting scenarios have differing asymmetric information structures; the equilibria of Propositions 2 and 3 are also different. The key difference between simultaneous and sequential contracting lies in the asymmetric information structure, namely that under sequential contracting the OEM learns Supplier 1's cost before contracting with Supplier 2. Nevertheless, this difference does not result in different profits, implying that the knowledge of Supplier 1's cost is irrelevant for the OEM's screening of Supplier 2 (see Section 5.1), while the OEM's profit does depend on Supplier 1's cost. The irrelevance of Supplier 1's cost in screening Supplier 2 follows from the structure of the optimal mechanism. In general, under an optimal mechanism, the agent's incentive is provided by information rents granted for each possible type, and the OEM's resulting marginal sourcing cost determines the purchase quantity. In an assembly setting, the OEM's total marginal sourcing cost is a sum of the marginal sourcing cost from each supplier without externalities (i.e., one supplier's cost does not affect another supplier's contribution to the OEM's total marginal sourcing cost). This explains why the knowledge of Supplier 1's cost is irrelevant for the OEM's screening of Supplier 2 in an *optimal* mechanism. As a result, under optimal simultaneous and sequential mechanisms the OEM has the same marginal sourcing costs and purchases the same

[4] The OEM's offer to Supplier 2 in Stage 2 apparently contains Supplier 1's cost c_1, however in this stage c_1 is a constant embedded in the OEM's offer rather than an unknown variable.

quantities, thus yielding the revenue equivalence. The OEM's total marginal sourcing cost being the sum of all suppliers' marginal costs is a definitive feature of assembly systems. Thus, the revenue equivalence of simultaneous and sequential contracting is a fundamental property of optimal procurement mechanisms for assembly.

Lastly, we distinguish our revenue equivalence from the *organizational equivalence* in the delegation literature (see Mookherjee 2006 for a review.) Organizational equivalence refers to that optimal *delegation*, where a firm first contracts with one supplier (contractor) for an input and then delegates to the contractor the procurement of the other input from another supplier (subcontractor), generates the same revenue for the firm as optimal *control*, where the firm directly contracts with both suppliers simultaneously (Baron and Besanko 1992, Melumad et al. 1995). While the control problem is technically equivalent to our simultaneous contracting for assembly, the delegation problem is different from our sequential contracting. Under delegation, the firm allows the contractor to be a principal in contracting with the subcontractor, whereas in our sequential contracting setting, the OEM retains control in contracting with both suppliers sequentially. In other words, this literature compares control versus delegation, whereas we investigate contracting timing with the OEM always in control. The two results also carry distinct insights. The insight of the organizational equivalence is that, in delegation, the firm in contracting with the contractor can anticipate and tax away the latter's information rent from its subsequent contracting with the subcontractor. The insight of the revenue equivalence is rather that, in optimal mechanisms, suppliers' marginal costs contribute to the OEM's total marginal sourcing cost without externalities, thus allowing the OEM to signal Supplier 1's information to Supplier 2 cost-free.

7. Extension: General convex costs

In this section we extend our model with linear supplier costs to one with general convex costs. Convex costs capture that when a supplier produces beyond its existing capacity, it needs to run extra shifts and/or make additional investments, causing the per-unit cost to increase (Dasgupta and Spulber 1990). Specifically, in this extension we assume that Supplier i's cost to produce q units of input i is $c_i J(q)$ where $J(q)$ is increasing and convex, common to both suppliers, and common knowledge.[5] The assumptions about c_i (which we call *base cost* in this extension) remain unchanged. The J function captures the common production technology in the industry, whereas c_i captures each supplier's idiosyncratic cost elements such as the local labor wage and the factory's operational efficiency.

[5] We note that the revenue equivalence result can actually be extended to even more general convex costs without this multiplicative structure. This extension is omitted from the paper for brevity and available from the authors.

Our goal in this extension is to show that the mechanism design problem with the above convex costs can be easily transformed into one with linear costs. Consider the example of simultaneous contracting. The problem formulation with convex costs is as follows:

$$\max_{Q,P_1,P_2} \int_{L_1}^{H_1}\int_{L_2}^{H_2}[R(Q(c_1,c_2)) - P_1(c_1,c_2) - P_2(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1)$$

$$\text{s.t.} \int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1 J(Q(c_1,c_2))]\,\mathrm{d}G_2(c_2) \geq V_1, \quad \forall c_1 \tag{IR1}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2 J(Q(c_1,c_2))]\,\mathrm{d}G_1(c_1) \geq V_2, \quad \forall c_2 \tag{IR2}$$

$$\int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1 J(Q(c_1,c_2))]\,\mathrm{d}G_2(c_2) \geq \int_{L_2}^{H_2}[P_1(c_1',c_2) - c_1 J(Q(c_1',c_2))]\,\mathrm{d}G_2(c_2), \quad \forall c_1, c_1' \tag{IC1}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2 J(Q(c_1,c_2))]\,\mathrm{d}G_1(c_1) \geq \int_{L_1}^{H_1}[P_2(c_1,c_2') - c_2 J(Q(c_1,c_2'))]\,\mathrm{d}G_1(c_1), \quad \forall c_2, c_2' \tag{IC2}$$

Define $\hat{R} \doteq R \circ J^{-1}$, $\hat{Q} \doteq J \circ Q$. It is easy to verify that $R \circ Q = \hat{R} \circ \hat{Q}$ and $\hat{R}$ is increasing and concave. Applying this transformation to the above formulation yields

$$\max_{\hat{Q},P_1,P_2} \int_{L_1}^{H_1}\int_{L_2}^{H_2}[\hat{R}(\hat{Q}(c_1,c_2)) - P_1(c_1,c_2) - P_2(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1)$$

$$\text{s.t.} \int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1 \hat{Q}(c_1,c_2)]\,\mathrm{d}G_2(c_2) \geq V_1, \quad \forall c_1 \tag{IR1}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2 \hat{Q}(c_1,c_2)]\,\mathrm{d}G_1(c_1) \geq V_2, \quad \forall c_2 \tag{IR2}$$

$$\int_{L_2}^{H_2}[P_1(c_1,c_2) - c_1 \hat{Q}(c_1,c_2)]\,\mathrm{d}G_2(c_2) \geq \int_{L_2}^{H_2}[P_1(c_1',c_2) - c_1 \hat{Q}(c_1',c_2)]\,\mathrm{d}G_2(c_2), \quad \forall c_1, c_1' \tag{IC1}$$

$$\int_{L_1}^{H_1}[P_2(c_1,c_2) - c_2 \hat{Q}(c_1,c_2)]\,\mathrm{d}G_1(c_1) \geq \int_{L_1}^{H_1}[P_2(c_1,c_2') - c_2 \hat{Q}(c_1,c_2')]\,\mathrm{d}G_1(c_1), \quad \forall c_2, c_2' \tag{IC2}$$

which is identical to the formulation with linear costs in Section 4.1. Therefore, all analyses and results thus far apply to the transformed linear cost model, which can then be transformed back to the convex cost model. Note that two-part tariff contracts in the transformed linear cost model will be transformed back into a modified format where under contract (w_i, f_i) the OEM pays $w_i J(Q) + f_i$ to Supplier i for Q units of input i.

8. Concluding discussions

In this paper we investigate a powerful OEM's optimal procurement of multiple inputs for assembly, where we (1) solve for the general optimal procurement mechanisms for assembly under simultaneous and sequential contracting and find that these mechanisms coordinate purchase quantities; (2) derive non-contingent implementations of these mechanisms by menus of two-part tariff contracts; and (3) show that optimal simultaneous and sequential mechanisms are revenue-equivalent.

These results have practical implications for managers procuring multiple inputs for assembly. The finding that optimal procurement mechanisms coordinate purchase quantities of inputs implies that it is suboptimal to contract with each supplier on independent quantity-payment terms. The implementations of optimal mechanisms by non-contingent two-part tariff contracts suggest that the managers need not use contingent contracts, but can contract with suppliers on pricing-only terms, which naturally coordinate purchase quantities. The revenue equivalence of optimal simultaneous and sequential mechanisms implies that the managers need not strategize contracting sequences, but should rather focus on achieving the best pricing with each supplier.

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Appendix

Proof of Lemma 1. We prove the lemma by contradiction. Suppose an optimal direct-revelation mechanism has $Q_1(c_1,c_2) > Q_2(c_1,c_2)$. Let the OEM lower $Q_1(c_1,c_2)$ to $Q_2(c_1,c_2)$, and lower $P_1(c_1,c_2)$ by $c_1(Q_1(c_1,c_2) - Q_2(c_1,c_2))$. Doing so changes neither supplier's profit, and has no impact on the OEM's revenue, but reduces the OEM's payment to Supplier 1. Suppose an optimal direct-revelation mechanism has $Q_1(c_1,c_2) \equiv Q_2(c_1,c_2) > Q(c_1,c_2)$. Let the OEM lower $Q_i(c_1,c_2)$ to $Q(c_1,c_2)$, and lower $P_i(c_1,c_2)$ by $c_i(Q_i(c_1,c_2) - Q(c_1,c_2))$, $i = 1,2$. Doing so changes neither supplier's profit, and has no impact on the OEM's revenue, but reduces the OEM's payments to both suppliers. These changes improve the OEM's profit without changing the suppliers' incentives, thus contradicting the assumed optimality of the mechanism. $\square$

Proof of Proposition 1. First ignore MN. Tighten IR1 and IC1 into the following constraints:

$$P_1(H_1,c_2) = V_1 + H_1 Q(H_1,c_2), \qquad \frac{\partial P_1(c_1,c_2)}{\partial c_1} = c_1 \frac{\partial Q(c_1,c_2)}{\partial c_1}$$

$$\Rightarrow P_1(c_1,c_2) = V_1 + H_1 Q(H_1,c_2) - \int_{c_1}^{H_1} s_1 \left.\frac{\partial Q(c_1,c_2)}{\partial c_1}\right|_{(s_1,c_2)} \mathrm{d}s_1 = V_1 + c_1 Q(c_1,c_2) + \int_{c_1}^{H_1} Q(s_1,c_2)\,\mathrm{d}s_1.$$

The last equality is by integration by parts. This solution also satisfies IR1 and IC1. Note that

$$\int_{L_1}^{H_1}\int_{L_2}^{H_2} P_1(c_1,c_2)\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1) = V_1 + \int_{L_2}^{H_2}\int_{L_1}^{H_1}\left[c_1 Q(c_1,c_2) + \int_{c_1}^{H_1} Q(s_1,c_2)\,\mathrm{d}s_1\right]\mathrm{d}G_1(c_1)\,\mathrm{d}G_2(c_2),$$

$$\int_{L_1}^{H_1}\int_{c_1}^{H_1} Q(s_1,c_2)\,\mathrm{d}s_1\,\mathrm{d}G_1(c_1) = \int_{L_1}^{H_1} Q(s_1,c_2)\int_{L_1}^{s_1}\mathrm{d}G_1(c_1)\,\mathrm{d}s_1 = \int_{L_1}^{H_1} Q(c_1,c_2)G_1(c_1)\,\mathrm{d}c_1.$$

Therefore,

$$\int_{L_1}^{H_1}\int_{L_2}^{H_2} P_1(c_1,c_2)\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1) = V_1 + \int_{L_1}^{H_1}\int_{L_2}^{H_2}\phi_1(c_1)Q(c_1,c_2)\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1).$$

Similarly

$$\int_{L_1}^{H_1}\int_{L_2}^{H_2} P_2(c_1,c_2)\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1) = V_2 + \int_{L_1}^{H_1}\int_{L_2}^{H_2}\phi_2(c_2)Q(c_1,c_2)\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1).$$

Consequently, the objective becomes

$$\max_{Q}\int_{L_1}^{H_1}\int_{L_2}^{H_2}[R(Q(c_1,c_2)) - (\phi_1(c_1)+\phi_2(c_2))Q(c_1,c_2)]\,\mathrm{d}G_2(c_2)\,\mathrm{d}G_1(c_1) - V_1 - V_2.$$

The integrant can be maximized point-wise, which straightforwardly yields the optimal mechanism and profit expressions in Proposition 1. Finally, Assumption 1 guarantees that the optimal mechanism satisfies monotonicity constraints MN and is thus valid. □

Proof of Proposition 2. Following IC1,

$$f_1'(c_1) = -\int_{L_2}^{H_2}\left[w_1'(c_1)q(c_1,c_2) + (w_1(c_1)-c_1)\frac{\partial q(c_1,c_2)}{\partial c_1}\right]\mathrm{d}G_2(c_2).$$

Combining the above and IR1 yields

$$f_1(c_1) = V_1 + (c_1 - w_1(c_1))\int_{L_2}^{H_2} q(c_1,c_2)\,\mathrm{d}G_2(c_2) + \int_{L_2}^{H_2}\int_{c_1}^{H_1} q(s_1,c_2)\,\mathrm{d}s_1\,\mathrm{d}G_2(c_2). \tag{A1}$$

Similarly,

$$f_2(c_2) = V_2 + (c_2 - w_2(c_2))\int_{L_1}^{H_1} q(c_1,c_2)\,\mathrm{d}G_1(c_1) + \int_{L_1}^{H_1}\int_{c_2}^{H_2} q(c_1,s_2)\,\mathrm{d}s_2\,\mathrm{d}G_1(c_1). \tag{A2}$$

Substituting $f_1(c_1)$ and $f_2(c_2)$ into the objective function yields

$$\max_{w_i}\int_{L_1}^{H_1}\int_{L_2}^{H_2}\Bigg[R(q(c_1,c_2)) - (c_1+c_2)q(c_1,c_2) - \int_{c_1}^{H_1} q(s_1,c_2)\,\mathrm{d}s_1 - \int_{c_2}^{H_2} q(c_1,s_2)\,\mathrm{d}s_2\Bigg]\,\mathrm{d}G_1(c_1)\,\mathrm{d}G_2(c_2) - V_1 - V_2.$$

Using integration by parts and taking derivatives with respect to $w_i(c_i)$ we obtain

$$(w_1(c_1) + w_2(c_2) - \phi_1(c_1) - \phi_2(c_2))\,\frac{\partial q(c_1,c_2)}{\partial w_1(c_1)} = 0.$$

Note that $\frac{\partial q(c_1,c_2)}{\partial w_1(c_1)} < 0$. Therefore, $w_1^*(c_1) = \phi_1(c_1) + \Delta$ and $w_2^*(c_2) = \phi_2(c_2) - \Delta$ are solutions to the above equation, where Δ is any real number. Substituting $w_1^*(c_1)$ and $w_2^*(c_2)$ into (A1) and (A2) yields $f_1^*(c_1)$ and $f_2^*(c_2)$ as in Proposition 2. The fact that $q^*(c_1,c_2)$ in Proposition 2 matches $Q^*(c_1,c_2)$ in Proposition 1 indicates that the two-part tariff mechanisms in Proposition 2 implement the optimal direct-revelation mechanism in Proposition 1. □

Proof of Lemma 2. We first ignore constraints MN and MIC, and solve the relaxed problem for each c_1 independently, similar to Proposition 2, to yield the solution in Lemma 2. It is straightforward to verify that the relaxed solution satisfies MIC, and thus is the valid RSW solution. Details are omitted.

To show the RSW solution's interim efficiency for the prior belief is to show that it solves the following problem, where M_1 is any strictly positive probability measure (Maskin and Tirole 1992):

$$\max_{w_2, f_2} \int_{L_1}^{H_1} \int_{L_2}^{H_2} [R(\bar{q}(c_1, c_2)) - (w_1(c_1) + w_2(c_2; c_1))\bar{q}(c_1, c_2) - f_1(c_1) - f_2(c_2; c_1)] \, \mathrm{d}G_2(c_2) \, \mathrm{d}M_1(c_1)$$

$$\text{s.t. } (w_2(H_2; c_1) - H_2)\bar{q}(c_1, H_2) + f_2(H_2; c_1) = V_2, \quad \forall c_1 \tag{IR2}$$

$$w_2'(c_2; c_1)\bar{q}(c_1, c_2) + [w_2(c_2; c_1) - c_2]\frac{\partial \bar{q}(c_1, c_2)}{\partial c_2} + f_2'(c_2; c_1) = 0, \quad \forall c_1, c_2 \tag{IC2}$$

$$\begin{aligned} &\int_{L_2}^{H_2} [R(\bar{q}(c_1, c_2)) - (w_1(c_1) + w_2(c_2; c_1))\bar{q}(c_1, c_2) - f_1(c_1) - f_2(c_2; c_1)] \, \mathrm{d}G_2(c_2) \\ \geq &\int_{L_2}^{H_2} [R(\bar{q}(c_1, c_2; c_1')) - (w_1(c_1) + w_2(c_2; c_1'))\bar{q}(c_1, c_2; c_1') - f_1(c_1) - f_2(c_2; c_1')] \, \mathrm{d}G_2(c_2), \quad \forall c_1, c_1' \end{aligned} \tag{MIC}$$

$$\frac{\mathrm{d}w_2(c_2; c_1)}{\mathrm{d}c_2} \geq 0, \quad \forall c_1 \tag{MN}$$

The above problem differs from Program V* of Maskin and Tirole (1992) in that the supplier's IR and IC constraints are type-by-type rather than in expectation of the principal's type, but Maskin and Tirole (1992) point out that this difference does not matter if the agent's profit function is quasi-linear, as is in our case. Since the RSW solution satisfies IR, IC, MIC, and MN, and pointwise maximizes its objective's integrant, it must be the solution to the above problem and is thus interim efficient for the prior belief. Following Corollary of Theorem 1 of Maskin and Tirole (1992), the RSW solution is the unique perfect Bayesian equilibrium of Stage 2 of the optimal sequential contracting problem. □

Proof of Proposition 3. Solving the Stage 1 problem is similar to the proof of Proposition 2 and details are omitted. To show that the resulting two-part tariff mechanism implements the general optimal sequential mechanism, we first note that the optimal simultaneous mechanism must weakly dominate the optimal sequential mechanism by the revelation principle, and then note that the OEM's expected profit under the two-part tariff mechanism in Proposition 3 equals that under the general optimal simultaneous mechanism in Proposition 1. These facts imply that the two-part tariff mechanism in Proposition 3 must implement the general optimal sequential mechanism. □

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