We investigate the procurement problem of an original equipment manufacturer (OEM) purchasing multiple components for assembly from suppliers with private cost information. The OEM has the ability to contract with the two suppliers either simultaneously or sequentially. We first examine which of these two contracting approaches maximizes the OEM’s profit when the OEM has relatively equal bargaining power with its suppliers and thus engages in a back-and-forth negotiation (the dynamic bargaining institution). We then consider the same problem when the OEM has considerable bargaining power over its suppliers and thus can make ultimatum offers (the mechanism design institution). For both of these bargaining institutions we theoretically show that the OEM and suppliers earn the same expected profits regardless of whether the OEM contracts with suppliers simultaneously or sequentially. We then test these results in a controlled human-subjects experiment and find a number of deviations from these normative predictions. One key result from our experiment is that when an OEM has considerable bargaining power, they earn significantly more in profit by contracting with suppliers sequentially.

**Key words:** procurement; asymmetric information; behavioral operations; contracting

**History:** August 7, 2018

1. **Introduction**

In today’s global marketplace original equipment manufacturers (OEMs) rely more than ever on sourcing inputs from external suppliers, rather than producing those same components in-house (Fung et al. 2008). For instance, Boeing procures engines from Rolls-Royce and nacelles from Goodrich Corp to assemble its 787 Dreamliner (Clark 2012, Bigelow 2007). Suppliers typically have private information about their unit costs. As such, the OEM is interested in attempting to extract this information in an effort to maximize its own profits. In assembly settings such as the
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case of Boeing, because the OEM is sourcing (different) components from multiple suppliers, one lever it has at its disposal is to decide whether it should contract with its suppliers simultaneously or sequentially. In this study, we investigate the procurement of an OEM purchasing two different components from two suppliers with their respective private cost information, and the OEM can contract with the suppliers simultaneously or sequentially.

Another dimension that may be important in resolving this question is the relative bargaining power between the OEM and suppliers. For instance, a less powerful OEM might be forced to engage in a more back-and-forth dynamic bargaining process, while a powerful OEM may be in a position to make take-it-or-leave-it (i.e., ultimatum) offers to suppliers. In this study we will also consider these two alternative contracting institutions between the OEM and its suppliers: dynamic bargaining and mechanism design.

While Hu and Qi (2017) theoretically analyze the case of a powerful OEM contracting with two suppliers, each of whom possess private cost information, much less is known about the case of more equal bargaining power between the OEM and suppliers. Therefore, given the importance of understanding procurement for assembly we have the following main research questions. First, when an OEM and its suppliers have relatively equal bargaining power, should an OEM contract with those suppliers simultaneously or sequentially? Second, how do these results change when the OEM is powerful enough to credibly make an ultimatum offer to its suppliers? As we will show, regardless of the bargaining power of the OEM, the contracts that arise should be screening contracts which differentiate between high and low cost suppliers. Thus a third question is whether OEMs actually use screening contracts, and, if not, what are the consequences of doing so?

Because human managers are integral to procurement decisions, we answer these research questions both theoretically and experimentally. A theoretical lens is advantageous in that it provides a set of normative predictions that are based on the classical assumption that decision makers are risk-neutral expected-profit maximizers. Then, once these benchmarks are established, we can test them by conducting a controlled human-subjects experiment, and determine whether any behavioral biases may be driving outcomes that differ from the theoretical benchmarks. In short, our theoretical analysis prescribes how managers should make decisions and our experimental exercise sheds light on how humans actually make decisions.

To this end, we begin by theoretically deriving a number of normative predictions. We consider a setting with an OEM procuring two different inputs – one each from its two suppliers – to assemble its end product, and the suppliers possess private cost information. The OEM needs to reach agreements with both suppliers regarding the procurement price and quantity. For the
case of equal bargaining power between the OEM and suppliers, we employ Myerson’s (1984a) bargaining solution concept under asymmetric information. The solution is an incentive-efficient mechanism satisfying individual rationality, incentive compatibility, and Pareto optimality. Under this mechanism, each player obtains his equitable share of profits. In this framework, we prove an equivalence result; namely, the OEM’s and suppliers’ expected profits are identical regardless of whether the OEM contracts with the suppliers simultaneously or sequentially. That is, the difference in the informational structures resulting from the contracting sequence being simultaneous or sequential affects neither the system efficiency nor each party’s expected profits. For the powerful OEM case, we also demonstrate the same equivalence between simultaneous and sequential contracting. In both bargaining protocols, the contracting process effectively separates high- and low-cost suppliers. The difference is that in the powerful OEM case, we assume that the OEM can make a menu of contract proposals — one that is optimal for each supplier cost-type. In the equal bargaining power case, the presumption is that this separation of supplier types occurs in the process of bargaining, but as with all cooperative bargaining solutions, how this precisely occurs is not specified. For the convenience of experiment design, we derive the two-part tariff implementation for each of the four scenarios, which systematically vary the bargaining power of the players and the contracting timing.

We then proceed to conduct a controlled human-subjects experiment. As mentioned previously, an experiment is useful because it allows us to observe actual decisions in a controlled environment, and whether those decisions lead to outcomes that differ from our theoretical predictions. In particular, we use our main theoretical results as benchmarks and convert them into a set of experimental hypotheses. Turning to our design, we conducted a $2 \times 2$ between-subjects experiment where the first factor manipulates the contract timing between the OEM and suppliers, simultaneous or sequential, and the second factor varies the bargaining institution, dynamic unstructured bargaining or mechanism design.

Our experiment yields a number of results that differ from our theoretical benchmarks. First, conditional on agreement, we observe that an OEM with considerable bargaining power earns a significantly higher profit, 14.93%, by contracting sequentially with suppliers, rather than contracting simultaneously. Furthermore, agreement rates are approximately equal under both contracting sequences. Therefore, the result holds unconditionally as well. Second, when parties have equal bargaining power, and so engage in unstructured dynamic bargaining, conditional on agreement, the OEM earns more under sequential contracting. However, unlike the powerful OEM case, the “conditional on agreement” qualifier is important. In particular, the agreement rate is 15.54% lower
under sequential contracting than simultaneous contracting. This appears to be driven by the OEM trying to “squeeze” the second supplier for extra profits during the second negotiation. Third, if an OEM does not know whether they will have a bargaining advantage over their suppliers – meaning that the bargaining institution is unknown – then they would earn 15.70% more by adopting a sequential contracting approach with their suppliers.

To explain our experimental results, we find that participants make decisions that are consistent with social preferences (Fehr and Schmidt 1999, Bolton and Ockenfels 2000). For example, consider the case where the OEM dynamically bargains with suppliers. Our normative benchmark predicts that the OEMs will earn 32.06% less in profit (ex ante) compared to the suppliers. However, in our experiment the difference is only 2.47%. In addition, in the powerful OEM scenario the normative theory predicts that the OEMs will earn six times more in earnings (ex ante) than suppliers. Yet, in our experiment OEMs only make 47.3% more than the suppliers. Thus, the payoffs are far more equal than theory predicts.

The rest of this paper is structured as follows. In §2 we highlight the most relevant literature to our work. In §3 we outline the theoretical setting and derive normative predictions under four settings: dynamic (unstructured) bargaining with simultaneous contracting, dynamic bargaining with sequential contracting, mechanism design with simultaneous contracting, and mechanism design with sequential contracting. We then detail our experimental design and hypotheses in §4, and present our experimental results in §5. We discuss the behavioral drivers of our results in §6 and conclude in §7 by summarizing our study, presenting managerial implications, and commenting on opportunities for future work.

2. Related Literature

The research most related to our study are those papers which investigate procurement in supply chains, dynamic bargaining between parties, and asymmetric information. Early theoretical research regarding procurement in supply chains typically considers a dyadic relationship with one buyer and one supplier under asymmetric information settings (see, e.g., Corbett et al. (2004), Yang et al. (2009), and Li et al. (2013)). Regarding procurement in assembly supply chains, there are a few related studies studying the aspects of managing information asymmetry, including the OEM with private information about demand (Kalkanci and Erhun 2012), and the suppliers with private information about production costs (Hu and Qi 2017, Fang et al. 2014).

There has also been theoretical research on bargaining between parties since the seminal paper by Nash (1950). When the parties own private information, both Harsanyi and Selten (1972) and
Myerson (1984b) propose a generalization of the Nash bargaining solution in a two-person bargaining problem, and Myerson (1984a) extends the solution in the latter to accommodate multiple players. For a more recent review on bargaining with asymmetric information, we refer the reader to Ausubel et al. (2002). In operations management, both bargaining with symmetric information (see, e.g., Lovejoy (2010), Nagarajan and Sošić (2008), Kuo et al. (2011) and Feng and Lu (2012)) and bargaining with asymmetric information between two players (see, e.g., Feng et al. (2014) and Bhandari and Secomandi (2011)) have been analyzed.

Turning to experimental research, there has been considerable effort toward investigating procurement through supply chain contracts. A majority of these studies include three key assumptions. First, that two only parties contract, most commonly a retailer and supplier. Second, that the two parties interact through one party making an ultimatum offer to the other. Third, that there is full information of all cost, price, and demand parameters. Some examples of experimental studies that consider such a setting include Ho and Zhang (2008), Katok and Wu (2009), Becker-Peth et al. (2013), Davis et al. (2014), and Zhang et al. (2015) (for a summary of the experimental supply chain contracting literature, please see Chen and Wu (2018)).

More recent experimental studies have begun to relax some of the aforementioned assumptions. For instance, one study which allows a retailer to interact with more than one supplier, through back-and-forth chat box communication, is Leider and Lovejoy (2016). After communicating with multiple suppliers, the retailer then contracts with a single supplier. Ozer et al. (2011) relax the full information assumption. They consider retailers with private information about demand who interact with a single supplier. Rather than bargaining about contract parameters, this paper focuses on forecast information sharing and the role of trust/trustworthiness in supply chains. Lastly, examples of studies that have diverged from highly structured (often ultimatum offers) bargaining and investigated dynamic bargaining in supply chains include Haruvy et al. (2014), who allow one party to make repeated offers to the other, and Davis and Leider (2018) and Davis and Hyndman (2018), both of which allow the two parties to make multiple offers with limited feedback.

Overall, we believe our study is the first to extend this rich literature by investigating an assembly supply chain where an OEM contracts with two suppliers in which suppliers have private cost information, and considering different relative bargaining powers among the parties. Furthermore, we investigate this setting theoretically by deriving normative predictions and then test these predictions through a controlled human-subjects experiment.
3. Theory

We consider an OEM that sources two different inputs from two individual suppliers (indexed as 1 and 2) and then assembles the final product from a unit of each input at zero assembly cost. Suppliers are better informed regarding their own production costs than the OEM. Therefore, we assume that each supplier, \( i \), may independently have high or low unit input costs, which we denote by \( c_H \) and \( c_L \) respectively. Each supplier’s two possible production costs as well as the prior probability of its cost being high, \( p \), are common knowledge. We define \( \bar{p} = 1 - p \), and \( \Delta = c_H - c_L > 0 \). Each supplier is privately informed of its actual cost (type). Note that the analysis is similar if the prior cost distributions are not identical for these two suppliers. Without loss of generality, we assume that each supplier and the OEM have reservation profit zero.

Depending on the bargaining powers of the OEM and suppliers, we consider two bargaining institutions: dynamic bargaining and mechanism design. Under the dynamic bargaining institution, when the OEM and suppliers have the same bargaining power, the three parties engage in dynamic back-and-forth bargaining with incomplete information; see Section 3.1. Under the mechanism design institution, when the OEM is powerful and has strong bargaining power over the suppliers, the OEM can make a take-it-or-leave-it ultimatum contract offer to suppliers; see Section 3.2. Under both institutions, since the OEM needs to contract with two suppliers, the OEM is faced with the issue of contracting timing: the OEM can contract with both suppliers simultaneously or sequentially.

The outcome under each institution, if transactions occur, is a set of contracts signed by both the OEM and the suppliers, which specifies the transfer \( P_i \) from the OEM to Supplier \( i \), and the quantity \( Q_i \) supplied by the corresponding supplier; \( i = 1, 2 \). The total output quantity by the OEM \( Q = \min\{Q_1, Q_2\} \), and we assume its market-clearing price is \( a - Q/2 \), where \( a \) is sufficiently large to guarantee a positive output.

Finally, we implement the equilibrium bargaining outcomes and optimal mechanisms in the form of two-part tariff contracts for their simplicity and non-contingence (Hu and Qi 2017) and for the convenience of the experiment design. If the OEM and each Supplier \( i \) enter into a two-part tariff contract \((w_i, f_i)\), where \( w_i \) is a wholesale price and \( f_i \) is a fixed payment, this contract obliges the OEM to pay \( w_i Q_i + f_i \) to Supplier \( i \) for ordering \( Q_i \) units from the latter. Given \((w_1, f_1)\) and \((w_2, f_2)\) it is straightforward to see that the OEM’s optimal order quantity for both inputs is \( a - w_1 - w_2 \), with which the OEM’s profit is \((a - w_1 - w_2)^2/2 - f_1 - f_2 \), and each Supplier \( i \)’s profit is \((w_i - c_{x_i})(a - w_1 - w_2) + f_i \) where \( x_i \in \{L, H\} \) represents Supplier \( i \)’s type.
3.1. Dynamic Bargaining in Assembly

Solving the dynamic bargaining problem involves two main elements. The first one is to maximize the efficiency gain. The second one is to split the gain equitably among the stakeholders. Under this institution, the three stakeholders – the OEM and two suppliers – have the same bargaining power. Without the presence of asymmetric information, each of the three stakeholders should cooperatively maximize their total profit, and obtain the same profit share according to the Shapley value, since each player is pivotal and their decision of not cooperating results in no-trading for all players.

In the presence of asymmetric information, however, we employ the bargaining solution by Myerson (1984a), which generalizes the concept of Shapley value in a cooperative game with multiple players. The basic idea is to find an incentive-efficient mechanism which is incentive compatible (IC), individually rational (IR), and Pareto optimal; under this mechanism, the three stakeholders obtain the equitable profit share. Next we show how to obtain the bargaining solution roughly following the procedure of Myerson (1984a).

3.1.1. Simultaneous bargaining

We first consider the OEM simultaneously bargaining with the two suppliers. Let $P_{iXY}$, $Q_{iXY}$ be the payment to and purchase quantity from Supplier $i$ respectively given that Supplier 1 has cost type $X$ and Supplier 2 has cost type $Y$. Note that it is easy to prove that $Q_{1XY} = Q_{2XY}$ in the optimal solution, and therefore we denote the quantity by $Q_{XY}$ in the following analysis. For convenience we denote the expected payment for Supplier 1 of type $X$ (resp., Supplier 2 of type $Y$) as $P_{1X} = pP_{1XH} + \bar{p}P_{1HL}$ (resp., $P_{2Y} = pP_{2HY} + \bar{p}P_{2LY}$).

The incentive compatible mechanisms $\{P_{1XY}, P_{2XY}, Q_{XY}\}$ are characterized by IR constraints for both the OEM and the suppliers, and IC constraints for the suppliers. For example, the IR and IC constraints for Supplier 1 are as follows:

\[
\begin{align*}
  p(P_{1HH} - c_HQ_{HH}) + \bar{p}(P_{1HL} - c_HQ_{HL}) &\geq 0 \quad \text{(IR}_{1H}\text{)} \\
  p(P_{1LH} - c_LQ_{LH}) + \bar{p}(P_{1LL} - c_LQ_{LL}) &\geq 0 \quad \text{(IR}_{1L}\text{)} \\
  p(P_{1HH} - c_HQ_{HH}) + \bar{p}(P_{1HL} - c_HQ_{HL}) &\geq p(P_{1LH} - c_HQ_{HL}) + \bar{p}(P_{1LL} - c_LQ_{LL}) \quad \text{(IC}_{1H}\text{)} \\
  p(P_{1LH} - c_LQ_{LH}) + \bar{p}(P_{1LL} - c_LQ_{LL}) &\geq p(P_{1HH} - c_HQ_{HH}) + \bar{p}(P_{1HL} - c_HQ_{HL}) \quad \text{(IC}_{1L}\text{)}
\end{align*}
\]

Since IR$_{1L}$ is implied by IR$_{1H}$ and IC$_{1L}$, and IC$_{1H}$ is implied with a monotonicity constraint on sourcing quantity if IC$_{1L}$ is binding, we obtain the simplified constraints for Supplier 1 as follows:

\[
\begin{align*}
  p(P_{1HH} - c_HQ_{HH}) + \bar{p}(P_{1HL} - c_HQ_{HL}) &\geq 0 \quad \text{(IR}_{1H}\text{)}
\end{align*}
\]

\footnote{In the scenario where IC$_{1L}$ is not binding under the bargaining solution (derived in Proposition 1), one may verify that IC$_{1H}$ is satisfied.}
\[ p(P_{1LH} - c_L Q_{LH}) + \bar{p}(P_{1LL} - c_L Q_{LL}) \geq p(P_{1HH} - c_L Q_{HH}) + \bar{p}(P_{1HL} - c_L Q_{HL}) \quad (IC_{1L}) \]
\[ Q_{HY} \leq Q_{LY}, \quad Y \in \{L, H\} \quad (MN_1) \]

Similarly, we can obtain the IR constraint for the OEM, denoted by IR_{o}, and the IR and IC constraint for Supplier 2, and apply similar simplification techniques. Then the incentive compatible mechanisms will be characterized by IR_{iH}, IC_{iL}, MN_i, and IR_{o}; i = 1, 2.

We next define the primal bargaining problem. Let the coefficient of Supplier \( i \)'s profit when her type is \( H \) by \( \lambda_i \in [0, 1] \) and correspondingly the coefficient when her type is \( L \) by \( \bar{\lambda}_i \equiv 1 - \lambda_i \). Then we have the primal bargaining problem as follows:

\[
\max_{P, Q} p^2[(a - Q_{HH}/2)Q_{HH} - P_{1HH} - P_{2HH}] + \bar{p}\bar{p}[(a - Q_{LL}/2)Q_{LL} - P_{1LL} - P_{2LL}] + \lambda_1[p(P_{1LH} - c_L Q_{LH}) + \bar{p}(P_{1LL} - c_L Q_{LL})] + \lambda_1[p(P_{1HH} - c_H Q_{HH}) + \bar{p}(P_{1HL} - c_H Q_{HL})] + \\
\bar{\lambda}_2[p(P_{2LH} - c_L Q_{LH}) + \bar{p}(P_{2LL} - c_L Q_{LL})] + \bar{\lambda}_2[p(P_{2HH} - c_H Q_{HH}) + \bar{p}(P_{2HL} - c_H Q_{HL})]
\]

s.t. IR_{o}, IR_{1H}, IR_{2H}, IC_{1L}, IC_{2L}, MN_1 and MN_2.

The weighted suppliers' profits are shown as the last two lines of the objective function. For any given \( \lambda_i \in [0, 1], \quad i = 1, 2 \), solving the primal problem above gives us an incentive-efficient mechanism. However, recall that the second objective of bargaining is to ensure each stakeholder obtains their equitable share of profits, which is guaranteed by a carefully chosen pair, \( (\lambda_i^*, \bar{\lambda}_i^*) \). We describe how this is achieved below.

Let us temporarily ignore the IR and MN constraints and verify them later. Let the shadow price of Supplier \( i \)'s IC_{iH} constraint be \( \alpha_i \). Following Myerson (1984a), we define the virtual utility \( v_o \) of the OEM and \( v_{iXY} \) of Supplier \( i \) given Supplier 1 and 2's types are \( X \) and \( Y \) respectively as follows. Since the OEM does not possess private information, his virtual utility equals his profit.

\[
v_o(P, Q) \triangleq p^2[(a - Q_{HH}/2)Q_{HH} - P_{1HH} - P_{2HH}] + \bar{p}\bar{p}[(a - Q_{LL}/2)Q_{LL} - P_{1LL} - P_{2LL}] + \lambda_1[p(P_{1LH} - c_L Q_{LH}) + \bar{p}(P_{1LL} - c_L Q_{LL})] + \bar{\lambda}_2[p(P_{2LH} - c_L Q_{LH}) + \bar{p}(P_{2LL} - c_L Q_{LL})]
\]

\[
v_{1LY}(P, Q, \lambda, \alpha) \triangleq \frac{\bar{\lambda}_1 + \alpha_1}{p} (P_{1LY} - c_L Q_{LY})
\]

\[
v_{1HY}(P, Q, \lambda, \alpha) \triangleq \frac{1}{p} [\lambda_1(P_{1HY} - c_H Q_{HY}) - \alpha_1(P_{1HY} - c_L Q_{HY})]
\]

\[
v_{2XL}(P, Q, \lambda, \alpha) \triangleq \frac{\lambda_2 + \alpha_2}{p} (P_{2XL} - c_L Q_{XL})
\]

\[
v_{2XH}(P, Q, \lambda, \alpha) \triangleq \frac{1}{p} [\lambda_2(P_{2XH} - c_H Q_{XH}) - \alpha_2(P_{2XH} - c_L Q_{XH})]
\]
Then the Lagrange dual problem can be presented using the virtual utilities as follows:

\[
\begin{align*}
\min_{\alpha_i, P, Q} & \quad v_o(P, Q) + \bar{p}v_{1LH}(P, Q, \lambda, \alpha) + p^2v_{1HH}(P, Q, \lambda, \alpha) + \bar{p}^2v_{1LL}(P, Q, \lambda, \alpha) + p\bar{p}v_{2HL}(P, Q, \lambda, \alpha) + p^2v_{2HH}(P, Q, \lambda, \alpha) + \bar{p}^2v_{2LL}(P, Q, \lambda, \alpha) + \bar{p}\bar{p}v_{2LH}(P, Q, \lambda, \alpha) \\
\text{s.t.} & \quad \alpha_i + p - \lambda_i = 0; \quad \alpha_i \geq 0, \quad i = 1, 2.
\end{align*}
\]

We note that the Lagrange function is the expected total virtual utilities of the assembly system. For the problem to be feasible, we require \(\lambda_i \geq p\).

Solving the problem, we have that the optimal shadow prices \(\alpha_i^* = \lambda_i - p; \quad i = 1, 2\). The optimal sourcing quantities \(Q_{XY}\) are as follows:

\[
\begin{align*}
Q_{HH}^* &= a - 2c_H - \left(\frac{\lambda_1 - p}{p}\right)\Delta - \left(\frac{\lambda_2 - p}{p}\right)\Delta, \\
Q_{LL}^* &= a - 2c_L, \\
Q_{LH}^* &= a - c_L - c_H - \left(\frac{\lambda_2 - p}{p}\right)\Delta, \\
Q_{HL}^* &= a - c_H - \left(\frac{\lambda_1 - p}{p}\Delta\right) - c_L. \\
\end{align*}
\]

(1)

It is trivial to verify that the monotonicity constraints \(MN_i\)'s are satisfied. The corresponding optimal objective value is

\[
\frac{p^2}{2} \left[ a - 2c_H - \left(\frac{\lambda_1 - p}{p}\right)\Delta - \left(\frac{\lambda_2 - p}{p}\right)\Delta \right]^2 + \frac{\bar{p}^2}{2} \left( a - 2c_L \right)^2 + \sum_{i=1}^2 \frac{\bar{p}p}{2} \left[ a - c_L - c_H - \left(\frac{\lambda_1 - p}{p}\Delta\right) \right]^2
\]

(2)

We observe that the above optimal objective value is the sum of expected virtual utilities of the assembly system; note that under the optimal quantities, the cost of \(c_H\) is effectively adjusted up to exaggerate the difference between the two cost levels.

We next derive the condition that guarantees the equitable share of profits among the stakeholders. For brevity we show the analysis for Supplier 1. Let \(\Delta_{1X}\) be the conditional expected virtual utility of the assembly system when Supplier 1's type is \(X\) as follows:

\[
\Delta_{1L} \triangleq \frac{p}{2} \left[ a - c_L - c_H - \left(\frac{\lambda_2 - p}{p}\Delta\right) \right]^2 + \frac{\bar{p}}{2} \left( a - 2c_L \right)^2; \\
\Delta_{1H} \triangleq \frac{p}{2} \left[ a - c_H - \left(\frac{\lambda_1 - p}{p}\Delta\right) - c_H - \left(\frac{\lambda_2 - p}{p}\Delta\right) \right]^2 + \frac{\bar{p}}{2} \left[ a - c_H - \left(\frac{\lambda_1 - p}{p}\Delta\right) - c_L \right]^2.
\]

We then solve for the warranted claims – the (real) profits for stakeholders of each type which guarantee that their corresponding virtual utilities equal to their equitable shares of the total virtual utility of the system. Since all the stakeholders are pivotal in the assembly system, each can make a rational threat of not producing or purchasing any quantity if not cooperating. Therefore, any type of stakeholder should obtain 1/3 of the conditional expected virtual utility of the assembly
system. Let $W_{1X}$ denote the warranted claim for Supplier 1 of type $X$. Recall that the optimal shadow price $\alpha_1^* = \lambda_1 - p$. The system of equations to solve for the warranted claims is as follows.

$$W_{1L} = \frac{\Delta_L}{3}, \quad W_{1H} = \frac{\lambda_1}{p} \left[\lambda_1 W_{1H} - (\lambda_1 - p)W_{1L}\right] = \frac{\Delta_H}{3}.$$ 

Solving the system of equations, we obtain the warranted claims as follows.

$$W_{1L}^* = \frac{\Delta_L}{3}, \quad W_{1H}^* = \frac{\lambda_1 - p}{\lambda_1} \cdot \frac{\Delta_H}{3}.$$ 

We show the bargaining solution by the definition in Myerson (1984a) in the following proposition. We note that it suffices to derive the expected payment $P_{1X}$ in each case. Also recall that we assume $a$ is large enough so the sourcing quantities are non-negative. Finally, the IR constraints for all stakeholders are satisfied since each type of the stakeholders obtain a non-negative profit. The detailed derivation of these solutions is relegated to the appendix.

**Proposition 1 (Simultaneous bargaining solution).**

Let $\bar{a} = 2c_L + \frac{(5+4p)\Delta}{4p}$ and $\underline{a} = 2c_L + \frac{(5+4p)\Delta}{4}$. There are three cases as specified below. In each case, the bargaining solution is an incentive-efficient mechanism, which guarantees each stakeholder of each type a profit that is greater than or equal to the corresponding warranted claim. The optimal quantity in each case is obtained by replacing $\lambda_i$ in equations (1) by the corresponding values below.

**Case 1:** $a \leq \underline{a}$. In this case, $\lambda_1 = \lambda_2 = \lambda^* = p$. The expected payments for a supplier with type $L$ and $H$ respectively are

$$P_{L}^* = c_L(a - 2c_L) - pc_L \Delta + \frac{p}{6} (a - c_L - c_H)^2 + \frac{\bar{p}}{6} (a - 2c_L)^2,$$

$$P_{H}^* = c_H(a - c_H - c_L) - pc_H \Delta + \frac{p}{6} (a - 2c_H)^2 + \frac{\bar{p}}{6} (a - c_H - c_L)^2.$$ 

**Case 2:** $\underline{a} < a < \bar{a}$. In this case, $\lambda_1 = \lambda_2 = \lambda^* = \frac{4p(a - 2c_L)}{(5+4p)\Delta}$. The expected payments for a supplier with type $L$ and $H$ respectively are

$$P_{L}^* = \frac{a^2(25 + 16p - 16p^2) + 2ac_L (32p^2 + 28p + 25) - 8c_L^2 (8p^2 + 22p + 25)}{6(5+4p)^2},$$

$$P_{H}^* = \frac{a^2(25 + 16p - 16p^2) + 2ac_L (32p^2 - 20p - 35) - 8c_L^2 (8p^2 - 2p - 5)}{6(5+4p)^2}.$$ 

**Case 3:** $a \geq \bar{a}$. In this case, $\lambda_1 = \lambda_2 = \lambda^* = 1$. The expected payments for a supplier with type $L$ and $H$ respectively are

$$P_{L}^* = \frac{a^2p + 2ac_Hp + 2c_Hc_L (4 - p) - 4c_H^2 (1 + p) - 2c_L^2 (2 + p)}{6p},$$

$$P_{H}^* = \frac{a^2p + 2ac_Hp + 2c_Hc_L (1 - p) - 4c_H^2 (1 + p) + 2c_L^2 (1 - p)}{6p}.$$
Lastly, the two-part tariff implementation of the bargaining solution is shown as follows. Note that the value of the wholesale price to each supplier can be an arbitrary value as long as the total wholesale price to the two suppliers adds up to the same constant. The potential difference in profit caused by the different wholesale prices is corrected by the respective fixed payments.

**Corollary 1 (Two-part tariff implementation of the bargaining solution).**

Let $\lambda^*, P^*_L$, and $P^*_H$ be those defined in Proposition 1. The following two-part tariff mechanism implements the simultaneous bargaining outcome, with $\delta$ being any real number.

The wholesale prices are:

$$w^*_2H = c_H + \frac{\Delta(\lambda^* - p)}{p} + \delta, \quad w^*_2L = c_L + \delta,$$

$$w^*_1H = c_H + \frac{\Delta(\lambda^* - p)}{p} - \delta, \quad w^*_1L = c_L - \delta.$$

The fixed payments are:

$$f^*_{iL} = P^*_L - w^*_iL(a - w^*_iL - \bar{w}j^*_L - pw^*_jH), \quad f^*_{iH} = P^*_H - w^*_iH(a - w^*_iH - \bar{w}j^*_L - pw^*_jH), \quad i, j \in \{1, 2\}, i \neq j.$$

3.1.2. **Sequential bargaining**

In sequential bargaining, we consider the incentive-efficient mechanisms with the two-part tariff implementation for brevity and without loss of generality. Under this setting, the OEM first bargains with Supplier 1 to learn her private information, and then bargains with Supplier 2. To capture the key difference in the informational structures between this scenario and simultaneous bargaining, we consider that the OEM and Supplier 1 form a sub-coalition after the first stage bargaining, and the sub-coalition bargains with Supplier 2 together. Thus, the veto power of Supplier 1 is retained until the end of the bargaining process. We note that in the second-stage bargaining, both the sub-coalition and Supplier 2 have their respective private information. (Recall that in the first-stage bargaining Supplier 1 also has her own private information.) This suggests that additional efficiency loss may be caused by the sequential bargaining process.

In what follows, we focus on discussing the impact of the informational structure on the efficiency of the bargaining outcome. Note that under the two-part tariff implementation, the efficiency of the system is determined by the wholesale prices to procure from both suppliers. After we analyze the impact of sequential bargaining on system efficiency, we discuss the equitable allocation via the fixed payments. We solve the second stage bargaining before considering the first stage.

**Second-stage bargaining.** In the first stage, the OEM bargains with Supplier 1 and they form a sub-coalition. The total virtual utility in the first-stage bargaining is the sub-coalition’s private
information. Let the sub-coalition’s type be Supplier 1’s cost type. We note that the bargaining outcome in the first stage is represented by a menu of two-part tariff contracts: \((w_{1X}, f_{1X})\) given Supplier 1’s type being \(X\). The payment terms for Supplier 1, \(w_{1X}, f_{1X}\), \(X = H, L\), are treated as constants in the second stage. In what follows, we use subscript 2XY, \(X, Y = H, L\) to denote the bargaining outcome intended for Supplier 2 of type \(Y\) given Supplier 1’s type being \(X\), and define \(w_{2X}, f_{2X} \equiv w_{2XH}, w_{2XL}, f_{2XH}, f_{2XL}, X = H, L\). Given the coefficient of Supplier 1’s profit in the objective of the first-stage bargaining being \(\lambda_1\) when her type is \(H\), and \(\bar{\lambda}_1 = 1 - \lambda_1\) when her type is \(L\), and following the fact that the fixed payment \(f_{1X}\) between the OEM and Supplier 1 is unbounded, the corresponding total virtual utility of the sub-coalition, denoted by \(V_{1X}\), is

\[
V_{1L}(w_{2L}, f_{2L}) = \bar{p} \left[ \frac{a + w_{1L} - w_{2LH}}{2} - c_L \right] \left[ a - w_{1L} - w_{2LH} - f_{2LH} \right] + \\
\bar{p} \left[ \frac{a + w_{1L} - w_{2LL}}{2} - c_L \right] \left[ a - w_{1L} - w_{2LL} - f_{2LL} \right];
\]

\[
V_{1H}(w_{2H}, f_{2H}) = p \left[ \frac{a + w_{1H} - w_{2HH}}{2} - c_H - (\lambda_1 - p)\Delta \right] \left[ a - w_{1H} - w_{2HH} - f_{2HH} \right] + \\
p \left[ \frac{a + w_{1H} - w_{2HL}}{2} - c_H - (\lambda_1 - p)\Delta \right] \left[ a - w_{1H} - w_{2HL} - f_{2HL} \right].
\]

In the second stage, both the sub-coalition and Supplier 2 are endowed with private information. Let the coefficient of Supplier 2’s profit (resp., the sub-coalition’s total virtual utility) when the type is \(H\) by \(\lambda_2 \in [0, 1]\) (resp., \(\lambda_2 \in [0, 1]\)) and correspondingly the coefficient when the type is \(L\) by \(\bar{\lambda}_2 \equiv 1 - \lambda_2\) (resp., \(\bar{\lambda}_2 \equiv 1 - \lambda_2\)). The primal bargaining problem is formulated as follows. We again focus on the scenario in which the IC constraints of the more efficient type may be binding and temporarily ignore the IR and MN constraints.

\[
\max_{w_{2H}, f_{2H}, w_{2L}, f_{2L}} \bar{\lambda}_2 V_{1L}(w_{2L}, f_{2L}) + \lambda_2 V_{1H}(w_{2H}, f_{2H}) + \\
\lambda_2 \left[ p \left( w_{2HL} - c_L \right) \left( a - w_{1H} - w_{2HL} \right) + f_{2HL} \right] + \bar{p} \left[ w_{2LL} - c_L \right] \left( a - w_{1L} - w_{2LL} + f_{2LL} \right] + \\
\lambda_2 \left[ p \left( w_{2HH} - c_h \right) \left( a - w_{1H} - w_{2HH} \right) + f_{2HH} \right] + \bar{p} \left[ w_{2HL} - c_h \right] \left( a - w_{1L} - w_{2HL} + f_{2HL} \right] \\
\text{s.t.} \ p \left[ w_{2HL} - c_L \right] \left( a - w_{1H} - w_{2HL} \right) + f_{2HL} \right] + \bar{p} \left[ w_{2LL} - c_L \right] \left( a - w_{1L} - w_{2LL} + f_{2LL} \right] \geq \\
\left[ w_{2HH} - c_L \right] \left( a - w_{1H} - w_{2HH} \right) + f_{2HH} \right] + \bar{p} \left[ w_{2HL} - c_L \right] \left( a - w_{1L} - w_{2HL} + f_{2HL} \right] \\
\left[ V_{1L}(w_{2L}, f_{2L}) \geq p \left[ \frac{a + w_{1L} - w_{2HH}}{2} - c_L \right] \left( a - w_{1L} - w_{2HH} \right) + f_{2HH} \right] + \\
\bar{p} \left[ \frac{a + w_{1L} - w_{2HL}}{2} - c_L \right] \left( a - w_{1L} - w_{2HL} \right) + f_{2HL} \right] \geq (IC_{2L})
\]

\[
\left[ V_{1H}(w_{2H}, f_{2H}) \geq p \left[ \frac{a + w_{1H} - w_{2HH}}{2} - c_L \right] \left( a - w_{1L} - w_{2HH} \right) + f_{2HH} \right] + \\
\bar{p} \left[ \frac{a + w_{1H} - w_{2HL}}{2} - c_L \right] \left( a - w_{1L} - w_{2HL} \right) + f_{2HL} \right] \geq (IC_{ML})
\]
Let the shadow price of Supplier 2’s IC constraint be $\alpha_2$ and the shadow price of the sub-coalition’s IC constraint be $\alpha_s$. We denote $\alpha = \{\alpha_2, \alpha_s\}$ and have the Lagrange dual problem as follows.

\[
\begin{align*}
\min_{\alpha} \quad & \max_{w_{2H}, f_{2L}, w_{2L}, f_{2H}} \lambda_2 V_{1L}(w_{2L}, f_{2L}) + \lambda_s V_{1H}(w_{2H}, f_{2H}) + \\
& \lambda_2 \left[ p \left( (w_{2HL} - c_L)(a - w_{1H} - w_{2HL}) + f_{2HL} \right) + \bar{p} \left( (w_{2LL} - c_L)(a - w_{1L} - w_{2LL}) + f_{2LL} \right) \right] + \\
& \lambda_s \left\{ \begin{array}{l}
V_{1L}(w_{2L}, f_{2L}) - p \left( \frac{w_{2HL} - w_{2HL} - c_L}{2} (a - w_{1L} - w_{2HL}) - f_{2HL} \right) - \\
\bar{p} \left[ (\frac{w_{2HL} - w_{2HL} - c_L}{2} (a - w_{1L} - w_{2HL}) - f_{2HL} \right] -
\end{array} \right\} + \\
& \text{s.t. } \alpha_2 + p - \lambda_2 = 0; \quad \alpha_s + p - \lambda_s = 0; \quad \alpha_2 \geq 0; \quad \alpha_s \geq 0.
\end{align*}
\]

For the problem to be feasible, we require $\lambda_s \geq p$ and $\lambda_2 \geq p$. Solving the problem yields the optimal $w_{2XY}^\dagger$’s as follows.

\[
\begin{align*}
w_{2HH}^\dagger &= c_H + \frac{(\lambda_2 - p)\Delta}{p^2} + \frac{\lambda_1 \lambda_s \Delta}{p^2} - (w_{1H} - c_L), \\
w_{2HL}^\dagger &= c_L + \frac{\lambda_1 \lambda_s \Delta}{p^2} - (w_{1H} - c_L), \\
w_{2LL}^\dagger &= c_L - (w_{1L} - c_L), \\
w_{2LH}^\dagger &= c_H + \frac{(\lambda_2 - p)\Delta}{p} - (w_{1L} - c_L).
\end{align*}
\]

We note that $\lambda_s \geq p$ and the OEM’s order quantity for given wholesale prices $w_1$ and $w_2$ are $a - w_1 - w_2$. Therefore, for any $\lambda_s > p$, the IC constraint of the sub-coalition is binding, the wholesale price is further distorted upwards, and therefore the optimal order quantity is further distorted downwards. When $\lambda_s = p$, this additional distortion does not occur, provided that we can verify the IC constraint of the sub-coalition $IC_{ML}$ is satisfied. We will show that the solution to our problem falls into the second case. In this case, we have the corresponding wholesale prices as

\[
\begin{align*}
w_{2HH}^\dagger &= 2c_H + \frac{(\lambda_2 - p)\Delta}{p} + \frac{(\lambda_1 - p)\Delta}{p} - w_{1H}, \\
w_{2HL}^\dagger &= c_H + \frac{(\lambda_1 - p)\Delta}{p} - w_{1H}, \\
w_{2LL}^\dagger &= 2c_L - w_{1L}, \\
w_{2LH}^\dagger &= c_H + c_L + \frac{(\lambda_2 - p)\Delta}{p} - w_{1L}.
\end{align*}
\]

Observing the expressions, we note that in each scenario, $w_{2XY}^\dagger + w_{1X}^\dagger$ remains a constant. In other words, provided that the IC constraint of the sub-coalition is not binding, the second stage bargaining will find the second-stage wholesale prices for any decision of first-stage wholesale prices, which yields the same total virtual utility of the system. In this case, the expected total virtual utility of the assembly system is

\[
\frac{p^2}{2} \left( a - 2c_H - \frac{(\lambda_1 - p)\Delta}{p} - \frac{(\lambda_2 - p)\Delta}{p} \right)^2 + \bar{p} \sum_{i=1}^{2} \left( a - c_L - c_H - \frac{(\lambda_i - p)\Delta}{p} \right)^2
\]
We note that the above total virtual utility resembles the one under simultaneous bargaining in equation (2). It can be inferred that the sequential bargaining outcome may be the same as the one under simultaneous bargaining, provided that under the sequential bargaining outcome, the sub-coalition’s IC constraint is not binding, which is guaranteed if the wholesale prices and the fixed payments are independent of Supplier 1’s type, i.e., the wholesale prices satisfy that $w_{2HL}^*=w_{2LL}^*$ and $w_{2HL}^*=w_{2LL}^*$, and the fixed payment satisfy that $f_{2LL}^*=f_{2HL}^*$ and $f_{2HL}^*=f_{2LL}^*$.

We postpone the verification of the above sufficient condition and the detailed expressions of the fixed payment until after we discuss the first stage bargaining below.

**First stage bargaining.** Consider the first stage bargaining where the OEM bargains with Supplier 1. We have the first stage primal bargaining problem as follows.

$$\max_{w_{1L}, f_1} \tilde{\lambda}_1 \left\{ p \left[ (w_{1L} - c_L) (a - w_{1L} - w_{2HL}^*) + f_{1L} \right] + \bar{p} \left[ (w_{1L} - c_L) (a - w_{1L} - w_{2LL}^*) + f_{1L} \right] \right\} +$$

$$\lambda_1 \left\{ p \left[ (w_{1H} - c_H) (a - w_{1H} - w_{2HH}^*) + f_{1H} \right] + \bar{p} \left[ (w_{1H} - c_H) (a - w_{1H} - w_{2HL}^*) + f_{1H} \right] \right\} +$$

$$p^2 \left[ \frac{(a - w_{1H} - w_{2HH}^*)^2}{2} - f_{1H} - f_{2HH}^* \right] + pp \left[ \frac{(a - w_{1H} - w_{2HL}^*)^2}{2} - f_{1H} - f_{2HL}^* \right] +$$

$$\bar{p} p \left[ \frac{(a - w_{1L} - w_{2LL}^*)^2}{2} - f_{1L} - f_{2LL}^* \right] + \bar{p}^2 \left[ \frac{(a - w_{1L} - w_{2HL}^*)^2}{2} - f_{1L} - f_{2HL}^* \right]$$

s.t. 

$$p \left[ (w_{1L} - c_L) (a - w_{1L} - w_{2HL}^*) + f_{1L} \right] + \bar{p} \left[ (w_{1L} - c_L) (a - w_{1L} - w_{2LL}^*) + f_{1L} \right]$$

$$\geq p \left[ (w_{1H} - c_L) (a - w_{1H} - w_{2HH}^*) + f_{1H} \right] + \bar{p} \left[ (w_{1H} - c_L) (a - w_{1H} - w_{2HL}^*) + f_{1H} \right] \quad \text{(IC1L)}$$

Let $\alpha_1$ denote the shadow price of Supplier 1’s IC1L constraint. Applying the constraint that $\alpha_1 = \lambda_1 - p$ to the Lagrange dual problem, the Lagrange function is simplified as follows.

$$p^2 \left[ \frac{(a + w_{1H} - w_{2HH}^*)}{2} - c_H - \frac{\lambda_1 - p}{p} \Delta \right] (a - w_{1H} - w_{2HH}^*) - f_{2HH}^* \right] +$$

$$pp \left[ \frac{(a + w_{1H} - w_{2HL}^*)}{2} - c_H - \frac{\lambda_1 - p}{p} \Delta \right] (a - w_{1H} - w_{2HL}^*) - f_{2HL}^* \right] +$$

$$\bar{p} p \left[ \frac{(a + w_{1L} - w_{2LL}^*)}{2} - c_L \right] (a - w_{1L} - w_{2LL}^*) - f_{2LL}^* \right] +$$

$$\bar{p}^2 \left[ \frac{(a + w_{1L} - w_{2HL}^*)}{2} - c_L \right] (a - w_{1L} - w_{2HL}^*) - f_{2HL}^* \right]$$

We observe that in the formulation above, with slight modification (specified in the proposition below) of the simultaneous bargaining solution derived in Corollary 1, the total virtual utility of the OEM and Supplier 1 is the same as the one in the simultaneous bargaining case, and it can
be verified that the IC<sub>ML</sub> constraint is implied. That is, in the second stage, the sub-coalition of the OEM and Supplier 1 is able to credibly signal its private information to Supplier 2 without incurring an additional signaling cost. Therefore, the simultaneous bargaining solution is still a bargaining solution in sequential bargaining and no additional efficiency loss is incurred due to the sequential bargaining procedure. We summarize this observation in the following proposition.

**Proposition 2 (Sequential bargaining solution).** Let \( \lambda_s = p \). Let \( \lambda_i, P_{L}^{*}, \) and \( P_{H}^{*} \) be those defined in Proposition 1. Let \( f_{iX}^{*} \) be those defined in Corollary 1. The simultaneous bargaining solution in Proposition 1 is also a bargaining solution under the sequential bargaining, and it can be implemented by two-part tariff contracts as follows.

The wholesale prices are

\[
\begin{align*}
w_{2HH}^{\dagger} &= w_{2LH}^{\dagger} = c_{H} + \frac{\Delta (\lambda_{1}-p)}{p} + \delta, \\
 w_{2HL}^{\dagger} &= w_{2LL}^{\dagger} = c_{L} + \delta, \\
 w_{1H}^{\dagger} &= c_{H} + \frac{\Delta (\lambda_{1}-p)}{p} - \delta, \\
 w_{1L}^{\dagger} &= c_{L} - \delta.
\end{align*}
\]

The fixed payments are

\[
\begin{align*}
f_{2LL}^{\dagger} &= f_{2HL}^{\dagger} = f_{2L}^{*}, \\
f_{2HH}^{\dagger} &= f_{2LH}^{\dagger} = f_{2H}^{*}, \\
f_{1L}^{\dagger} &= f_{1L}^{*}, \\
f_{1H}^{\dagger} &= f_{1H}^{*}.
\end{align*}
\]

Under this set of bargaining solutions, the simultaneous bargaining and sequential bargaining are revenue-equivalent.

**Remark:** In sequential bargaining, we consider the OEM and Supplier 1 forming a sub-coalition. Doing so allows us to focus on the impact on efficiency due to the change in the informational structure by retaining the veto power of Supplier 1 until the end of the bargaining process and eliminating the impact of the fixed payment between the OEM and Supplier 1 on the second stage bargaining. We note that if the OEM bargains with Supplier 2 alone in the second stage, in addition to her private cost information, Supplier 2 would have known that Supplier 1 has agreed to a contract with the OEM and did not exercise the veto power. Then the bargaining outcome could be affected in a non-trivial way. In addition, the fixed payment between the OEM and Supplier 1, which is not observable to Supplier 2 but can be contingent upon the second-stage bargaining outcome, affects the total virtual utility of the OEM and Supplier 2. This case requires additional analyses beyond the scope of this paper.
3.2. Mechanism Design in Assembly

In this section we assume that the OEM has the power to offer a take-it-or-leave-it menu of contracts to suppliers. All other specifics are the same as the model in Section 3.1. For brevity, we focus on the case where the OEM and each Supplier $i$ enter into a two-part tariff contract $(w_i, f_i)$.

The key difference between the dynamic bargaining institution in Section 3.1 and the mechanism design institution in this section, is the bargaining power between the OEM and the suppliers. Under the dynamic bargaining institution, the bargaining power is evenly distributed between the OEM and the suppliers, which results in the equitable allocation on the virtual utility scale among the three stakeholders. Under the mechanism design institution, the OEM has the power to make a take-it-or-leave-it ultimatum offer, allowing him to extract the surplus from the suppliers except for the information rent due to the suppliers’ private information.

Within each of the two institutions, the difference between the simultaneous and sequential decision making lies in the difference in the informational structure. Under the dynamic bargaining institution, if the bargaining is sequential, the OEM and Supplier 1 form a sub-coalition with the private information of Supplier 1 being the private information of the sub-coalition when bargaining with Supplier 2. Under the mechanism design institution, when the OEM contracts with Supplier 2 (after contracting with Supplier 1), he also possesses the private information of Supplier 1, making him an informed principal in the contracting process. We establish below that although it is possible that the principal with private information may need to incur a signaling cost, he can actually credibly signal his private information without incurring the signaling cost. This results in the revenue equivalence between the simultaneous and sequential contracting processes.

We note that the analysis of the mechanism design institution is analogous to Hu and Qi (2017). Thus, we focus on discussing the connection between this institution and the dynamic bargaining institution, which allows us to derive testable hypotheses for our subsequent experiment. We omit the technical details and refer the reader to Hu and Qi (2017). The relevant technical results are listed below.

The optimal simultaneous mechanism is as follows.

**Proposition 3 (Optimal simultaneous mechanism).** The following are revenue-equivalent optimal simultaneous contracting mechanisms: the OEM offers the menu $\{(w_{1H}^*, f_{1H}^*), (w_{1L}^*, f_{1L}^*)\}$ to Supplier $i$, $i = 1, 2$, where

\[
\begin{align*}
    w_{1L}^* &= c_L + \delta, \quad w_{1H}^* = c_L + \delta + \Delta/p, \quad w_{2L}^* = c_L - \delta, \quad w_{2H}^* = c_L - \delta + \Delta/p, \\
    f_{1L}^* &= (-\delta + \Delta)(a - 2c_L - \Delta) - \Delta^2/p, \quad f_{1H}^* = -(\Delta\bar{p}/p + \delta)(a - 2c_L - \Delta - \Delta/p),
\end{align*}
\]
\[ f_{2L}^* = (\delta + \Delta)(a - 2c_L - \Delta) - \Delta^2/p, \quad f_{2H}^* = -\left(\Delta\bar{p}/p - \delta\right)(a - 2c_L - \Delta - \Delta/p). \]

Here \( \delta \) is any real number. These optimal mechanisms yield the expected profit for the OEM
\[ \Pi^* = (a - 2c_L)(a - 2c_L - 4\Delta)/2 + \frac{\Delta^2}{p} + \Delta^2, \]
the expected profit for Supplier \( i \), \( i = 1, 2 \)
\[ \pi_i^* = (a - 2c_L)\bar{p}\Delta - \Delta^2\bar{p}/p - \bar{p}\Delta^2. \]

Similar to the simultaneous bargaining solution, there is not a single, but instead a system of revenue-equivalent optimal mechanisms which satisfy \( w_{1L}^* + w_{2L}^* = 2c_L, \ w_{iH}^* = w_{iL}^* + \Delta/p, \ i = 1, 2 \). The intuition behind the system of equivalent optimal mechanisms is that the OEM as an assembler does not care how its total variable cost is allocated between the two inputs as long as the low-cost suppliers’ total variable-payment terms are first-best \( (w_{1L}^* + w_{2L}^* = c_L + c_L) \), and each high-cost supplier’s variable-payment term is upward distorted compared with its low-cost counterpart \( (w_{iH}^* = w_{iL}^* + \Delta/p) \); note that \( \Delta/p > \Delta = c_H - c_L \). (The suppliers do not care either, because any “unfair” variable-payment terms are compensated for via fixed payments.) Once again we note that our upward distortion in price is actually consistent with the common mechanism design wisdom of downward distortion in quantity.

The optimal mechanisms presented in Proposition 3 contain an arbitrary constant \( \delta \). Clearly, \( \delta = 0 \) yields the most intuitive and “fair” mechanism wherein each low-cost supplier is offered the variable-payment term equal to its cost. For simplicity of presentation we slightly abuse the terminology and refer to the mechanism with \( \delta = 0 \) as the optimal simultaneous contracting mechanism.

The optimal sequential mechanism is as follows.

**Proposition 4 (Optimal sequential mechanism).** The following is the unique equilibrium sequential contracting mechanism: in Stage 1 the OEM offers the menu \{\((w_{1L}^Q, f_{1L}^Q), (w_{1H}^Q, f_{1H}^Q)\)\} to Supplier 1 where
\[ w_{1L}^Q = c_L, \quad w_{1H}^Q = c_L + \Delta/p, \]
\[ f_{1L}^Q = \Delta(a - 2c_L - \Delta) - \Delta^2/p, \quad f_{1H}^Q = -\Delta(a - 2c_L - \Delta)\bar{p}/p + \Delta^2\bar{p}/p^2. \]

If Supplier 1 is revealed to have high costs, then in Stage 2 the OEM offers the menu \{\((w_{2H}^Q, f_{2HH}^Q), (w_{2HL}^Q, f_{2HL}^Q)\)\} to Supplier 2 where
\[ w_{2HL}^Q = c_L, \quad w_{2HH}^Q = c_L + \Delta/p, \]
\[ f_{2HL}^Q = \Delta(a - 2c_L - \Delta) - \Delta^2/p, \quad f_{2HH}^Q = -\Delta(a - 2c_L - \Delta)\bar{p}/p + \Delta^2\bar{p}/p^2. \]
\[
Q_{2HL}^Q = \Delta(a - 2cL - \Delta/p) - \Delta^2/p, \quad Q_{2HH}^Q = -\Delta(a - 2cL - \Delta/p)\bar{p}/p + \Delta^2\bar{p}/p^2.
\]

If Supplier 1 is revealed to have low costs, then in Stage 2 the OEM offers the menu \{(w_{2LH}^Q, f_{2LH}^Q), (w_{2LL}^Q, f_{2LL}^Q)\} to Supplier 2 where

\[
w_{2LL}^Q = c_L, \quad w_{2LH}^Q = c_L + \Delta/p, \\
f_{2LL}^Q = \Delta(a - 2cL - \Delta^2/p), \quad f_{2LH}^Q = -\Delta(a - 2cL)\bar{p}/p + \Delta^2\bar{p}/p^2.
\]

This equilibrium mechanism yields the expected profit for the OEM

\[
\Pi^Q = (a - 2cL)(a - 2cL - 4\Delta)/2 + \Delta^2/p + \Delta^2,
\]

the expected profit for Supplier \(i\), \(i = 1, 2\)

\[
\pi_i^Q = (a - 2cL)\bar{p}\Delta - \Delta^2\bar{p}/p - \bar{p}\Delta^2.
\]

Note that \(\pi_i^Q\) are the same for both suppliers. Also, by observing Propositions 3 and 4 one can immediately arrive at the following conclusion:

**Corollary 2.** The optimal simultaneous and sequential procurement mechanisms for assembly yield equal expected profits for the OEM as well as each supplier. In addition, the OEM and both suppliers are indifferent regarding the contracting sequence in sequential contracting.

The revenue equivalence of optimal simultaneous and sequential procurement mechanisms for assembly suggests that the OEMs do not need to worry about contracting timing in two-part tariff procurement mechanisms. Simultaneous and sequential contracting are revenue-equivalent because the two suppliers are decoupled when the OEM contracts with them on pricing first and postpones the input order quantity decisions until after information asymmetry is resolved.

Finally, we conclude the section by comparing the OEM and suppliers’ profits between the dynamic bargaining institution (Corollary 1 and Proposition 2) and the mechanism design institution (Propositions 3 and 4).

**Corollary 3 (Comparison between dynamic bargaining and mechanism design institutions).** Let \(a \geq \bar{a}\). The ex ante supply chain profits are the same under the dynamic bargaining institution and under the mechanism design institution. However, the OEM earns a higher profit under the mechanism design institution, while the suppliers earn a higher expected profit under the dynamic bargaining institution.
Recall that the contracting timing does not result in a profit difference for all parties under both institutions. This corollary further establishes that the ex ante supply chain profits do not differ under both institutions (although their distributions across the supply chain depend on the institution). In other words, both dynamic bargaining and optimal mechanism design can attain the same level of supply chain efficiency (distorted only by the necessary information rents). These observations will constitute our testable hypotheses in the next section.

4. Experimental Design

Our experiment consisted of a $2 \times 2$ between-subject design aimed to coincide with the four settings outlined in Section 3. The first factor manipulated the institution type: the OEM interacts with the two suppliers through a back-and-forth dynamic bargaining process or through the optimal screening mechanism. The second factor manipulated the timing of contracting between parties: the OEM contracts with suppliers simultaneously or sequentially. Overall the four treatments were (1) bargaining with simultaneous contracting (‘Barg-Sim’), (2) bargaining with sequential contracting (‘Barg-Seq’), (3) the mechanism design with simultaneous contracting (‘Mech-Sim’), and (4) the mechanism design with sequential contracting (‘Mech-Seq’). Each treatment included 72 participants for a total of 288 participants, depicted in Table 1.

In each treatment participants were first assigned a role of an OEM, Supplier 1, or Supplier 2, which remained fixed for the duration of the session. Nine participants comprised a single cohort. In each round, within a cohort, one of each role was randomly placed into a trio. All treatments consisted of eight rounds and used the following parameters: \( a = 75 \), \( c_L = 5 \), \( c_H = 15 \), \( p_L = \frac{1}{2} \), and \( p_H = \frac{1}{2} \). In order to prevent bounded rationality from driving results we automated the quantity decisions such that \( q = a - w_1 - w_2 \). Therefore, our primary focus is on the fixed fee and wholesale price contract terms between the OEM and each supplier. In addition, we provided all players with decision support where they could enter test values of fixed fees and wholesale prices and observe the profits for themselves and the other players in their trio. The experimental predictions for our design are given in Table 2.

\footnote{Due to a technical issue, one cohort of nine in Mech-Seq only completed six rounds.}

\footnote{When applicable, players would see the supplier’s profits for both \( c_L \) and \( c_H \).}

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**Table 2  Experimental Predictions**

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<tr>
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<td>1462.5</td>
<td>1462.5</td>
<td>1462.5</td>
<td>1462.5</td>
</tr>
<tr>
<td><strong>Ex Ante OEM Expected Profit</strong></td>
<td>370.83</td>
<td>370.83</td>
<td>1112.5</td>
<td>1112.5</td>
</tr>
<tr>
<td><strong>Ex Ante Supplier Expected Profit</strong></td>
<td>545.83</td>
<td>545.83</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td><strong>Wholesale Price Low ((w_L))</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Wholesale Price High ((w_H))</strong></td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>Fixed Fee Low ((f_L))</strong></td>
<td>720.83</td>
<td>720.83</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td><strong>Fixed Fee High ((f_H))</strong></td>
<td>20.83</td>
<td>20.83</td>
<td>-350</td>
<td>-350</td>
</tr>
</tbody>
</table>

Note: The Ex Ante Supply Chain Expected Profit is given by the Ex Ante OEM Expected Profit plus twice the Ex Ante Supplier Expected Profit.

Turning to the specifics of each treatment, in the two dynamic bargaining treatments, the parties engaged in a back-and-forth negotiation. To create this environment we employed a protocol similar to one that has been used in recent operations bargaining studies (Davis and Hyndman 2018, Davis and Leider 2018). Specifically, the parties were given a fixed amount of time to negotiate contract terms. During this time they could make as many offers as they would like, where each offer was comprised of a fixed fee and wholesale price. A receiving party could send feedback about the most recent offer they received by clicking a button and ‘rejecting’ either the fixed fee, the wholesale price, or both. This information would then be shown to the proposing party (note that the receiving party could still accept the offer, so long as it was still the most recent offer received). Overall, this protocol mimicked a more natural bargaining process while allowing us to observe specific bargaining dynamics pertaining to offers and feedback.

In the Barg-Sim condition the OEM bargained with Supplier 1 and Supplier 2 simultaneously (six minutes in rounds 1-2 and four minutes in rounds 3-8). The OEM could make a fixed fee and wholesale price offer to Supplier 1 and/or a separate fixed fee and wholesale price to Supplier 2. Each supplier could also make their own offers to the OEM. Each supplier could not see the negotiation details taking place between the OEM and the other supplier. If a supplier chose to accept an offer or the OEM chose to accept an offer from a specific supplier, then an agreement was made between those two parties, and the OEM and remaining supplier continued to negotiate. If the OEM came to an agreement with both suppliers in the allotted time then all three parties earned their profits, otherwise the trio earned a profit of zero. The Barg-Seq treatment was identical except that in each round the OEM first bargained only with Supplier 1 (four minutes in rounds 1-2 and 2.5 minutes in rounds 3-8). If they came to an agreement then the OEM and Supplier 2 bargained. During this latter negotiation, consistent with our sub-coalition assumption, Supplier 1 could observe the offers made between the OEM and Supplier 2, provide feedback on offers, and make their own contract suggestions to the OEM (but could not directly make proposals to
Supplier 1). If all three parties agreed on a specific offer then they earned their respective profits, otherwise they earned a profit of zero.

In the Mech-Sim condition, each round began with the OEM making a take-it-or-leave-it offer of two sets of fixed fees and wholesale prices to both suppliers simultaneously. Each supplier then chose to accept one of the two sets of contract terms or reject both. If either supplier chose to reject then all three players in the trio earned a profit of zero, otherwise they earned their respective profits. The Mech-Seq treatment was identical except that decisions were made sequentially: the OEM first made a set of contract offers to Supplier 1, Supplier 1 then made their decision to accept one of the two sets of offers or reject both, if Supplier 1 accepted an offer then the OEM made a set of offers to Supplier 2, and Supplier 2 then made their accept/reject decision.

The experiment was designed using z-Tree (Fischbacher 2007) and took place at a large northeast university. Sessions took between 60 and 90 minutes, with average earnings of $24.68. Subjects were compensated for all rounds.

4.1. Hypotheses

With this experimental design we will compare our experimental results directly to the point predictions outlined in Table 2. In addition, we will also formally test the following experimental hypotheses, which parallel a number of our normative theoretical results from Section 3:

**Hypothesis 1.** The frequency of agreements in all four settings is 100%.

**Hypothesis 2.** For both the dynamic bargaining and mechanism design institutions, earnings for specific parties do not differ whether contract timing is simultaneous or sequential.

**Hypothesis 3.** The OEM earns more and suppliers earn less in the mechanism design institution than in the dynamic bargaining institution.

**Hypothesis 4.** The OEM sets screening contracts in the two mechanism design treatments.

5. Experimental Results

We present our experimental results in three subsections. First, we focus on outcomes pertaining to agreement rates, total supply chain profit, and distribution of profits (i.e., Hypotheses 1-3). Second, we examine specific decisions relating to screening, signaling, and contracts, and thus conclude on Hypothesis 4. Third, we evaluate the drivers of agreements and disagreements between parties.

Unless otherwise noted, all hypothesis tests are $t$-tests where a single cohort of nine participants represents an independent observation, and regressions are run with random effects and clustered standard errors at the cohort level. While there were some dynamics over time in our data, the details of which can be found in online Appendix B, they do not affect our primary results, hence we include all decisions in our analysis (no observations are removed).
Table 3  Agreement Rates

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Agreement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barg-Sim</td>
<td>77.08</td>
</tr>
<tr>
<td>Barg-Seq</td>
<td>65.10</td>
</tr>
<tr>
<td>Mech-Sim</td>
<td>79.03</td>
</tr>
<tr>
<td>Mech-Seq</td>
<td>77.96</td>
</tr>
</tbody>
</table>

5.1. Outcomes

Table 3 illustrates the observed agreement rates for all treatments. In the Barg-Seq treatment, 65.10% of the time an agreement is made, while in the other treatments the frequency of agreement is between 77.08% and 79.03%. While we will explore drivers of agreements later, one reason for the difference between the Barg-Seq treatment and other three settings is the negotiation between the OEM and Supplier 2. In particular, the OEM and Supplier 1 reach an agreement 84.9% of the time, while, conditional on an agreement between the OEM and Supplier 1, the OEM and Supplier 2 reach an agreement only 76.4% of the time (difference is statistically significant at $p = 0.049$). In general, the lack of 100% agreements may suggest that a behavioral bias may be affecting outcomes, which we will discuss in Section 6. Nevertheless, we have our first result:

**Result 1** *In contrast to Hypothesis 1, the frequency of agreements is significantly less than 100% ($p < 0.01$). Moreover, agreements are significantly less likely in the sequential dynamic bargaining environment ($p < 0.01$).*

We now turn our attention to profits, conditional on agreement, which are found in Table 4. First, concerning total supply chain profit in Table 4a, we see that for both the dynamic bargaining and the mechanism design institution, total supply chain profit is higher under sequential contracting than simultaneous contracting. Looking at each bargaining institution separately, the difference is nearly statistically significant between sequential and simultaneous contracting (mechanism $p = 0.099$, bargaining $p = 0.153$). However, pooling over institutions allows one to conclude that sequential contracting leads to significantly higher supply chain profit than simultaneously contracting (1450.06 versus 1384.00, $p = 0.025$).

In addition to the supply chain profit difference between the simultaneous and sequential environments, there are also some differences with respect to the distribution of profits between parties. First, in Table 4b, OEMs benefit, earning 14.93% more in profits, from sequential contracting under the mechanism design institution (639.71 versus 556.61, $p = 0.077$) and 15.70% more when pooled across institutions (574.85 versus 496.84, $p = 0.081$). For suppliers, the order of negotiating with the OEM matters. In particular, Supplier 1 earns 11.57% more when in the sequential setting
Table 4  Profit Results (Conditional on Agreement)

<table>
<thead>
<tr>
<th></th>
<th>(a) Supply Chain Profit</th>
<th>(b) OEM Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sim</td>
<td>Seq</td>
</tr>
<tr>
<td>Barg</td>
<td>1394.66</td>
<td>1453.05</td>
</tr>
<tr>
<td>Mech</td>
<td>1373.26</td>
<td>1447.48</td>
</tr>
<tr>
<td>Pooled</td>
<td>1384.00</td>
<td>1450.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>(c) Supplier 1 Profit</th>
<th>(d) Supplier 2 Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sim</td>
<td>Seq</td>
</tr>
<tr>
<td>Barg</td>
<td>478.59</td>
<td>572.80</td>
</tr>
<tr>
<td>Mech</td>
<td>408.32</td>
<td>427.78</td>
</tr>
<tr>
<td>Pooled</td>
<td>443.58</td>
<td>494.92</td>
</tr>
</tbody>
</table>

(Table 4c, 494.92 versus 443.58, \( p = 0.061 \)), while Supplier 2 earns 16.64% more in the simultaneous setting (Table 4d, 443.58 versus 380.29, \( p = 0.027 \)). Thus we have the following result:

**Result 2** *In contrast to Hypothesis 2, conditional on reaching an agreement, sequential contracting yields significantly higher OEM profit under the mechanism design institution. Pooling across institutions, sequential contracting leads to higher OEM profit, supply chain profit, and Supplier 1 profit, than simultaneous contracting.*

We now turn to Hypothesis 3, which posits that OEMs – due to their greater bargaining power – earn more and suppliers earn less under the mechanism design institution, compared to the dynamic bargaining institution. Table 4b shows that OEMs do indeed earn more under the mechanism design institution (597.88 versus 465.93, \( p = 0.001 \)). However, the difference in actual OEM earnings between these two institutions is smaller than the normative predictions of 1112.50 for the mechanism design and 370.83 for the bargaining institution. This suggests that OEMs do not fully exploit their bargaining power in the mechanism design setting. We also note that the total supplier payoff (i.e., the sum of the two suppliers’ earnings) is significantly lower under the mechanism design institution compared to the dynamic bargaining institution (\( p = 0.002 \)). However, again, the difference is less than theory predicts because suppliers extract considerably more than the theoretical prediction of 175.00 in the mechanism design setting. These results are qualitatively consistent with social preferences, which we will explore later. Thus we have:

**Result 3** *Consistent with Hypothesis 3, OEMs earn significantly more and suppliers earn significantly less under the mechanism design than the dynamic bargaining institution. However, compared to theory, OEMs do not fully exploit their bargaining power under the mechanism design institution.*
Figure 1  The Frequency of Contract Types under the Mechanism Design Institution (in %)

Note: In the sequential contracting treatments, we compute whether offers are separating or pooling under the assumption that the other supplier type receives the same set of proposals.

5.2. Screening, Signaling, and Contracts

Our previous results show that, in terms of supply chain profit, actual profits are close to the theoretical prediction in the mechanism design setting (1373.26 in Mech-Sim and 1447.48 in Mech-Seq, versus predictions of 1462.50). However, this does not guarantee that the OEM’s proposals are consistent with the theoretically predicted screening offers; i.e., one contract for a low-cost supplier and the other contract for a high-cost supplier.\(^\text{4}\) We consider this in Figure 1, which shows the frequencies that the menu of contracts separated suppliers by their type, induced pooling (in which both supplier cost types preferred the same contract) or was neither separating nor pooling.

One can see that between 69.35\% and 80.11\% of contract menus offered by OEMs should induce pooling by suppliers on the same contract, while only between 16.13\% and 22.54\% of menus successfully separate the high and low cost suppliers. However, it is not generally the case that OEMs explicitly try to make a pooling offer by setting the wholesale price to be the same in each of their proposals. Indeed, between 81\% and 89\% of the proposals, the wholesale prices differed.\(^\text{5}\)

In the dynamic bargaining institution, the OEM cannot offer a menu of contracts, which makes screening difficult. However, it may attempt to achieve some kind of temporal screening by proposing \(w < 15\) early in the bargaining period with the idea that high-cost suppliers will be more willing to hold out for a wholesale price \(w' \geq 15\) than low-cost suppliers. Therefore, we can look at initial

\(^{4}\) Indeed, the optimal pooling contract, which consists of a wholesale price of 15 and a fixed payment of 0, yields the same expected supply chain profit but it does so at a higher total cost to the OEM; high cost suppliers still earn their reservation profit of 0, while low cost suppliers earn more than under the optimal screening contract.

\(^{5}\) Let \(\bar{w} = \max\{w_A, w_B\}\) and \(\underline{w} = \min\{w_A, w_B\}\). It is interesting to note that of the 81-89\% of menu proposals in which \(\bar{w} > \underline{w}\), less than 50\% of these offers are such that \(\underline{w} < 15 \leq \bar{w}\). This may suggest that the OEMs did not fully understand how to separate suppliers by their cost type.
Table 5  Initial Offers By OEM and Supplier Cost Type in the Dynamic Bargaining Institution

<table>
<thead>
<tr>
<th>Player Making Offer</th>
<th>Wholesale Price</th>
<th>Fixed Payment</th>
<th>% w &lt; 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEM</td>
<td>12.67</td>
<td>21.08</td>
<td>58.73</td>
</tr>
<tr>
<td>Low Cost Supplier</td>
<td>22.82</td>
<td>335.59</td>
<td>12.87</td>
</tr>
<tr>
<td>High Cost Supplier</td>
<td>26.06</td>
<td>334.52</td>
<td>1.69</td>
</tr>
</tbody>
</table>

(b) Barg-Seq

<table>
<thead>
<tr>
<th>Player Making Offer</th>
<th>Wholesale Price</th>
<th>Fixed Payment</th>
<th>% w &lt; 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEM to Supplier 1</td>
<td>14.69</td>
<td>100.58</td>
<td>41.27</td>
</tr>
<tr>
<td>Low Cost Supplier 1</td>
<td>22.97</td>
<td>237.37</td>
<td>9.68</td>
</tr>
<tr>
<td>High Cost Supplier 1</td>
<td>25.96</td>
<td>270.60</td>
<td>1.10</td>
</tr>
<tr>
<td>OEM to Supplier 2</td>
<td>13.47</td>
<td>34.26</td>
<td>51.57</td>
</tr>
<tr>
<td>Low Cost Supplier 2</td>
<td>20.09</td>
<td>220.92</td>
<td>13.92</td>
</tr>
<tr>
<td>High Cost Supplier 2</td>
<td>24.17</td>
<td>278.13</td>
<td>3.75</td>
</tr>
</tbody>
</table>

offers by the OEM. Additionally, we can also look at initial offers of suppliers by cost type in order to see if they signal their type with their initial offer. The results of this analysis are in Table 5.

As can be seen, the average OEM initial wholesale price offer is always below 15 and between 41.27% and 58.73% of initial OEM wholesale price offers are below 15, which suggests that many OEMs do attempt to screen between low and high-cost suppliers. For suppliers, the average initial wholesale price offer is always higher than 15, where high-cost suppliers' initial offers are higher than low-cost suppliers'. Moreover, a small but non-negligible fraction of initial offers by low-cost suppliers, 9.68% to 12.87%, are for wholesale prices \( w < 15 \), which should be a strong signal that the supplier has a low cost, while high-cost suppliers almost never propose an initial wholesale price less than 15 (1.10% to 3.75%). This suggests that there is some attempt at screening by OEMs and signaling by low-cost suppliers but it is by no means the dominant behavior.

A slightly different perspective on screening in the bargaining institution can be seen in Figure 2, which shows a histogram of the time remaining at which OEMs’ wholesale price offers to a supplier is 15 or higher. As one can observe, there is a great deal of variation and nearly 15% of the time OEMs never propose a wholesale price of 15 or higher. However, we also see a large mass over the first 30 seconds of bargaining in which OEMs propose a wholesale price of 15 or higher. Consistent with Table 5, this suggests that there is a great deal of heterogeneity in OEMs’ willingness to engage in temporal screening.

Finally, having considered OEM proposals in the mechanism institution and initial offers in the bargaining institution, we are ready to look at agreed contract parameters by supplier cost

\[^6\] There are a few instances in which an OEM never proposes a wholesale price of 15 or higher but they accepted such a wholesale price offer made by a supplier. In these instances, we take the time when such an offer was accepted.
to determine how successful the limited attempts at screening/signaling are. This information is contained in Table 6. For the wholesale price, the predicted difference between the high and low cost supplier is 20 ($w_L = 5$ and $w_H = 25$), yet, the average difference is never more than 3. Similarly, for the fixed payment, the predicted difference is 700 (with the low cost supplier receiving the higher fixed payment), yet again, the average difference is never more than 60. Further, in the Barg-Seq treatment the high-cost supplier receives, on average, a higher fixed payment. Therefore, the bargaining institution is no more effective at separating low and high cost suppliers. Of course, given the similarity in contract parameters, low cost suppliers earn more than twice as much as high cost suppliers (584.51 vs. 247.40; $p < 0.01$). We can summarize this discussion with the following:

**Result 4** Contrary to Hypothesis 4, OEMs engage in limited attempts to screen between high- and low-cost suppliers. Consequently, the difference in agreed contract parameters between the two supplier types is small in comparison to the theoretical predictions and closer to a pooling equilibrium.

5.3. The Drivers of Agreement

We now seek to understand the drivers of agreement and disagreement in our experiment. In Table 7 we present logit regressions with random effects where the dependent variable is whether an
agreement was made in the two dynamic bargaining treatments. The independent variables represent the difference in final contract terms proposed between the OEM and supplier and whether the supplier is high cost. Unsurprisingly, negotiating with a high cost supplier decreases the chance of coming to an agreement, whereas the smaller the difference in final offers between the two parties leads to a higher chance of coming to an agreement. However, this difference is not always significant with respect to wholesale prices. Rather, the difference in fixed payments appears to be a key aspect of coming to an agreement.

While not depicted, we conducted a similar set of logit regressions for whether an OEM contract offer was accepted by a supplier in the two mechanism design treatments. We find once again the likelihood of coming to an agreement is lower when the supplier has a high cost. We also observe that agreements are weakly increasing in both wholesale prices and fixed payments offered by the OEM. Thus we have:

Result 5 In the dynamic bargaining institution, agreements are more likely the closer final offers are between the OEM and suppliers. Under the mechanism design institution, agreement rates are increasing in the wholesale prices and fixed payments offered by the OEM. In all treatments, disagreement is more likely to occur when negotiating with a high-cost supplier.

Recall that agreement rates were significantly lower in the Barg-Seq treatment compared to the remaining three treatments (Table 3). One clue to explain this result can be seen in Tables 4c and 4d, which show that in both the Barg-Seq and Mech-Seq treatments Supplier 1 earned significantly more than Supplier 2. This suggests that OEM’s may have taken a strategy of “going easy” on Supplier 1 in order to ensure the possibility of an ultimate agreement and then trying to “squeeze” Supplier 2. If true, we should expect significantly fewer agreements between the OEM and Supplier 2 (conditional on an agreement between the OEM and Supplier 1) than between the OEM and Supplier 1. Indeed, this is true. In Barg-Seq the relevant agreement rates are 76.5% and 84.9%,
Table 8  Offers Received By the Supplier 1 and Supplier 1 in the Sequential Setting

(a) Mech-Seq

<table>
<thead>
<tr>
<th>Supplier</th>
<th>$w$</th>
<th>$F_w$</th>
<th>$\bar{w}$</th>
<th>$F_{\bar{w}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.83</td>
<td>180.78</td>
<td>18.99</td>
<td>53.58</td>
</tr>
<tr>
<td>2</td>
<td>11.21</td>
<td>168.19</td>
<td>16.70</td>
<td>23.36</td>
</tr>
<tr>
<td>$p-$value</td>
<td>0.012</td>
<td>0.584</td>
<td>0.004</td>
<td>0.324</td>
</tr>
</tbody>
</table>

(b) Barg-Seq (Final Offers)

<table>
<thead>
<tr>
<th>Supplier</th>
<th>By OEM</th>
<th>By Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>$F$</td>
<td>$w$</td>
</tr>
<tr>
<td>1</td>
<td>16.94</td>
<td>136.64</td>
</tr>
<tr>
<td>2</td>
<td>15.43</td>
<td>71.79</td>
</tr>
<tr>
<td>$p-$value</td>
<td>0.035</td>
<td>0.185</td>
</tr>
</tbody>
</table>

Note: $w$ is the lesser of the two wholesale price offers, while $F_w$ is the fixed payment associated with this wholesale price offer. $\bar{w}$ is the higher of the two wholesale price offers while $F_{\bar{w}}$ is the fixed payment associated with this wholesale price offer.

which are significantly different ($p = 0.049$). Similarly, in Mech-Seq the relevant agreement rates are 83.2% and 93.9%, which are significantly different ($p < 0.01$).

To complete this argument, we need to show that Supplier 2 receives worse offers than Supplier 1. In Table 8a, which shows the offers made by the OEM in the Mech-Seq treatment (organized by lower vs. higher wholesale price), we see that the OEMs offer consistently lower wholesale prices to Supplier 2 than Supplier 1 ($p < 0.012$). They also offer lower fixed payments to Supplier 2 but the difference is not statistically significant. Table 8b depicts a similar picture for the Barg-Seq treatment, where we report average final offers by the OEM and suppliers. The OEM’s final offer involves a significantly lower wholesale price to Supplier 2 than Supplier 1 ($p = 0.035$); the fixed payment is lower too, but as with Mech-Seq, the difference is not statistically significant. It also appears that, through the bargaining process, Supplier 2 demands a significantly lower wholesale price than Supplier 1 ($p = 0.043$) and a smaller, but not significantly so, fixed payment. Thus:

**Result 6** In the Barg-Seq and Mech-Seq treatments, Supplier 2 receives significantly worse offers than Supplier 1. This explains why Supplier 2 earns less than Supplier 1 and why disagreements are more likely to arise between the OEM and Supplier 2.

### 6. Behavioral Drivers and Discussion

We have observed a number of experimental results which deviate from our normative predictions. This suggests that one or more behavioral biases may be influencing decisions. One that we believe is a key driver of our data is social preferences – in particular, fairness (Fehr and Schmidt 1999, Bolton and Ockenfels 2000). To support this claim, first, observe that agreements were well below
Figure 3  **Predicted and Observed Absolute Difference in Average Profits Between the OEM and Suppliers**

(a) Bargaining

(b) Mechanism Design

100% in all four treatments. Further, it is likely that a large portion of those rejected offers (over 65% of all rejected offers in the Mechanism treatments and 100% of rejected offers in the Bargaining treatments) would lead to positive profits. Combined with the fact that all players earned an outside option profit of zero in the case of disagreement, this strongly suggests that responders may have been concerned with something more than simply maximizing expected profits.

In addition to the prevalence of disagreements, the observed distribution of profits between the OEM and suppliers were more equitable than theory predicts. Figures 3a and 3b depict the predicted and observed absolute difference in ex-ante expected profits between the OEM and suppliers. One can see that in the dynamic bargaining treatments, the normative prediction is a difference of 175.00 between the OEM and suppliers, whereas the observed differences in average profits were 41.11 in Barg-Sim and 22.91 in Barg-Seq. Under the mechanism design institution earnings were even more equitable relative to the normative theory. In particular, the normative theory predicts a difference of 937.50, whereas we observed differences of only 148.29 in Mech-Sim and 235.82 in Mech-Seq in average profits.

It is interesting to note that while the distribution of profits between the parties was more equal than theory predicts, this did not appear to come at a cost of decreased efficiency. Specifically, the theoretical prediction for the ex-ante supply chain expected profit in all four treatments is 1462.50. The fraction of this total that was earned in each treatment was (see Table 4a): 95.36% in Barg-Sim (1394.66), 99.35% in Barg-Seq (1453.05), 93.90% in Mech-Sim (1373.26), and 98.97% in Mech-Seq (1447.48). This follows for two reasons. First, a pooling contract with a wholesale price

7It is difficult to say that they definitely would have led to positive expected profits because, from a supplier’s perspective, she must form beliefs about the agreement between the OEM and the other supplier. The numbers reported in the text are valid under the assumption that the other supplier gets the same contract/menu of contracts as proposed.
of 15, regardless of cost, achieves the same expected surplus as in the optimal separating contract. Second, as we showed in Figure 1, rather than propose separating contracts, OEMs set pooling contracts a vast majority of the time: 69.35% in Mech-Sim, 80.11% to Supplier 1 in Mech-Seq, and 73.99% to Supplier 2 in Mech-Seq. Table 6 also showed that there was little actual separation between low- and high-cost suppliers. A key difference between separating and pooling contracts in our case is that the distribution of surplus is more equitable. This is further evidence that fairness matters in both the bargaining and mechanism settings.

While fairness/inequality aversion appear to provide a convincing explanation for deviations from theoretical predictions within a treatment, it is not clear that they, alone, can explain the difference between the simultaneous and sequential contracting protocols. Indeed, if (due to fairness concerns) the parties implement a pooling contract, there should be no difference between simultaneous and sequential contracting. As we noted, in the sequential setting, it appears that the OEM was eager to secure an agreement, even if it meant giving up more with Supplier 1, and then appeared to try to “squeeze” Supplier 2. In our study, if Supplier 2 erroneously believes that she is getting the same contract terms as Supplier 1, then she may be more likely to accept because then she expects to earn the same as Supplier 1 (which she considers to be a fair outcome). The net result is to break the equivalence between simultaneous and sequential protocols, making the sequential protocol more attractive to the OEM and Supplier 1.

In summary, while other biases may be present, we believe that the rejection of contract offers, earnings that are more equitable than theory predicts, total supply chain profits that are similar to the normative predictions, and OEMs making pooling offers, are all evidence of fairness being a key driver for our data. Lastly, fairness combined with mis-perceptions by Supplier 2 about Supplier 1’s agreement, can also explain the non-equivalence between simultaneous and sequential contracting.

7. Conclusion

In this study we investigate a setting with a single OEM who must procure two distinct components from two suppliers, who have private costs, in order to assemble a product. The OEM has two options in how to contract with these suppliers, simultaneously or sequentially. We also consider

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8 This is similar to a result in Ho et al. (2014), where a second retailer receives a lower profit than a first retailer (with a single supplier).

9 We have abstained from providing a more structural analysis of fairness because it is not at all clear how such a model would look since we have three players and private information. Several questions would have to be resolved: (1) How do players, in particular, evaluate inequality with respect to the OEM and/or the other supplier? (2) Are players concerned with ex ante, ex interim (i.e., after suppliers learn their cost) or ex post inequality? This would be an interesting avenue for future work but one that we believe is beyond the scope of our study.
two bargaining institutions for the OEM: first, that the OEM and its suppliers have relatively equal bargaining power and engage in a natural back-and-forth dynamic bargaining process, and second, that the OEM has substantial bargaining power and can make ultimatum offers to its suppliers.

We begin by examining these settings from a theoretical perspective. We show that for an OEM that has similar bargaining power as its suppliers, and will likely engage in a back-and-forth negotiation, in equilibrium, the expected profits of the respective parties are the same regardless of whether the OEM bargains with the suppliers simultaneously or sequentially. Similarly, even when the OEM has considerable bargaining power and can make ultimatum offers to its suppliers, once again, the expected profits of the parties are the same depending on whether the OEM makes offers simultaneously or sequentially.

After deriving theoretical predictions as to how an OEM and its suppliers should make decisions under the assumption of risk-neutral expected-profit maximizers, we then test these predictions through a controlled human-subjects experiment. We conduct this step because human decision-makers are involved in most contracting decisions, and may be susceptible to various behavioral biases that alter decisions and outcomes. Indeed, after administering our experiment we observe a number of observations that deviate from our normative predictions.

A few of the key managerial implications from our experiment are that: (1) conditional on agreement, an OEM with considerable bargaining power earns a higher profit by sequentially making contract offers to the suppliers; (2) an OEM with relatively equal bargaining power with its suppliers should prefer negotiating with suppliers simultaneously because the increased likelihood of agreement more than compensates for any advantage of sequential contracting (conditional on an agreement); (3) an OEM that is unsure of its bargaining power over specific suppliers (i.e. pooling over bargaining institutions), will earn a higher expected profit by adopting a sequential approach.

Aside from these main managerial insights, we also show that OEMs do not propose screening contracts and instead opt for simpler pooling contracts. In our setting, the preference for pooling contracts is generally disadvantageous to OEMs but there is no overall efficiency loss in using them. It would be interesting to see if pooling contracts continue to be used even when they are inefficient. We also observe that decision makers appear to be influenced by fairness concerns, leading to more equitable splits of earnings between parties. This last result is particularly important in that fair outcomes may engender more collaborative relationships between parties, which in turn may lead to further long-term benefits.
We believe our study is the first in the operations management literature to theoretically and experimentally investigate assembly supply chains with three players, alternative bargaining institutions, and asymmetric information. However, one limitation of our study relates to our assumption of a sub-coalition forming between the OEM and the first supplier prior to negotiating with the second supplier. While we believe that an OEM and first supplier may reach an agreement which depends on the subsequent negotiation between the OEM and second supplier, we admit that this assumption may not always be valid. A second limitation is that we assumed that the suppliers were symmetric. For example, while Apple likely has considerable power over many of its component suppliers, its relationship with Samsung is almost surely more balanced as it is a leading supplier of several key components. Investigating a setting where an OEM has bargaining power over one supplier but not another might be an exciting, and challenging, avenue for future work.

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References


Appendix

A. Proofs

For the results whose derivation is complete in the main paper, we do not repeat the proof here for brevity. For the derivation of results in Section 3.2, we refer the reader to Hu and Qi (2017).

Proof of Proposition 1: We complete the derivation of the bargaining solutions as follows. Recall that $P_{iX}$ denotes the expected payment to Supplier $i$ when her type is $X$, and also $a$ is sufficiently large so the procurement quantities are non-negative. We first solve for the scenario in which $\lambda_i \in (p, 1)$. To obtain the value of the two coefficients $\lambda_i$ as well as the four expected payments $P_{iX}$, we have a system of six equations with six variables: the first four equations are from equating the profit of suppliers of each type to the corresponding warranted claim, and the last two equations are from the binding IC constraints since $\lambda_i \in (p, 1)$.

\[
\begin{align*}
    P_{1L} - c_L(a - 2c_L) + c_L \Delta \lambda_2 &= W^*_{1L}, \\
    P_{1H} - c_H \left( a - c_H - \frac{(\lambda_1 - p)\Delta}{p} - c_L \right) + c_H \Delta \lambda_2 &= W^*_{1H}, \\
    P_{2L} - c_L(a - 2c_L) + c_L \Delta \lambda_1 &= W^*_{2L}, \\
    P_{2H} - c_H \left( a - c_H - \frac{(\lambda_2 - p)\Delta}{p} - c_L \right) + c_H \Delta \lambda_1 &= W^*_{2H}, \\
    P_{1L} - c_L(a - 2c_L) &= P_{1H} - c_L \left( a - c_H - \frac{(\lambda_1 - p)\Delta}{p} - c_L \right), \\
    P_{2L} - c_L(a - 2c_L) &= P_{2H} - c_L \left( a - c_H - \frac{(\lambda_2 - p)\Delta}{p} - c_L \right).
\end{align*}
\]
Thus we obtain the following solutions on \( \lambda_i \)'s and \( P^*_i \)'s.

\[
\begin{align*}
\lambda_1 &= \lambda_2 = \frac{4p(a - 2c_L)}{(5 + 4p)\Delta}, \\
P^*_{1L} &= P^*_{2L} = \frac{a^2 (25 + 16p - 16p^2) + 2ac_L (32p^2 + 28p + 25) - 8c_L^2 (8p^2 + 22p + 25)}{6(5 + 4p)^2}, \\
P^*_{1H} &= P^*_{2H} = \frac{a^2 (25 + 16p - 16p^2) + 2ac_L (32p^2 - 20p - 35) - 8c_L^2 (8p^2 - 2p - 5)}{6(5 + 4p)^2}.
\end{align*}
\]

Defining the following critical values, where \( \bar{\pi} \geq a \):

\[
\begin{align*}
\bar{\pi} &= 2c_L + \frac{(5 + 4p)\Delta}{4p}, \\
a &= 2c_L + \frac{(5 + 4p)\Delta}{4},
\end{align*}
\]

we note that when \( a < a < \bar{a} \), we have \( \lambda_1^* = \lambda_2^* = \frac{4p(a - 2c_L)}{(5 + 4p)\Delta} \in (p, 1) \).

To complete the analysis, we need to consider two more scenarios: \( a \leq a \) and \( a \geq a \). We focus on the symmetric solutions where \( \lambda_1 = \lambda_2 \) and \( P_{1X} = P_{2X} \) due to the \textit{ex ante} symmetry of the two suppliers.

\textbf{Scenario 1}. When \( a \leq a \), we have \( \lambda = p \). In this case, the dual variable \( \alpha^* = 0 \). We have the conditional expected total virtual utility as

\[
\Delta_L = \frac{p}{2} (a - c_L - c_H)^2 + \frac{\bar{p}}{2} (a - 2c_L)^2, \quad \Delta_H = \frac{p}{2} (a - 2c_H)^2 + \frac{\bar{p}}{2} (a - c_H - c_L)^2.
\]

We next solve for the warranted claims:

\[
W^*_L = \frac{\Delta_L}{3}, \quad W^*_H = \frac{\Delta_H}{3}.
\]

Then we have the expected payments to each type of the supplier as

\[
\begin{align*}
P^*_{1L} &= c_L(a - 2c_L) - c_L \Delta p + \frac{p}{6} (a - c_L - c_H)^2 + \frac{\bar{p}}{6} (a - 2c_L)^2, \\
P^*_{1H} &= c_H(a - c_H - c_L) - c_H \Delta p + \frac{p}{6} (a - 2c_H)^2 + \frac{\bar{p}}{6} (a - c_H - c_L)^2.
\end{align*}
\]

We can verify the IC constraints for suppliers of \( L \) types are non-binding, i.e.,

\[
P^*_{1L} - c_L(a - 2c_L) > P^*_{1H} - c_L (a - c_H - c_L).
\]

It can also be verified that under the assumption of \( a \) being sufficiently large that the sourcing quantities are positive, the IC constraints for suppliers of \( H \) type are not binding either. Therefore, we have obtained the bargaining solution in this case.

\textbf{Scenario 2}. When \( a \geq \bar{\pi} \), we have \( \lambda = 1 \). In this case, the dual variable \( \alpha^* = \bar{p} > 0 \). We have the conditional expected total virtual utility as

\[
\Delta_L = \frac{p}{2} \left( a - c_L - c_H - \frac{\bar{p}\Delta}{p} \right)^2 + \frac{\bar{p}}{2} \left( a - 2c_L \right)^2, \quad \Delta_H = \frac{p}{2} \left( a - 2c_H - \frac{2\bar{p}\Delta}{p} \right)^2 + \frac{\bar{p}}{2} \left( a - c_H - \frac{\bar{p}\Delta}{p} - c_L \right)^2.
\]

We next solve for the warranted claim:

\[
W^*_L = \frac{\Delta_L}{3}, \quad W^*_H = \frac{p\Delta_H}{3} + \frac{\bar{p}\Delta_L}{3}.
\]
Then we have

\[ P_L - c_L (a - 2c_L) + c_L \Delta \geq W_L^*, \]
\[ P_H - c_H \left( a - c_H - \frac{\bar{p}\Delta}{p} - c_L \right) + c_H \Delta = W_H^*, \]
together with the binding IC constraint

\[ P_L - c_L (a - 2c_L) = P_H - c_L \left( a - c_H - \frac{\bar{p}\Delta}{p} - c_L \right). \]

So we have

\[ P_L^* = \frac{a^2 + 2ac_H p + 2c_H c_L (4 - p) - 4c_H^2 (1 + p) - 2c_L^2 (2 + p)}{6p}, \]
\[ P_H^* = \frac{a^2 + 2ac_H p + 2c_H c_L (1 - p) - 4c_H^2 (1 + p) + 2c_L^2 (1 - p)}{6p}. \]

To verify this is indeed the bargaining solution, we consider \( \bar{\lambda} = \epsilon \), and show that the OEM and suppliers' profits are greater than the limiting warranted claim as \( \epsilon \to 0 \). We have the conditional expected total virtual utility when \( \bar{\lambda} = \epsilon \) as follows.

\[ \Delta_L (\epsilon) = \frac{p}{2} \left[ a - c_L - c_H - \frac{(\bar{p} - \epsilon) \Delta}{p} \right]^2 + \frac{\bar{p}}{2} \left[ a - 2c_L \right]^2, \]
\[ \Delta_H (\epsilon) = \frac{p}{2} \left[ a - 2c_H - \frac{2(\bar{p} - \epsilon) \Delta}{p} \right]^2 + \frac{\bar{p}}{2} \left[ a - c_H - \frac{(\bar{p} - \epsilon) \Delta}{p} - c_L \right]^2. \]

We note that the warranted claims for the suppliers and the OEM are as follows.

\[ W_L^* (\epsilon) = \frac{\Delta_L (\epsilon)}{3}, \quad W_H^* (\epsilon) = \frac{\bar{p} \Delta_H (\epsilon)}{3 (1 - \epsilon)} + \frac{\bar{p} - \epsilon}{1 - \epsilon} \Delta_L (\epsilon) \]
\[ = \frac{\bar{p} \Delta_L (\epsilon) + p \Delta_H (\epsilon)}{3}. \]

We note that

\[ \lim_{\epsilon \to 0} W_L^* (\epsilon) = W_L^*, \quad \lim_{\epsilon \to 0} W_H^* (\epsilon) = W_H^*, \quad \lim_{\epsilon \to 0} W_O^* (\epsilon) = \frac{\bar{p} \Delta_L + p \Delta_H}{3}. \]

The profits of the suppliers of each type and the OEM are greater than or equal to their respective limiting warranted claims. Then we have obtained the bargaining solution in this case.

\[ \square \]

B. Experimental Dynamics

Given the richness of our experiment, it is plausible that players learn over time and modify their strategy in one way or another. For example, OEMs may learn to more fully exploit their bargaining power in the mechanism environment or players may, jointly, agree to terms which increase the efficiency of the supply chain. Figure B.1 shows the evolution of total supply chain profit (panel (a)), variable procurement costs (panel (b)) and fixed procurement costs (panel (c)), conditional on agreement. As can be seen, in all treatments the total supply chain profit is increasing over time, though it does not change our earlier result that the sequential mechanism generates higher supply chain profit.

As panel (b) shows, the increase in supply chain profit is largely driven by the fact that variable costs decline over time in three of four treatments.\(^\text{10}\) Given that supply chain profit is increasing and variable costs

\(^\text{10}\) In Barg-Seq, supply chain profit appears to increase over time (panel (a)) even though variable procurement costs increase over time (panel (b)). Instead, the increase in supply chain profit over time appears to be driven by the fact that the total cost of suppliers is below average in later periods. Indeed, in a random effects regression of supply chain profit on period, as well as dummies for total supplier costs, the effect of period is actually significantly negative in Barg-Seq \( (p = 0.017) \). In all other treatments, even controlling for supplier costs, the effect of period is positive and (at least weakly) significant (Barg-Sim: \( p = 0.065 \); Mech-Seq: \( p = 0.004 \); Mech-Sim: \( p = 0.022 \)).
are declining, without changes in the fixed payment, this would indicate that OEM profit should increase and supplier profit should decrease over time. However, as panel (c) shows, in three treatments total fixed costs are increasing. Therefore, we cannot immediately conclude that OEM profit increases and supplier profit decreases over time.

Figure B.2 addresses the question of OEM and supplier earnings over time, conditional on agreement. As can be seen in panel (a), in three treatments OEM profits are increasing while in the Barg-Seq treatment they are relatively flat. On the other hand, as panel (b) shows, only in the Barg-Seq treatment do supplier profits increase, while in the two mechanism design settings profits actually decline slightly and in Barg-Sim, profits are flat. The fact that OEM profits increase and supplier profits decrease in the mechanism setting is consistent with OEMs learning to more fully exploit their bargaining power. In contrast, the dynamics in the Barg-Seq treatment suggest that the distribution of earnings is becoming more equitable, while there is no clear interpretation for dynamics in the Barg-Sim treatment.

**Result 7** Total supply chain profit is increasing over time. With the exception of Barg-Seq, this is because
variable procurement costs \((w_1 + w_2)\) are declining over time. In the mechanism design setting, OEMs capture all of this increase in profit – thus learning to better-exploit their bargaining power – since total supplier profits modestly decline over time. In the bargaining setting, both OEMs and suppliers see profits that increase, or are at least flat, over time. This is consistent with the parties’ more equal bargaining power.