Procurement for Assembly under Asymmetric Information: Theory and Evidence

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We study an original equipment manufacturer (OEM) purchasing two inputs for assembly from two suppliers with private cost information. The OEM can contract with the two suppliers either simultaneously or sequentially. We consider both cases in which the OEM has relatively equal bargaining power (the *dynamic bargaining* institution) or substantial bargaining power (the *mechanism design* institution). For the dynamic bargaining institution, we show that in sequential bargaining, the supply chain profit is higher, the OEM earns a lower profit, the first supplier earns a higher profit, and the second supplier may earn a higher or lower profit, than compared to simultaneous bargaining. For the mechanism design institution, we show that all players' profits are the same in simultaneous and sequential contracting. We also benchmark against a case where the OEM procures both inputs from a single integrated supplier (a *dyadic* supply chain). We then test these predictions in a human-subjects experiment, which support many of the normative predictions qualitatively with some deviations: an OEM with relatively equal bargaining power weakly prefers to contract with suppliers simultaneously while an OEM with substantial bargaining power prefers to contract with suppliers sequentially. In addition, the supply chain efficiency and the OEM's profit are higher in the dyadic supply chain than the assembly system.

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1. Introduction

In today's global marketplace original equipment manufacturers (OEMs) rely more than ever on sourcing inputs from external suppliers, rather than producing inputs in-house (Fung et al. 2008). For instance, to assemble its 787 Dreamliner, Boeing procures engines from Rolls-Royce and nacelles from Goodrich Corp (Clark 2012, Bigelow 2007). Assembly supply chains relate to a number of manufacturing industries such as transportation equipment, electronics and computers, and machinery (which generated \$1.73 trillion in shipments in the United States in 2018 (U.S. Census Bureau 2020)). In most of these cases suppliers have private cost information. As such, an OEM is interested in extracting this information to help maximize its own profit. Because OEMs often source inputs from multiple suppliers, one lever they have at their disposal is to contract with suppliers simultaneously or sequentially. In this study, we investigate the procurement problem of an OEM purchasing two inputs from suppliers who both have private cost information, and the OEM can contract with the suppliers simultaneously or sequentially.

We analyze this three-party assembly supply chain, where an OEM contracts with suppliers simultaneously or sequentially, under two different levels of bargaining power. When the OEM has relatively equal bargaining power with its suppliers, they engage in a back-and-forth dynamic bargaining process, whereas if the OEM has considerably more bargaining power then they make take-it-or-leave-it ultimatum offers to suppliers. For both levels of bargaining power, we aim to address the following research question: in an assembly supply chain, should OEMs contract with suppliers simultaneously or sequentially?

While OEMs often require specialized components, necessitating multiple suppliers, there are times when OEMs may have the ability to sole-source their needs as well. For example, Volkswagen procured both the light source and control module for its headlamps in the Volkswagon Golf VI from a single supplier, but opted for separate suppliers in the Volkswagon Golf VII (Chen et al. 2018). As another example, road and mountain bike assemblers such as Trek, Giant, and Cannondale, often choose between purchasing all or some of the components for a bike's drivetrain from a single or multiple suppliers, such as Shimano or SRAM. Therefore, a second research question we address in this study is: how does a three-party assembly setting compare to a *dyadic* supply chain, where both inputs are sourced from a single integrated supplier, in terms of supply chain, OEM, and supplier profit? Even if an OEM cannot choose between an assembly system or a dyadic supply chain, studying the dyadic setting serves as a useful benchmark to understand the unique characteristics of the assembly system.

Because human managers are integral to procurement decisions, we answer these research questions theoretically and experimentally. Using both methods is advantageous as the former generates normative predictions and the latter identifies whether humans conform to those predictions. There are a number of experimental studies which demonstrate that human-decisions makers deviate from the normative theory in settings such as supply chain contracting, auctions, and forecasting (Donohue et al. 2019). Neglecting to recognize such deviations can lead to erroneous managerial recommendations and negatively impact profits. Ultimately, by developing and testing the normative theory for assembly supply chains, we can identify when the theory is validated versus those instances where there are deviations, which translates into more useful insights for managers.

To this end, we begin by deriving a number of theoretical predictions for the assembly setting in which the OEM procures two different inputs – one each from two suppliers who possess private cost information. The OEM must reach agreements with both suppliers regarding the price and quantity. For the case of equal bargaining power between the OEM and suppliers (the *dynamic bargaining* institution), we employ Myerson's (1984a) solution concept. The solution is an incentive-efficient mechanism satisfying individual rationality, incentive compatibility, and Pareto optimality. In this framework we show that, while the total supply chain profit is higher when bargaining sequentially, the OEM actually prefers to bargain simultaneously. This is because when bargaining sequentially, the OEM needs to transfer an outsized fixed payment to the first supplier in order to reduce incentive distortion in the second bargaining stage, leading to lower OEM profit. In contrast, for the powerful OEM case (the *mechanism design* institution), we demonstrate an equivalence between simultaneous and sequential contracting in terms of OEM (and supplier) profit.

In both institutions, the contracting process effectively separates high and low-cost suppliers. The difference is that in the mechanism design case, we assume that the OEM can make a menu of contract proposals – one that is optimal for each supplier cost-type, and in the dynamic bargaining case, that this separation of supplier types occurs in the process of bargaining. We also analyze a dyadic supply chain where the OEM procures the two inputs from an integrated supplier, which helps shed light on the impact of the assembly structure.

We then report the results of a human-subjects experiment. In particular, we use our main theoretical results as benchmarks that our experiment rigorously tests. Turning to our design, we conduct a 2×3 between-subjects experiment with 396 participants. The first factor manipulates the institution, dynamic bargaining or mechanism design, and the second factor varies the supply chain structure and contract timing: assembly with simultaneous contracting, assembly with sequential contracting, or dyadic supply chain.

Our experimental results confirm that, at a high level, the broad comparative static predictions of the theory hold. However, we also document some managerially relevant deviations. First, our dyadic supply chain setting achieves higher agreement rates and, even conditional on agreement, higher supply chain profit, than an assembly system. Second, whereas theory predicts that the OEM and suppliers will earn unequal profits, we observe that these differences are more equal than predicted. Third, OEMs with considerable bargaining power earn higher profit under sequential contracting than simultaneous contracting. Fourth, in assembly systems under sequential contracting, the first supplier earns more than the second supplier, for both the bargaining and mechanism design institution. Last, we observe that OEMs often neglect to successfully screen suppliers.

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 recent papers 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 2018, Fang et al. 2014). These papers consider one stakeholder with strong bargaining power to make take-it-or-leave-it offers to other stakeholders; none of them consider the scenario with relatively equal bargaining power among the OEM and the suppliers, as studied in this paper, which calls for a solution to a multilateral bargaining problem with asymmetric information.

There has also been theoretical research on bargaining among stakeholders since the seminal paper by Nash (1950). In the operations management literature, bargaining with symmetric information has been studied (see, e.g., Lovejoy 2010, Nagarajan and Sošić 2008, Kuo et al. 2011, and Feng and Lu 2012). None of these papers evaluate the impact of asymmetric information on bargaining. When the stakeholders have 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 his solution 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, bargaining with asymmetric information between two players has been analyzed. For example, Feng et al. (2014) study the dynamic bilateral bargaining problem between one seller and one buyer privately informed of the demand information. Both stakeholders are impatient and make alternating offers until an agreement is reached. They characterize the perfect Bayesian equilibrium of the bargaining game. Bhandari and Secomandi (2011) consider an infinite-horizon revenue management problem in which the seller is privately informed of his inventory level, discount factor, and the arrival probability of buyers, and engages in bilateral bargaining with each buyer. They compare the seller's performance under four bargaining mechanisms: buyer posted price, seller posted price, a neutral bargaining solution, and the split-the-difference mechanisms. In contrast with these two papers, the assembly supply chain we investigate imposes a unique challenge because bargaining is multilateral, involving multiple stakeholders. In addition, the potential contracting timing – simultaneous or sequential contracting – between the OEM and the two suppliers imposes another challenge: while simultaneous bargaining can be solved using the solution concept by Myerson (1984a), sequential bargaining requires us to extend the concept to accommodate the change in the informational structure during the bargaining process.

There has been considerable experimental research studying procurement through supply chain contracts. Many of these studies include three assumptions: (1) only two parties contract, most commonly a buyer and supplier; (2) the two parties interact through a proposing party making an ultimatum offer to the responding party; and (3) there is full information of all cost, price, and demand parameters (for a summary, see Chen and Wu (2019)). In contrast, we investigate a three-party assembly supply chain, dynamic bargaining, and private cost information.

Some recent experimental studies in operations management have begun to relax the aforementioned assumptions. For instance, Johnsen et al. (2019) study a context where a retailer has private forecast information and investigate whether pre-set screening contracts are effective at separating supplier types. They find that certain biases play a role in supplier decisions, most notably bounded rationality and fairness (Fehr and Schmidt 1999, Bolton and Ockenfels 2000). In many ways our work extends their research in that we too find evidence of these behavioral drivers. However, we consider a three-party assembly supply chain, dynamic bargaining, and also allow OEMs to endogenously set contract terms. Leider and Lovejoy (2016) deviate from ultimatum offers and allow a retailer to interact with more than one supplier through chat-box communication. However, after communicating with multiple suppliers, the retailer then contracts with a single supplier. Davis and Leider (2018) and Davis and Hyndman (2019) explore back-and-forth negotiations, similar to our study, albeit under full information in a two-party supply chain. Also, an important feature of our assembly supply chain is that an OEM may contract with suppliers simultaneously or sequentially. The only operations management experiment that we are aware of which investigates simultaneous or sequential offers to responding parties is Ho et al. (2014). They consider full information where a supplier makes ultimatum wholesale price offers to two retailers, whereas we consider dynamic bargaining in an assembly supply chain with private information.

There is also a large literature on bargaining from experimental economics. We refer the interested reader to Roth (1995) and Camerer (2003), but highlight some important aspects here. In particular, much of the experimental economics research on bargaining focuses on relatively simple environments, most notably ultimatum and dictator games, where the surplus is fixed and where a proposer makes an ultimatum offer to a responder. A robust finding is that human participants exhibit fairness preferences, where proposers offer more than the normative prediction and responders reject many offers that are actually quite profitable (Camerer 2003, Ch. 2). Expanding social preferences further, Ho and Su (2009) extend the standard ultimatum game so that there is one proposer and two responders, and show that peer induced fairness among responders plays a role in accept/reject decisions as well. Importantly, while fairness is a robust finding in these papers, they consider environments with full information. As we will show in Section 6, our experiment builds on this literature by finding that fairness is also useful in explaining profit outcomes under one-sided private information, for all settings we investigate.

Our study contributes to the literature in the following ways. First, we study an assembly supply chain where an OEM interacts with two suppliers (simultaneously or sequentially). We believe that this is an important missing feature in the extant literature: in practice, OEMs usually require multiple inputs from multiple suppliers. Second, we consider a dynamic bargaining environment that mimics a more realistic bargaining interaction. Third, we allow for suppliers to have private information, which is common in industry but has not been studied extensively in the literature.

3. Theory

We consider an OEM sourcing two different inputs respectively from two individual suppliers (indexed 1 and 2) and then assembles the final product from a unit of each input at zero assembly cost. For simplicity, we assume the two inputs and suppliers to be symmetric, namely that *ex ante* they have identical parameters; the analysis for asymmetric inputs and suppliers is similar. Suppliers are typically 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 $\bar{p} \doteq 1 - p$, and $\Delta \doteq c_H - c_L > 0$. Each supplier is privately informed of its actual cost (type). Without loss of generality, we assume that each supplier and the OEM have reservation profit zero. As discussed in the Introduction, the assembly setting is widely seen in industries, and sourcing from two individual suppliers perfectly complementary inputs (i.e., having one without the other yields no value) poses unique challenges.

Depending on the bargaining power 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 comparable bargaining power, the three parties engage in dynamic back-and-forth bargaining with incomplete information, which is explored in Section 3.1. Under the mechanism design institution, when the OEM has dominant bargaining power over the suppliers, the OEM can make a take-it-or-leave-it ultimatum contract offer to suppliers, which is explored in Section 3.2. Under each institution, since the OEM needs to contract with two suppliers, it is faced with the issue of contracting timing: the OEM can contract with both suppliers simultaneously or sequentially. Therefore, a total of four models need to be analyzed.

The outcome under each institution, if transactions occur, is a set of contracts signed by both the OEM and the suppliers, which effectively specifies the monetary transfer P_i from the OEM to Supplier i, and the quantity of input Q_i supplied by the corresponding supplier; $i = 1, 2$. The total output quantity by the OEM is $Q = \min\{Q_1, Q_2\}$ because in an assembly system both inputs are needed to produce the output. We assume that the OEM faces market-clearing price $a - Q/2$ for outputting Q units. We also assume that a is above a threshold ($\bar{a}$, defined in Appendix A), to ensure positive optimal outputs and rule out other less interesting cases.

Following Hu and Qi (2018), we implement equilibrium bargaining outcomes and optimal mechanisms in the form of two-part tariff contracts. A two-part tariff contract (w_i, f_i), where w_i specifies a wholesale price and f_i specifies a fixed payment, allows the OEM to choose any purchase quantity Q_i from Supplier i while obliging the OEM to pay $w_i Q_i + f_i$ to 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. Hu and Qi (2018) show that the two-part tariff implementation has a major advantage. They find that optimal mechanisms implemented in the original quantity-payment terms (Q_i, P_i) may be contingent, namely that the contract terms offered to one supplier may depend on another supplier's choices, whereas two-part tariff implementations of optimal mechanisms do not contain contingency and are also simpler in form. Contingent contracts are challenging to implement in practice or in a lab. For these reasons, we implement equilibrium bargaining outcomes and optimal mechanisms in the form of two-part tariff contracts so that the experimental participants find them intuitive and relatable.

3.1. Dynamic Bargaining in Assembly

When the OEM and suppliers have comparable bargaining power, the three stakeholders engage in dynamic back-and-forth bargaining. In the assembly setting, the lack of cooperation of any party results in non-trading and zero profit for everyone. Therefore, when there is no information asymmetry, the Shapley value would predict that the three stakeholders cooperatively maximize their total profit, and equally share the profit three-way. Myerson (1984a) generalizes the Shapley value to allow private information. The high-level idea of the generalization is to find an *incentive-efficient* mechanism which is incentive compatible (IC), individually rational (IR), and Pareto optimal (PO); under the incentive-efficient mechanism, the stakeholders obtain equitable profit shares that are "fair" in the sense of a virtual utility capturing the impact of the IC and IR constraints. We adopt Myeron's (1984a) framework in solving our dynamic bargaining models. For readability, we relegate all technical analyses to Appendix A and only present formulations, results, and intuitions in the main text.

3.1.1. Simultaneous Bargaining Consider that the OEM simultaneously bargains 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. It is straightforward that any efficient outcome must have $Q_{1XY} = Q_{2XY}$, and thus we denote the equal order quantity by Q_{XY} henceforth. For convenience we denote the expected payment for Supplier 1 of type X (resp., Supplier 2 of type Y) as $P_{1X} \doteq pP_{1XH} + \bar{p}P_{1XL}$ (resp., $P_{2Y} \doteq pP_{2HY} + \bar{p}P_{2LY}$).

A bargaining solution $\{P_{1XY}, P_{2XY}, Q_{XY}\}$ should first be individually rational and incentive-compatible, namely that it satisfies IR constraints for both the OEM and the suppliers of each type (i.e., they need to receive non-negative expected profits), and IC constraints for the suppliers (i.e., they need to be willing to reveal their true types). An example of the IR and IC constraints for Supplier 1 is provided in the Appendix A.1.

A bargaining solution should also be Pareto optimal for all stakeholders. Myerson (1984a) shows that incentive-efficient mechanisms, i.e., mechanisms that are IR, IC, and PO, must solve the following *primal bargaining problem*, where $\lambda_i \in [0,1]$, $i = 1,2$ are some weights of the high-type suppliers' profits and $\bar{\lambda}_i \doteq 1 - \lambda_i$ are those on the low-type suppliers' profits:

$$\begin{aligned}
\max_{\mathbf{P},\mathbf{Q}}\ & p^2[(a - Q_{HH}/2)Q_{HH} - P_{1HH} - P_{2HH}] + \bar{p}p[(a - Q_{LH}/2)Q_{LH} - P_{1LH} - P_{2LH}] + \\
& p\bar{p}[(a - Q_{HL}/2)Q_{HL} - P_{1HL} - P_{2HL}] + \bar{p}^2[(a - Q_{LL}/2)Q_{LL} - P_{1LL} - P_{2LL}] + \\
& \bar{\lambda}_1[p(P_{1LH} - c_L Q_{LH}) + \bar{p}(P_{1LL} - c_L Q_{LL})] + \lambda_1[p(P_{1HH} - c_H Q_{HH}) + \bar{p}(P_{1HL} - c_H Q_{HL})] + \\
& \bar{\lambda}_2[p(P_{2HL} - c_L Q_{HL}) + \bar{p}(P_{2LL} - c_L Q_{LL})] + \lambda_2[p(P_{2HH} - c_H Q_{HH}) + \bar{p}(P_{2LH} - c_H Q_{LH})] \\
\text{s.t. }& \text{IR, IC for all stakeholders and their types.}
\end{aligned}$$

Solving the problem with the approach by Myerson (1984a), we find the following two-part tariff bargaining solutions; recall that we focus on cases with sufficiently large a. The free parameter δ is a transfer between the wholesale prices and fixed payments that, although technically arbitrary, is likely to be 0 in practice which leads to the most intuitive contract. For any value of δ, the expected payments and quantities are the same. Thus, the two-part tariff bargaining solutions are *effectively* unique. For simplicity of presentation we slightly abuse the terminology and refer to the outcome with $\delta = 0$ as *the* simultaneous bargaining outcome. The detailed analysis are relegated to Appendix A.1.

PROPOSITION 1 **(Simultaneous bargaining solution)**. *The following two-part tariff mechanisms implement the simultaneous bargaining outcome, with δ being any real number. The wholesale prices and the fixed payments are:*

$$w_{1H}^* = c_H + \frac{\bar{p}}{p}\Delta - \delta,\ w_{1L}^* = c_L - \delta,\ w_{2H}^* = c_H + \frac{\bar{p}}{p}\Delta + \delta,\ w_{2L}^* = c_L + \delta,$$
$$f_{iH}^* = \frac{a^2 + 2ac_L - 4c_L^2}{6} - \frac{2c_L^2}{3p} + \Delta\frac{pa - (3+5p)c_L}{3p} - 2\Delta^2\frac{1+p}{3p} - w_{iH}^*(a - w_{iH}^* - \bar{p}w_{jL}^* - pw_{jH}^*),$$
$$f_{iL}^* = \frac{(a - 2c_L)(a + 4c_L)}{6} + \Delta\frac{a - 5c_L}{3} - 2\Delta^2\frac{1+p}{3p} - w_{iL}^*(a - w_{iL}^* - \bar{p}w_{jL}^* - pw_{jH}^*),\ \ i,j \in \{1,2\}, i \neq j.$$

3.1.2. Sequential bargaining Consider without loss of generality that the OEM first bargains and enters a contract with Supplier 1, in the process learning its private information, before bargaining with Supplier 2. Since the trade requires all stakeholders' participation, we assume that the OEM's initial contract with Supplier 1 is tentative and Supplier 1 retains the veto power over the contract during the OEM's bargaining with Supplier 2, although no change of the contract terms is allowed[1]. The key feature of sequential bargaining is that the OEM when bargaining with Supplier 2 is equipped with the private information of Supplier 1, and the bargaining involves double-sided private information. Similar to the simultaneous bargaining case, the bargaining solution in the sequential bargaining is also an incentive-efficient mechanism which guarantees the equitable share of all stakeholders on the virtual utility scale.

To find the bargaining solution, we first analyze the OEM's bargaining with Supplier 2. We also directly assume the two-part tariff format from now on. We present an outline of the analysis and key results in the main text; the detailed analysis are relegated to Appendix A.2.

Second-stage bargaining. Assume that the OEM and Supplier 1 have reached the temporary agreement with a menu of two-part tariff contracts $(w_{1X}^\dagger, f_{1X}^\dagger)$ where X is Supplier 1's type. In what follows, we use subscript $2XY,\ X,Y = H,L$ to denote the bargaining outcome with Supplier 2 of type Y given Supplier 1's type being X, and define $\mathbf{w_{2X}}, \mathbf{f_{2X}} \doteq w_{2XH}, w_{2XL}, f_{2XH}, f_{2XL}, X = H, L$. Similar to Section 3.1.1, we present the following primal bargaining problem, where $\lambda_2 \in [0,1]$ is the weight of the high-type Supplier 2's profit, and $\lambda_o \in [0,1]$ is the weight of the high-type OEM's (i.e., an OEM having learned that Supplier 1 is of the high type) profit; $\bar{\lambda}_i \doteq 1 - \lambda_i,\ i \in \{2, o\}$, are respectively the weights of the low-type profits.

$$\max_{\substack{\mathbf{w_{2H}},\mathbf{f_{2H}},\\ \mathbf{w_{2L}},\mathbf{f_{2L}}}} \bar{\lambda}_o \left\{ p\left[\frac{(a - w_{1L}^\dagger - w_{2LH})^2}{2} - f_{1L}^\dagger - f_{2LH}\right] + \bar{p}\left[\frac{(a - w_{1L}^\dagger - w_{2LL})^2}{2} - f_{1L}^\dagger - f_{2LL}\right]\right\} +$$

[1] The assumption is relevant for the off-equilibrium threat that Supplier 1 may impose in the negotiation process. In the equilibrium bargaining solution, Supplier 1 will not use its veto power after reaching agreement with the OEM in the first-stage bargaining.

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

$$\bar{\lambda}_2\{p[(w_{2HL}-c_L)(a-w_{1H}^\dagger - w_{2HL}) + f_{2HL}] + \bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger - w_{2LL}) + f_{2LL}]\}+$$

$$\lambda_2\{p[(w_{2HH}-c_H)(a-w_{1H}^\dagger - w_{2HH}) + f_{2HH}] + \bar{p}[(w_{2LH}-c_H)(a-w_{1L}^\dagger - w_{2LH}) + f_{2LH}]\}$$

s.t. IR, IC constraints for both OEM and Supplier 2 and their types.

By simplifying the constraints, defining virtual utilities, and solving for equitable shares in the dual problem, we find a bargaining outcome subject to the OEM's IC constraint where the expected fixed payment to Supplier 2 of type $Y = H, L$ is $f_{2Y}^\dagger \doteq p f_{2HY}^\dagger + \bar{p} f_{2LY}^\dagger$:

$$\begin{aligned}
&w_{2HH}^\dagger = c_H + \frac{\bar{p}}{p}\Delta, \quad w_{2LL}^\dagger = c_L, \quad w_{2HL}^\dagger = c_L, \quad w_{2LH}^\dagger = c_H + \frac{\bar{p}}{p}\Delta,\\
f_{2H}^\dagger = &\frac{(a-c_L)^2}{4} + \frac{(4-3p)\Delta^2}{4p^2} - \frac{(2-p)\Delta}{2p}(a - c_L - p w_{1H}^\dagger - \bar{p} w_{1L}^\dagger) - \\
&\frac{p}{2}\left[f_{1H}^\dagger + w_{1H}^\dagger\left(a - c_L - w_{1H}^\dagger/2\right)\right] - \frac{\bar{p}}{2}\left[f_{1L}^\dagger + w_{1L}^\dagger\left(a - c_L - w_{1L}^\dagger/2\right)\right],\\
f_{2L}^\dagger = &\frac{(a-c_L)^2}{4} - \frac{3\Delta^2}{4p} + \frac{\Delta}{2}(a - c_L - p w_{1H}^\dagger - \bar{p} w_{1L}^\dagger) - \\
&\frac{p}{2}\left[f_{1H}^\dagger + w_{1H}^\dagger\left(a - c_L - w_{1H}^\dagger/2\right)\right] - \frac{\bar{p}}{2}\left[f_{1L}^\dagger + w_{1L}^\dagger\left(a - c_L - w_{1L}^\dagger/2\right)\right].
\end{aligned}$$

Additionally, for this outcome to satisfy the OEM's IC constraint, we need to require

$$f_{1L}^\dagger - f_{1H}^\dagger \geq \frac{1}{2}(w_{1H}^\dagger - w_{1L}^\dagger)(2a - 2c_H - w_{1H}^\dagger - w_{1L}^\dagger), \qquad (\mathrm{IC}'_{OL})$$

for the first-stage bargaining outcome.

Comparing the bargaining outcome above to the simultaneous bargaining solution in Proposition 1, we note that although the OEM also has private information, there is no additional distortion in the wholesale price for Supplier 2 (and the resulting sourcing quantity). For the bargaining outcome to be feasible, the fixed payment difference between the low-type and high-type Supplier 1 should be sufficiently large, which is reflected by the IC'_{OL} constraint.

First-stage bargaining. The first-stage primal bargaining problem incorporates the anticipated second-stage bargaining outcome where the sum of the first four terms in the objective function represents the expected total virtual utility of the OEM and Supplier 2 in the second-stage bargaining, including the anticipated condition (IC'_{OL}) required by the second-stage outcome:

$$\max_{\mathbf{w_1},\mathbf{f_1}} \bar{p}p\left[\frac{(a-w_{1L}-w_{2LH}^\dagger)^2}{2} - f_{1L} + \left(w_{2LH}^\dagger - \frac{1}{p}c_H + \frac{\bar{p}}{p}c_L\right)(a - w_{1L} - w_{2LH}^\dagger)\right] +$$

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

$$p^2\left[\frac{(a-w_{1H}-w^\dagger_{2HH})^2}{2}-f_{1H}+\left(w^\dagger_{2HH}-\frac{1}{p}c_H+\frac{\bar{p}}{p}c_L\right)(a-w_{1H}-w^\dagger_{2HH})\right]+$$
$$p\bar{p}\left[\frac{(a-w_{1H}-w^\dagger_{2HL})^2}{2}-f_{1H}+(w^\dagger_{2HL}-c_L)(a-w_{1H}-w^\dagger_{2HL})\right]+$$
$$\bar{\lambda}_1\{p[(w_{1L}-c_L)(a-w_{1L}-w^\dagger_{2LH})+f_{1L}]+\bar{p}[(w_{1L}-c_L)(a-w_{1L}-w^\dagger_{2LL})+f_{1L}]\}+$$
$$\lambda_1\{p[(w_{1H}-c_H)(a-w_{1H}-w^\dagger_{2HH})+f_{1H}]+\bar{p}[(w_{1H}-c_H)(a-w_{1H}-w^\dagger_{2HL})+f_{1H}]\}$$

s.t. IR, IC constraints for all stakeholders and their types, IC'_{OL}.

By simplifying the constraints, defining virtual utilities, and solving for equitable shares in the dual problem, we find a bargaining outcome as summarized in the following proposition.

PROPOSITION 2 **(Sequential bargaining solution)**. *The first-stage bargaining outcome is*

$$w^\dagger_{1H}=c_H,\quad w^\dagger_{1L}=c_L,\quad f^\dagger_{1H}=\frac{1}{3}\left[p\frac{(a-2c_H-\frac{\bar{p}}{p}\Delta)^2}{2}+\bar{p}\frac{(a-c_H-c_L)^2}{2}\right];$$
$$f^\dagger_{1L}=\frac{1}{3}\left[p\frac{(a-2c_H-\frac{\bar{p}}{p}\Delta)^2}{2}+\bar{p}\frac{(a-c_H-c_L)^2}{2}\right]+\frac{1}{2}(c_H-c_L)(2a-3c_H-c_L).$$

The second-stage bargaining outcome is

$$w^\dagger_{2HH}=c_H+\frac{\bar{p}}{p}\Delta,\quad w^\dagger_{2LL}=c_L,\quad w^\dagger_{2HL}=c_L,\quad w^\dagger_{2LH}=c_H+\frac{\bar{p}}{p}\Delta,$$
$$f^\dagger_{2H}=\frac{(a-2c_L)^2}{12}+\frac{\Delta(a-2c_L)(3p^2+p-6)}{6p}+\frac{\Delta^2(3p+21p\bar{p}-11)}{12p}+\frac{\Delta^2}{p^2},$$
$$f^\dagger_{2L}=\frac{(a-2c_L)^2}{12}+\frac{\Delta(a-2c_L)(3p+1)}{6}+\frac{\Delta^2(4-7p)}{4}-\frac{11\Delta^2}{12p}.$$

The most notable finding in the solution process is that constraint IC'_{OL} is binding while Supplier 1's IC constraint is not binding because it is implied by the former. As a result, there is no distortion in the wholesale price paid to Supplier 1, and the supply chain efficiency is *higher* compared to the simultaneous bargaining case. The intuition is that anticipating the second stage bargaining outcome, for the OEM not to introduce additional incentive distortion in the second stage bargaining, the fixed payment difference between the low-type and high-type Supplier 1 should be sufficiently large, which is achieved by increasing the supply chain efficiency by reducing the distortion of the wholesale price paid to Supplier 1 and at the same time, increasing the fixed payment to Supplier 1.

The following proposition compares the simultaneous and sequential bargaining outcomes.

PROPOSITION 3 **(Simultaneous vs. sequential bargaining)**. *Compare the outcomes under simultaneous and sequential bargaining for assembly. The sequential bargaining yields (1) a higher* *profit of the supply chain, (2) a lower profit of the OEM, (3) a higher profit of Supplier 1, (4) a higher profit of Supplier 2 if* $\frac{3-\sqrt{3}}{6} \le p \le \frac{3+\sqrt{3}}{6}$*, and a lower profit for Supplier 2 otherwise.*

Note that sequential bargaining leads to less distortion on the wholesale prices, resulting in a higher supply chain profit. Also observe that sequential bargaining leads to a higher fixed payment to Supplier 1, who is better off under sequential bargaining. The OEM must pay more to the suppliers under sequential bargaining and earns a lower profit. For Supplier 2, whether it will earn a higher or lower profit depends on the difference between the increased supply chain profit and the increased payments to Supplier 1. When the suppliers' types are more ambiguous (i.e., $\frac{3-\sqrt{3}}{6} \le p \le \frac{3+\sqrt{3}}{6}$), Supplier 2 benefits more from the increased supply chain profit and earns a higher profit under sequential bargaining. Otherwise, it earns a lower profit under sequential bargaining.

3.2. Mechanism Design in Assembly

When the OEM has dominant bargaining power over the suppliers, it can offer a menu of take-it-or-leave-it contracts to suppliers. The mechanism design institution represents the limiting case of alternating offer bargaining when the OEM has all of the power (Wang 1998). We keep all other assumptions and parameters unchanged from Section 3.1, and analyze the OEM's optimal contracting mechanism with the suppliers. Unlike the dynamic bargaining institution, under the mechanism design institution, the OEM's dominant power allows it to extract most profits of the suppliers except for the information rents warranted by the suppliers' private information. That said, the informational structure difference between simultaneous and sequential decision making in mechanism design remains similar to that in dynamic bargaining. In sequential mechanism design, when the OEM designs a menu of contracts for Supplier 2 after contracting with Supplier 1, it is equipped with the private information of Supplier 1, making the OEM an *informed principal* in the second-stage contracting process.

The simultaneous and sequential mechanism design problems have been studied by Hu and Qi (2018) in a more general form. Here, we present relevant results from their work (adapted to our notation and special cases) and relegate the formulations to Appendix B. The optimal simultaneous mechanism is presented in the proposition below.

Proposition 4 **(Optimal simultaneous mechanism)**. *The following two-part tariff mechanisms implement the optimal simultaneous mechanism, with* δ *being any real number: the OEM offers the menu* $\{(w^S_{iH}, f^S_{iH}), (w^S_{iL}, f^S_{iL})\}$ *to Supplier* i*,* $i = 1, 2$*, where*

$$w^S_{1L} = c_L + \delta, \quad w^S_{1H} = c_L + \delta + \Delta/p, \quad w^S_{2L} = c_L - \delta, \quad w^S_{2H} = c_L - \delta + \Delta/p,$$
$$f^S_{1L} = (-\delta + \Delta)(a - 2c_L - \Delta) - \Delta^2/p, \quad f^S_{1H} = -(\Delta\bar{p}/p + \delta)(a - 2c_L - \Delta - \Delta/p),$$
$$f^S_{2L} = (\delta + \Delta)(a - 2c_L - \Delta) - \Delta^2/p, \quad f^S_{2H} = -(\Delta\bar{p}/p - \delta)(a - 2c_L - \Delta - \Delta/p).$$

Similar to the simultaneous bargaining solution, all values of δ lead to the same expected profit for the suppliers and the OEM. Therefore, the two-part tariff optimal simultaneous mechanisms are effectively unique. While the parameter δ is technically arbitrary, $\delta=0$ leads to the most intuitive contract which is most likely to be used in practice. For simplicity, we slightly abuse the terminology and refer to the mechanism with $\delta=0$ as *the* optimal simultaneous contracting mechanism. The optimal sequential mechanism is presented in the following proposition.

PROPOSITION 5 **(Optimal sequential mechanism)**. *The following two-part tariff mechanism implements the optimal sequential mechanism: in the first stage the OEM offers the menu* $\{(w_{1H}^Q, f_{1H}^Q), (w_{1L}^Q, f_{1L}^Q)\}$ *to Supplier 1 where*

$$w_{1L}^Q = c_L, w_{1H}^Q = c_L + \Delta/p, f_{1L}^Q = \Delta(a - 2c_L - \Delta) - \Delta^2/p, f_{1H}^Q = -\Delta(a - 2c_L - \Delta)\bar{p}/p + \Delta^2\bar{p}/p^2.$$

If Supplier 1 is revealed to have high (resp., low) costs, then in the second stage the OEM offers the menu $\{(w_{2HH}^Q, f_{2HH}^Q), (w_{2HL}^Q, f_{2HL}^Q)\}$ *(resp.,* $\{(w_{2LH}^Q, f_{2LH}^Q), (w_{2LL}^Q, f_{2LL}^Q)\}$*) to Supplier 2 where*

$$w_{2HL}^Q = c_L, w_{2HH}^Q = c_L + \Delta/p, f_{2HL}^Q = \Delta(a - 2c_L) - 2\Delta^2/p, f_{2HH}^Q = -\Delta(a - 2c_L - \Delta/p)\bar{p}/p + \Delta^2\bar{p}/p^2;$$
$$w_{2LL}^Q = c_L, w_{2LH}^Q = c_L + \Delta/p, f_{2LL}^Q = \Delta(a - 2c_L) - \Delta^2/p, f_{2LH}^Q = -\Delta(a - 2c_L)\bar{p}/p + \Delta^2\bar{p}/p^2.$$

By observing Propositions 4 and 5 one can immediately arrive at the following conclusion:

PROPOSITION 6 **(Optimal simultaneous vs. sequential mechanisms)**. *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 between optimal simultaneous and sequential mechanisms is notable. While the two contracting sequences have different informational structures, namely that under sequential contracting the OEM learns Supplier 1's cost before contracting with Supplier 2, this difference does not result in a profit difference for the OEM. It suggests that the OEM need not worry about contracting timing. Proposition 6 is in direct contrast with Proposition 3. These observations will constitute our experimental predictions for the assembly setting in Section 3.4.

3.3. Benchmark: Dyadic Supply Chain with an Integrated Supplier

A key premise of our analysis is the assembly setting. The need for the OEM to contract with *both* suppliers creates unique challenges, as noted previously. For a basis of comparison, we now analyze a dyadic supply chain where the OEM procures the two inputs from *one* supplier, who possesses private cost information about *both* inputs. That is, we analyze optimal mechanism design and dynamic bargaining if the two suppliers *were integrated into one*. Since the integrated supplier provides two symmetric inputs whose costs may each be high or low, the supplier has three possible types: HH for high-high (when both costs are high), LL for low-low (when both costs are low), and HL for high-low (when one cost is high and the other is low). The prior probabilities are $p_{HH} = p^2$, $p_{LL} = \bar{p}^2$, and $p_{HL} = 2p\bar{p}$. All other assumptions and parameters remain the same.

The mechanism design problem is formulated and solved following a standard approach and we relegate all details to Appendix C.1. Comparing the profits of all the stakeholders with those derived in Propositions 4 and 5 yields the following:

Proposition 7 **(Dyadic vs. assembly supply chains under optimal mechanisms)**. *Comparing the supply chain's, OEM's, and suppliers' profits between the assembly and dyadic supply chains under the optimal mechanisms yields:*

1. *The supply chain's profit is higher under an assembly supply chain.*
2. *The OEM's profit is higher under a dyadic supply chain.*
3. *The suppliers' (total) profit is higher under an assembly supply chain.*

The bilateral dynamic bargaining problem is formulated and solved following Myerson (1984b). Similar to Davis and Hyndman (2020), while the problem is numerically solvable, the analytical solutions are algebraically cumbersome and intractable. Thus, we provide the formulation and the key steps to compute the bargaining solution in Appendix C.2, which is used to derive the normative prediction of the bargaining outcome in the dyadic supply chain in the next section.

3.4. Experimental Predictions

As described in the Introduction, it is important to test the theory with a behavioral lens for our assembly setting. To this end, our experiment consisted of a 2×3 between-subject design aimed to coincide with the six settings outlined above. The first factor manipulated the institution type: the OEM interacts with the supplier(s) through a dynamic bargaining process (Barg) or by offering a menu of take-it-or-leave-it offers (Mech). The second factor manipulated the supply chain structure: an assembly supply chain in which the OEM contracts with two independent suppliers (i) simultaneously (Sim) or (ii) sequentially (Seq), and (iii) a baseline dyadic supply chain (Dyad) in which the OEM contracts with a single integrated supplier who supplies both inputs.

In all treatments we set $a = 75$. The four assembly settings set: $c_L = 5$, $c_H = 15$, $p_L = \frac{1}{2}$, and $p_H = \frac{1}{2}$. In the two dyadic settings, the integrated supplier had three costs, $c_{LL} = 10$ (w.p. 0.25), $c_{HL} = 20$ (w.p. 0.5) and $c_{HH} = 30$ (w.p. 0.25), which mimics the cost distribution in the assembly treatments and ensures a fair comparison. The experimental predictions for our design are in Table 1. While

Proposition 7 provides the predicted differences between assembly and dyadic supply chains under the optimal mechanism, we use this table to generate predictions between assembly and dyadic supply chains under dynamic bargaining:

1. *The supply chain profit is higher under an assembly supply chain.*
2. *The OEM's profit is higher under a dyadic supply chain.*
3. *The suppliers' (total) profit is higher under an assembly supply chain.*

Table 1 Experimental Predictions

(a) Assembly Setting

	Barg-Sim	Barg-Seq	Mech-Sim	Mech-Seq
Ex Ante Supply Chain Expected Profit	1462.5	1512.5	1462.5	1462.5
Ex Ante OEM Expected Profit	370.83	354.17	1112.5	1112.5
Ex Ante Supplier Expected Profit	545.83	(604.17, 554.17)	175	175
Wholesale Price Low (w_L)	5	5	5	5
Wholesale Price High (w_H)	25	(15, 25)	25	25
Fixed Fee Low (f_L)	720.83	(854.17, 754.17)	350	350
Fixed Fee High (f_H)	20.83	(354.17, -45.83)	-350	-350

(b) Dyadic Setting

	Barg-Dyad	Mech-Dyad
Ex Ante Supply Chain Expected Profit	1445.4	1418.75
Ex Ante OEM Expected Profit	598.64	1181.25
Ex Ante Supplier Expected Profit	846.77	237.50
Wholesale Price Low (w_{LL})	10	10
Wholesale Price Med (w_{LH})	25	25
Wholesale Price High (w_{HH})	56.21	60
Fixed Fee Low (f_{LL})	1268.75	650
Fixed Fee Med (f_{LH})	518.75	-100
Fixed Fee High (f_{HH})	88.30	-450

Note: For pairs of numbers, (A, B), A represents the contract term to Supplier 1, while B represents the contract term to Supplier 2. If there is only one number, then it applies for both suppliers.

4. Experimental Methodology

As noted, our experiment consisted of a 2×3 between-subject design aimed to coincide with the six settings outlined in Section 3. Each assembly treatment included 72 participants while each dyadic treatment included 54 participants for a total of 396 participants, depicted in Table 2.

Table 2 Experimental Design and Number of Participants

		Timing and Supply Chain Structure		
		Sim(ultaneous)	Seq(uential)	Dyad(ic)
Institution	Barg(aining)	72	72	54
	Mech(anism)	72	72	54

Participants were first assigned a role of an OEM, Supplier 1, or Supplier 2 (in the four Assembly treatments), which remained fixed for the duration of the session. Nine (six) participants comprised a single cohort in the Assembly (Dyadic) treatments, yielding eight cohorts in each treatment. In each round, within a cohort, one participant of each role was randomly placed into a triad/dyad, and this random rematching process was repeated every round. Furthermore, at the beginning of each round each supplier's cost was randomly and independently drawn from the relevant cost distribution (which differed between the Assembly and Dyadic treatments). All treatments consisted of eight rounds.[2] We automated the quantity decisions so that $q = 75 - w_1 - w_2$ and provided all participants with decision support where they could enter test values of fixed fees and wholesale prices and observe the profits for themselves and the other player(s) in their triad/dyad.[3]

Turning to the specifics of each treatment, in the three dynamic bargaining treatments, the parties engaged in a back-and-forth negotiation (though to be sure, one player could make multiple offers in a row without waiting for their bargaining partner to make a counteroffer). To create this environment we employed a protocol similar to one that has been used in recent operations bargaining studies. 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' the fixed fee, the wholesale price, or both. This information would then be shown to the proposing party (the receiving party could still accept the offer if it was still the most recent offer received). Overall, this protocol mimicked a more natural bargaining process while allowing us to observe offers and feedback over time.

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 triad 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

[2] Due to a technical issue, one cohort of nine in Mech-Seq only completed six rounds.

[3] When applicable, players would see the suppliers' profits for c_L and c_H (c_{LL}, c_{HL}, and c_{HH} in the Dyadic treatments).

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. If the OEM and Supplier 2 agreed on a specific offer then all three earned their respective profits, otherwise they earned a profit of zero. The Dyadic bargaining treatment, Barg-Dyad, followed the same protocol as Barg-Sim and Barg-Seq except that the OEM bargained with a single integrated supplier (please see Section 3.4 for detailed parameters). If they could not come to an agreement within the allotted time then they both earned a profit of zero.

In the Mech-Sim condition, each round began with the OEM making a take-it-or-leave-it offer consisting of two wholesale price and fixed fee pairs, $\{(w_1, f_1), (w_2, f_2)\}$ 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 triad 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 Dyadic mechanism design condition, Mech-Dyad, was the same except that the OEM made a take-it-or-leave-it offer of three wholesale price and fixed fee pairs to a single supplier (see Section 3.4), who then made an accept/reject decision.

As mentioned previously, to ensure a fair comparison between all treatments, the cost distribution of the single integrated supplier in the Dyadic treatments was engineered such that it was equivalent to the Assembly setting with two suppliers. Lastly, the experimental interface 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 roughly \$28. Subjects were compensated for all rounds.

5. Experimental Results

Because the theory that we have developed is rich, rather than presenting several formal hypotheses, in Table 3 we provide the theoretical *directional* predictions along with whether they are validated in our experimental data. To organize this information, we have sub-tables comparing the Assembly and Dyadic treatments to each other, the Assembly treatments separately, and whether or not theory predicts an equivalence or a difference. Further, the predictions are color-coded according to whether they pertain to agreements and supply chain profit, OEM profit, or supplier profits (see Table 3 note). In the next three sub-sections we provide details for each colored category: agreements and supply chain profit (Section 5.1), the OEM (Section 5.2), and suppliers (Section 5.3). Given that our study is one of the first to experimentally investigate screening contracts in operations management, we also focus on screening and signaling in Section 5.4.

Before proceeding, in Table 3, one can see that a number of directional predictions are validated in our data. This is especially true for predictions regarding the OEM and supplier profits. However, although the theory is affirmed in these directional cases, few of the specific point predictions (from Table 1) are confirmed. While we discuss these in more detail in Section 6, for now we note that across all six of our experimental treatments, theory predicts a larger difference in profits between the OEM and suppliers, than what we observe in the data.

Lastly, in what follows we devote more attention to those results which yield particularly meaningful managerial insights. We include all eight rounds of data in our analysis.[4] Unless otherwise noted, all hypothesis tests are $t-$tests, where a single cohort of nine (Assembly) or six (Dyadic) participants represents an independent observation and regressions are run with random effects and clustered standard errors at the cohort level.

5.1. Analysis of Agreements and Supply Chain Profit

Table 4a illustrates the details on agreements. Agreement rates are below 100% in both the Assembly and Dyadic treatments. Moreover, they are significantly lower ($p = 0.033$) in the Assembly treatments (73.96-79.03%) than in the Dyadic treatments (83.33%). Not surprisingly – although contrary to theory – this suggests that it is more difficult for the relevant parties to come to an agreement in an assembly supply chain compared a dyadic setting with an integrated supplier.

Looking at agreements in the four Assembly treatments, there is some variation, but the differences are not significant either on the Barg vs. Mech or Sim vs. Seq dimensions ($p \gg 0.1$ in both cases). In Tables 4b and 4c, we see that, in contrast to the theoretical prediction, disagreements are more likely to occur when a supplier has a higher cost (in all cases $p < 0.038$). This suggests that the parties use the possibility of disagreement to distinguish between cost types, which is common in more structured bargaining environments.[5] As we show later, this is likely due to the fact that OEMs are poor at separating between supplier types.

We depict supply chain profit, conditional on agreement, in Table 5. Recall in Table 3b, that supply chain profit should be higher in the Assembly treatments than in the corresponding Dyadic

[4] We explore learning later, but here note that nearly all of our results outlined in Table 3 are confirmed even when dropping the first half of the data. There are three times when significance changes that are worth detailing: (a) agreement rates in Dyad are still higher than Assembly ($p = 0.033$ to $p = 0.314$), (b) supply chain profit in Dyad-Mech is no longer significantly higher than Assembly-Mech ($p = 0.869$), and (c) OEM profit in Mech-Seq is still higher than Mech-Sim ($p = 0.077$ to $p = 0.125$). Given that the experiment consisted of only 8 rounds and that we base our analysis on cohort averages, focusing on the last half of the experiment leads to noisier data, and so should be evaluated with caution. In Appendix E.1, we examine time trends with regressions.

[5] In Appendix E.2 we provide further information about agreements. Unsurprisingly, 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.

Table 3 **Table of Key Directional Predictions and Summary of Results**

(a) Dyadic vs Assembly (Theory Predicts Equivalence)

Prediction	No Sig. Diff.	Sig. Diff.	Note
Agreement rates equal b/w Dyadic and Assembly		✓ ($p = 0.033$)	Dyadic higher

(b) Dyadic vs Assembly (Theory Predicts Difference)

Prediction	Correct Dir. (* Sig.)	Incorrect Dir.
Supply chain profit is higher in Assembly (Barg.)		✓ ($p = 0.090$)
Supply chain profit is higher in Assembly (Mech.)		✓ ($p = 0.105$)
OEM profit is higher in Dyadic (Barg.)	✓*	
OEM profit is higher in Dyadic (Mech.)	✓*	
Supplier (total) profit is higher in Assembly (Barg.)	✓*	
Supplier (total) profit is higher in Assembly (Mech.)	✓*	

(c) Assembly (Theory Predicts Equivalence)

Prediction	No Sig. Diff.	Sig. Different	Note
OEM profit is equal b/w Mech-Seq/Sim		✓ ($p = 0.077$)	Seq higher
Supplier (total) profit is equal b/w Mech-Seq/Sim	✓		
Sup. 1 profit is equal to Sup. 2 in Mech-Seq	✓		

(d) Assembly (Theory Predicts Difference)

Prediction	Correct Dir. (* Sig.)	Incorrect Dir.
Supply chain profit is highest in Barg-Seq		✓
OEM profit is higher in Barg-Sim than Barg-Seq	✓	
Sup. 1 profit is higher than Sup. 2 in Barg-Seq	✓*	
Supplier (total) profit is higher in Barg-Seq than Barg-Sim	✓	

Note 1: The predictions are divided into three categories: (1) agreements and supply chain profit (light gray), (2) OEM (medium gray), and (3) suppliers (dark gray).
Note 2: We adopt a conservative approach to testing. Specifically, when theory predicts no difference, we mark the result as significantly different if the $p-$value is 0.10 or lower, and we note the direction of the difference. On the other hand, when theory predicts a difference, we mark it as "Correct Dir. (* Sig.)" if the $p-$value is 0.05 or lower.

Table 4 **Agreement Rates (%)**

(a) Overall

	Sim		Seq		Dyad	
Barg	77.08	(10.45)	73.96	(9.64)	83.33	(7.51)
Mech	79.03	(12.88)	77.96	(11.34)	83.33	(10.21)

(b) Dyadic Treatments

	$c = 10$		$c = 20$		$c = 30$	
Barg	93.85	(10.22)	82.90	(9.86)	73.33	(21.91)
Mech	98.15	(5.56)	93.52	(10.02)	53.17	(26.89)

(c) Assembly Treatments

	Supplier 1				Supplier 2			
	$c = 5$		$c = 15$		$c = 5$		$c = 15$	
Barg-Sim	89.67	(6.25)	81.90	(9.16)	89.67	(6.25)	81.90	(9.16)
Barg-Seq	92.94	(9.60)	76.94	(15.00)	92.41	(9.93)	82.01	(8.16)
Mech-Sim	96.38	(5.83)	77.32	(13.58)	96.38	(5.83)	77.32	(13.58)
Mech-Seq	98.86	(3.21)	85.74	(11.82)	100.00	(0.00)	68.45	(16.46)

Note 1: In the sequential treatments, the OEM and Supplier 2 would not bargain unless an agreement was reached between the OEM and Supplier 1. Hence, the agreement rates for Supplier 2 are conditional on an agreement with Supplier 1.
Note 2: Standard deviations, based on the cluster averages are in parentheses.

treatments. However, in contrast to these predictions, supply chain profit is actually higher in the Dyadic treatments for both the bargaining and mechanism institutions (and nearly significantly so, $p = 0.090$ in Barg and $p = 0.105$ in Mech). Thus, an important managerial insight is that agreements are not only more likely when an OEM negotiates with a single integrated supplier but the supply chain profit is also higher, conditional on an agreement being reached, compared to a three-party assembly setting where an OEM must negotiate with two suppliers. Combining these effects by including disagreements (i.e., zero profit), the difference between the supply chain profit of the Dyadic and Assembly treatments is even larger: 1195.70 Dyadic versus 1042.86 Assembly in Barg ($p < 0.019$), and 1226.35 Dyadic versus 1095.58 Assembly in Mech ($p = 0.061$).

Table 5 **Supply Chain Profit (Conditional on Agreement)**

	Sim		Seq		Dyad	
Barg	1394.25	(72.52)	1360.85	(97.61)	1437.90	(75.56)
Mech	1359.08	(108.58)	1450.21	(97.25)	1476.17	(83.21)

Note: Standard deviations, based on the cluster averages are in parentheses.

Result 1 *Agreement rates and supply chain profit, conditional on agreement, are higher in a dyadic supply chain with an integrated supplier versus a three-party assembly setting, for both the bargaining and mechanism institutions.*

5.2. Analysis of the OEM

We now turn to OEMs, who deserve special emphasis because they have a choice as to whether they approach suppliers simultaneously or sequentially in an assembly setting. Beginning with the Assembly treatment in the mechanism design institution, in Table 6, we see that the OEM earns a higher profit when approaching suppliers sequentially (650.69 versus 554.30, $p = 0.077$), where theory predicts that there should be no difference. Under the bargaining institution and assembly, the OEM weakly prefers simultaneous bargaining, though the difference is not significant and theory predicts they are equal (445.57 versus 394.35, $p = 0.493$). The remaining comparisons are consistent with the theoretical predictions. For instance, the OEM earns a significantly higher profit in the dyadic supply chain compared to an assembly supply chain ($p \ll 0.01$).

Table 6 **OEM Profits (Conditional on Agreement)**

	Sim		Seq		Dyad	
Barg	445.57	(114.84)	394.35	(170.49)	720.62	(45.55)
Mech	554.30	(105.15)	650.69	(96.56)	842.23	(93.17)

Note: Standard deviations, based on the cluster averages are in parentheses.

Result 2 *In an assembly system under the mechanism design institution, an OEM earns a higher profit by contracting with suppliers sequentially. Further, the OEM earns significantly higher profit in a dyadic supply chain with an integrated supplier versus a three-party assembly system.*

There appear to be interesting bargaining power dynamics vis-à-vis the bargaining and mechanism institutions and also comparing dyadic supply chains and assembly. Specifically, in all three dynamic bargaining treatments, OEMs earn *more* than the theoretical predictions (Barg-Sim 445.57>370.83, Barg-Seq 394.35>354.17, Barg-Dyad 720.62>598.64). On the other hand, in all three mechanism design treatments, we observe that OEMs earn *less* than predicted (Mech-Sim 554.30<1112.50, Mech-Seq 650.69<1112.50, Mech-Dyad 842.23<1181.25). This suggests that OEMs are unable to fully exploit their bargaining power when they have it (as in the mechanism design institution) and vice-versa.

Moreover, in the bargaining institution the gap between observed and predicted OEM earnings is *larger* (and positive) in the dyadic supply chain than in the assembly system. Similarly, in the mechanism institution, the gap between observed and predicted OEM earnings is *smaller* (and negative) in the dyadic supply chain than in the assembly system. Both of these differences suggest that the relative bargaining power of the OEM appears to be *higher* in a dyadic supply chain than an assembly system. We will explore potential drivers of these outcomes in Section 6.

Result 3 *OEMs do not fully take advantage of their bargaining power in the mechanism design institution, but earn a higher profit than theory in the dynamic bargaining institution. Moreover, in a three-party assembly system, the OEM's bargaining power is diminished compared to a dyadic supply chain with an integrated supplier, relative to theory.*

5.3. Analysis of Suppliers

Table 7 depicts average supplier profits in our experiment, which are generally supportive of the theoretical predictions – at least directionally (see Tables 3b - 3d). To highlight some results: (1) total supplier profit is higher in the Assembly treatments (average 879.87) compared to the Dyadic treatments (average 675.61), for both the bargaining and mechanism institutions, (2) Supplier 1 earns significantly more than Supplier 2 in the Barg-Seq treatment – where a difference is predicted ($p = 0.034$), and (3) in Mech-Seq, Supplier 1 earns more than Supplier 2, but the difference is not significant ($p = 0.130$) and it is not predicted to be.

There is one unsurprising, yet important, managerial result to highlight: although the sum of supplier profits under assembly are higher than the lone supplier's profits in the dyadic system, it is still the case that the lone supplier supplying *both* inputs is better-off than any supplier who supplies only one input. For instance, the highest individual supplier profit among the four Assembly treatments is 534.68, whereas the integrated supplier's profit in the two Dyadic treatments are

717.27 and 633.94. This result is especially interesting because it indicates that both an OEM and a supplier earn a higher profit in a dyadic supply chain.[6]

Table 7 Supplier Profit (Conditional on Agreement)

(a) Total Supplier Profit

	Sim		Seq		Dyad	
Barg	948.67	(126.08)	966.50	(134.85)	717.27	(70.67)
Mech	804.78	(177.43)	799.53	(90.38)	633.94	(81.33)

(b) Supplier 1 Profit

	Sim		Seq		Dyad	
Barg	474.34	(63.04)	534.68	(99.59)	717.27	(70.67)
Mech	402.39	(88.72)	428.34	(51.39)	633.94	(81.33)

(c) Supplier 2 Profit

	Sim		Seq		Dyad
Barg	474.34	(63.04)	431.81	(90.98)	n/a
Mech	402.39	(88.72)	371.19	(76.63)	n/a

Note: Standard deviations, based on the cluster averages are in parentheses.

As noted in (2) and (3) above, in the sequential versions of both institutions, Supplier 1 earned more than Supplier 2 (534.68 and 431.81 in Barg, 428.34 and 371.19 in Mech). More importantly, in the bargaining institution this difference is double the theoretical prediction and weakly significant (predicted profits 604.17 and 554.17). In the mechanism institution, while the difference is not significant, theory predicts that the two suppliers earn exactly the same profit.[7] This anomaly deserves more attention, which we will provide in Section 6.

Result 4 *The directional predictions for supplier profits are largely borne out in the data. One exception is that Supplier 1, in both Barg-Seq and Mech-Seq, earns the same or more than Supplier 2, relative to what theory predicts. In addition, supplier profit is higher in a dyadic supply chain versus an assembly system.*

5.4. Screening and Signaling

Our experiment supports many of the theoretical predictions in terms of comparative statics. In addition, observed supply chain profits are quite close to the theoretical point predictions (within 7.1% in all cases except Barg-Seq, where the difference is 10%). However, the theory is based on the notion that the OEM is able to differentiate between different types of suppliers, and we have already seen a hint that this is not the case with our finding that disagreements are more likely for high-cost suppliers. In this section we now look more closely at screening and signaling.

[6] To be sure, this overlooks other factors that might be important in determining whether it is better to source both inputs from the same supplier or each input separately. Future work should study this more carefully.

[7] The lack of significance in the mechanism institution could be due to a lack of power. Indeed, taking a less conservative approach by using subject averages, rather than cohort the difference is marginally significant at $p = 0.051$.

We begin by studying the agreed contract terms. Although suppliers' costs were private information, we can analyze the agreed contract parameters by supplier cost. The results are shown in Table 8. In the Assembly treatments, average agreed wholesale prices are always above 15, even for low-cost suppliers (where they should be 5). In the Dyadic treatments, average agreed wholesale prices are between 27.78 and 39.09. And while it is true that average wholesale prices increase with supplier cost, the differences are much smaller than theory predicts (e.g., predicted wholesale prices for the three cost types in Dyadic are 5, 25, and 56.21/60, see Table 1). Regarding the average observed fixed fee, they generally decrease in supplier cost (there are exceptions in Barg-Seq and Mech-Dyad), but the differences are again smaller than theory predicts.

Table 8 Average Agreed Contract Parameters

(a) Assembly Treatments

	Barg-Sim	Barg-Seq	Mech-Sim	Mech-Seq
Wholesale Price Low (w_L)	17.17	(19.06, 16.14)	17.44	(16.41, 15.50)
Wholesale Price High (w_H)	20.18	(20.18, 18.18)	18.48	(17.41, 16.64)
Fixed Fee Low (f_L)	163.27	(211.45, 179.19)	153.61	(150.36, 132.22)
Fixed Fee High (f_H)	157.21	(224.22, 166.78)	127.67	(142.15, 116.82)

(b) Dyadic Treatments

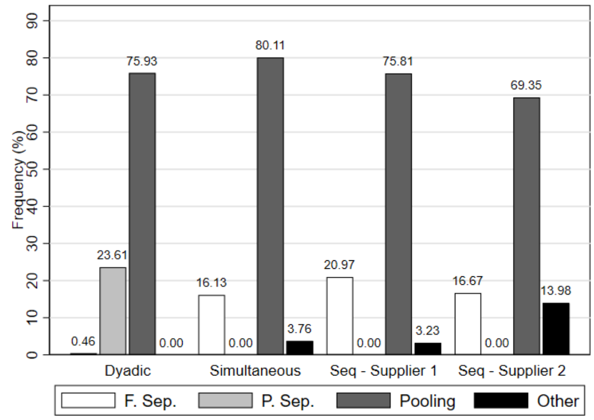
	Barg-Dyad	Mech-Dyad
Wholesale Price Low (w_{LL})	29.12	27.78
Wholesale Price Med (w_{LH})	34.94	33.19
Wholesale Price High (w_{HH})	39.09	34.74
Fixed Fee Low (f_{LL})	229.74	267.12
Fixed Fee Med (f_{LH})	142.53	74.43
Fixed Fee High (f_{HH})	128.52	123.54

Note: For pairs of numbers, (A, B), A represents the contract term to Supplier 1, and B the contract term to Supplier 2.

We turn now to the issue of whether OEMs were able to successfully differentiate between supplier types. The fact that the agreed contract terms are similar across different costs is suggestive that it was difficult to separate suppliers. Beginning with the mechanism institution, Figure 1 shows the frequencies that the menu of contracts separated suppliers by their type, induced pooling (in which all supplier cost types preferred the same contract) or was neither separating nor pooling.[8] In the Dyadic setting, a contract can either be fully separating (F. Sep.) if it separates all three cost types or partially separating (P. Sep.) if the menu of contracts makes it possible to distinguish one supplier cost type, while leaving the other two types indistinguishable.

[8] In some cases, a contract may be neither separating nor pooling if the actions are not consistent with beliefs. For example, under the assumption of pooling, one supplier type may prefer to take the non-pooling contract, while under the assumption of separation, one supplier type may prefer to mimic the other type.

Figure 1 The Frequency of Contract Types under the Mechanism Design Institution (in %)



Note 1: 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. Note that for a contract to be either pooling or separating requires the confluence of beliefs (about what the other supplier will do) and best-response behavior. Therefore, it may be possible for a set of proposed contracts to be *neither* pooling *nor* separating.
Note 2: "F. Sep." means that the contract menu was fully separating between all types, while "P. Sep." means that the contract menu is only able to identify one type, while the other two types are indistinguishable. This distinction is only important in the Dyadic treatment.

One can see that 69.35% to 80.11% of contract menus offered by OEMs should induce pooling by suppliers on the same contract, while only 16.13% to 24.07% of menus successfully separate supplier cost types – either partially or fully. In fact, in the Dyadic setting, there was only *one* proposal that fully separated all three cost types, while another 23.61% of contract menu proposals were partially separating. Observe that explicitly pooling offers (with the two wholesale price offers $w_A = w_B$) were rare, occurring between 9% to 19% of the time. However, consistent with Figure 1, attempts at screening were minimal. Less than half of the offers in which $\bar{w} := \max\{w_A, w_B\} > \min\{w_A, w_B\} =: \underline{w}$ are such that $\underline{w} < 15 \leq \bar{w}$. In the Dyadic treatment, only 2.3% of offers make a minimal attempt to separate the three types with $w_l < 20 \leq w_m < 30 \leq w_h$, where l, m and h subscripts indicate the lowest, middle and highest wholesale price offer.[9] Lastly, for the mechanism institution, one might wonder whether OEMs who made separating contract offers earned more than OEMs who did not. While there is no significant difference in Mech-Sim and Mech-Dyad, separating contract proposals in Mech-Seq did generate significantly higher earnings for the OEM.

We also investigated whether there is learning happening with respect to proposing separating contracts by the OEM. Between the first and second half of rounds, the frequency in which OEMs offer separating contracts (either partial or full) increases, but not significantly so in any of the three

[9] However, this may not represent a lack of understanding as OEMs used the decision support feature to test the profit implications of many potential contracts. For example, in Mech-Sim, OEMs tested an average of 6.49 contracts per period and in Mech-Seq, they tested an average of 9.34. Moreover, a strong majority of the time, an OEM tested at least one contract pair that involved one wholesale price less than 15 and the other 15 or higher.

Table 9 **Initial Offers By OEM and Supplier Cost Type in the Dynamic Bargaining Institution (Assembly Only)**

(a) Barg-Sim

Player Making Offer	Wholesale Price		Fixed Payment		% $w < 15$	
OEM	12.67	(2.47)	31.81	(198.75)	58.29	(16.49)
Low Cost Supplier	22.87	(3.43)	329.37	(87.20)	11.59	(15.62)
High Cost Supplier	26.09	(2.48)	333.32	(62.10)	1.90	(2.68)

(b) Barg-Seq

Player Making Offer	Wholesale Price		Fixed Payment		% $w < 15$	
OEM to Supplier 1	13.49	(3.89)	68.22	(133.84)	53.17	(21.46)
Low Cost Supplier 1	24.57	(4.76)	303.27	(78.24)	12.23	(19.81)
High Cost Supplier 1	27.16	(2.54)	317.10	(85.31)	0.00	(0.00)
OEM to Supplier 2	12.67	(3.42)	38.00	(123.22)	59.19	(21.05)
Low Cost Supplier 2	19.27	(2.24)	235.95	(114.88)	20.08	(17.27)
High Cost Supplier 2	23.75	(2.92)	286.53	(104.76)	3.65	(6.84)

Note: Standard deviations, based on the cluster averages are in parentheses.

mechanism treatments (second half overall average of 23.5%). Interestingly, this modest increase coincides with a significant increase in OEM profit but not supplier profit (i.e., OEM's learn to increase their profit while keeping suppliers' constant).

Regarding the dynamic bargaining institution, in the interest of space, we focus on the Assembly setting. In this setting 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 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 9.

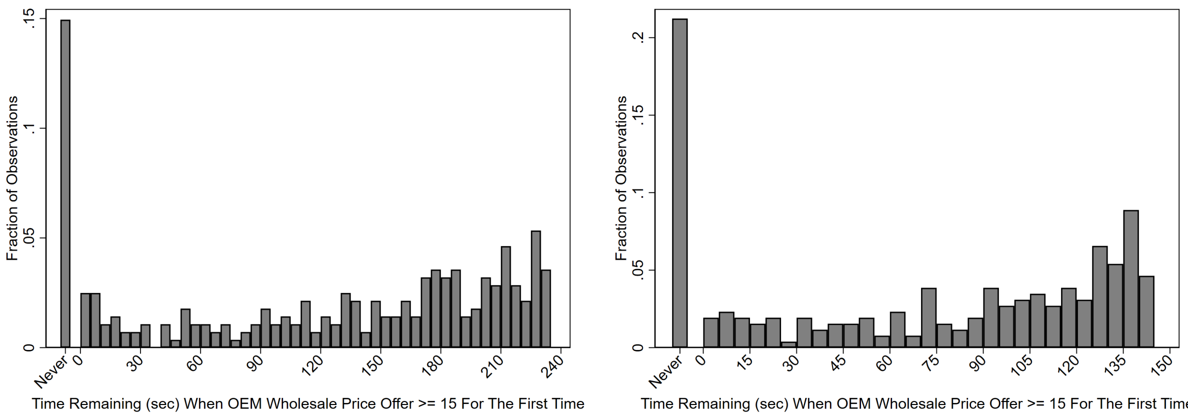
As one can see, the average OEM initial wholesale price offer is always below 15, and between 53.17% and 59.19% of initial OEM wholesale price offers are below 15, which suggests that a majority of OEMs do attempt to screen between suppliers cost types. For suppliers, the average initial wholesale price 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, 11.59% to 20.08%, 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 (0.00% to 3.65%). This suggests that there is some attempt at screening by OEMs and some 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 for the first time.[10] As one can observe, there is a great deal of variation and 15%

[10] There are a few instances in which an OEM never proposes a wholesale price of 15 or higher but they accepted

Figure 2 **Temporal Screening By OEMs in the Dynamic Bargaining Institution (Assembly Treatments Only)**

(a) Barg-Sim (b) Barg-Seq



and 20% 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 9, this suggests that there is a great deal of heterogeneity in OEMs' willingness to engage in temporal screening.

Result 5 *OEMs engage in limited attempts to screen between high and low-cost suppliers, particularly in the mechanism institution. In the bargaining institution, OEMs attempt temporal screening about half the time, but most eventually give up and offer a wholesale price greater than 15.*

6. Discussion

In this section we seek to provide a discussion of the underlying behavioral drivers of our experimental results and to summarize how our results fit within the broader literature.

6.1. Behavioral Drivers: Bounded Rationality and Fairness

We believe that there are two biases that are influencing outcomes in our setting: bounded rationality and fairness. At a high level, bounded rationality relates to the notion that decision makers are limited in their cognitive abilities and are therefore prone to errors. When designing our experiment we aimed to minimize the role that bounded rationality played in explaining any differences across treatments (by providing decision support), but it is still likely that a certain degree of bounded rationality is present. This is especially true given the complexity of decisions in our experiment, resulting in participants potentially making errors or opting for simpler alternatives. This would not be without precedent. For instance, multiple supply chain experiments have found that decision

such a wholesale price offer made by a supplier. In these instances, we take the time when such an offer was accepted.

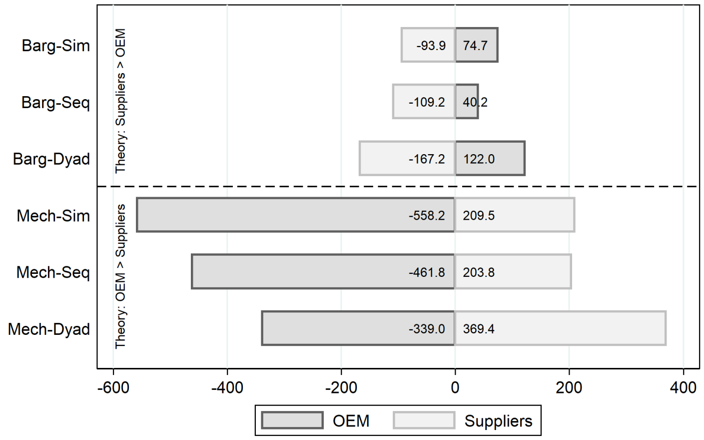
makers are rarely able to leverage the benefits of more complicated contracts and end up preferring simpler contracts (e.g., Kalkanci et al. (2011), Cui et al. (2020)).

Turning to fairness, there is an extensive literature showing that when one party is predicted to earn significantly more than another party, the observed magnitude of this difference is often less than predicted (Fehr and Schmidt 1999, Bolton and Ockenfels 2000). In addition to this *distributional* fairness, more recent research has shown that *peer-induced* fairness can also affect decisions. For example, in a three-player ultimatum game with one proposer and two responders, Ho and Su (2009) show that distributional fairness can exist (between responders and the proposer) simultaneously with peer-induced fairness (between responders). In our setting, there are a couple of reasons why fairness is plausible. In all of our treatments one party is predicted to make considerably more than the other. If distributional fairness is present then we should see more equitable payoffs between OEMs and suppliers, along with the rejection of profitable offers by responding parties. Also, because our assembly environment involves two suppliers, it is possible that peer-induced fairness may influence outcomes (e.g., this may explain why the OEM's bargaining power appears weaker in the assembly versus dyadic setting). Lastly, it is important to note that fairness, in conjunction with bounded rationality, has been observed in a number of related contracting experiments (e.g., Kalkanci et al. (2014), Johnsen et al. (2019)).

We believe that bounded rationality and fairness can rationalize our key experimental results. First consider Result 5, which states that OEMs often set pooling contracts. One can show – see Appendix D – that the screening contracts are not robust to bounded rationality. In short, if OEMs are prone to errors, they may be better off setting a – cognitively less demanding – pooling contract than a poorly designed contract which attempts to separate supplier types. Moreover, observe that the optimal pooling contract generates more equitable payoffs than the optimal separating contact, which is consistent with our result that more powerful parties do not fully exploit their bargaining power (Result 3). To provide further support for the role of fairness, consider Figure 3 which plots the difference between actual and predicted profits for the OEM and suppliers for each treatment. A positive (negative) number indicates that the party earns more (less) than theory predicts. As can be seen, for all of the Mech treatments, the OEM consistently earns less than theory and suppliers consistently earn more than theory. On the other hand, for all of the Barg treatments, the reverse is true. We also see evidence of fairness when we look at rejections, where we observe suppliers rejecting positive expected value (but unequal) offers.[11]

[11] The Mech-Dyad treatment is best-suited to this analysis. Over 75% of rejected offers would have generated positive profit to the supplier. However, they also heavily favored the proposer. In the Barg-Dyad treatment, in the case of

Figure 3 Difference in Profits Relative to Theory for the OEM and Suppliers



Note: Average interim profits for suppliers.

We also believe that fairness and bounded rationality can explain our two results about sequential contracting. Specifically, recall that Supplier 2 earned a lower profit than Supplier 1 under sequential contracting (Result 4), which is due to the OEM making less favorable offers to Supplier 2. If Supplier 2 incorrectly believes – a form of bounded rationality – that she is getting the same contract terms as Supplier 1, and if she is motivated by peer-induced fairness, she may be willing to accept the OEM's offer, even though it actually leads to a lower profit than Supplier 1. This can also explain the experimental result that the OEM prefers sequential contracting in the mechanism design institution (Result 2), because the OEM can more easily exploit Supplier 2's bounded rationality and fairness concerns in such a setting.

Lastly, fairness and bounded rationality can explain both the higher agreement rate and the higher supply chain profit in the dyadic supply chain than assembly system (Result 1). For example, uncertainty about what constitutes a fair deal may lead to disagreement and, if fairness ideals are heterogeneous (and independent), then the likelihood of disagreement is higher with three parties. Regarding supply chain profit, first observe while the supply chain profit is lower in a dyadic supply chain, assuming the use of separating contracts, the optimal pooling contract achieves the same profit in a dyadic supply chain as in assembly. Thus, the fact that most contracts are pooling removes the penalty to the dyadic supply chain. To see how supply chain profit can be higher under a dyadic supply chain we appeal to fairness. In our setting, the optimal pooling contract in both the

eventual disagreement, final offers were also quite unequal (in favor of the proposer), despite frequently providing the other player with a positive profit. In the assembly environment, it is more difficult to say that an offer would have led to positive expected profit because the expected profit calculation relies on the supplier's beliefs about the agreement between the OEM and the other supplier. However, with a plausible assumption on beliefs (that suppliers receive the same offers) then a majority of disagreements would have led to positive profit for all parties in the assembly environment as well.

dyadic and assembly settings gives the OEM the same profit. The difference is that under assembly, the amount left over must be divided across two suppliers. Therefore, the difference between each supplier's profit and the OEM's profit is greater under assembly. To compensate for this, we see that OEMs offer higher total wholesale prices in assembly (i.e., $w_1 + w_2$) than the dyadic supply chain (i.e., w), which reduces the efficiency of the assembly system relative to the dyadic system.[12]

6.2. Connection to Literature

We now distinguish between those results which we believe are entirely new versus those which have been observed in related experiments and therefore extend to our setting. While our discussion focuses on the experimental findings, we stress that our theoretical analysis of dynamic bargaining in assembly with private information is novel to the literature. Importantly, certain aspects of it are validated experimentally as well, such as many qualitative profit predictions.

Regarding our experiment, we believe that there two important and new experimental results, which correspond to our research questions. First, powerful OEMs earn higher profits by contracting with suppliers sequentially. Second, moving from a dyadic supply chain to an assembly system comes at a cost, both in terms of more frequent disagreement and lower supply chain profit conditional on agreement.

The remaining experimental results can be considered as extensions of previous research, including the presence of bounded rationality and fairness. First, more equitable profit distributions between proposers and responders have been observed in various supply chain experiments with a single supplier (e.g., Kalkanci et al. (2014)). Second, Supplier 2, earning a lower profit than Supplier 1 under sequential contracting, echoes a result first found in Ho et al. (2014). In particular, they find that in a game between a powerful supplier and two (responding) retailers, with full information and ultimatum offers, the second retailer earns less than the first. Third, the low prevalence of screening contracts, notably in the presence of bounded rationality and fairness, has been observed in related private information studies with ultimatum offers (e.g., Johnsen et al. (2020)).

7. Concluding Remarks

In this paper we study the contracting problem of an OEM who needs to procure two distinct inputs, which it then assembles into a final product. Our main focus and contribution is to consider an assembly system in which the OEM procures one input from each supplier, each of which is privately informed of its cost. In this basic setting, we seek to understand whether the timing of

[12] To be sure, the OEM could have increased compensation to suppliers via the fixed payment, without reducing efficiency. The fact that they did not is another indication of bounded rationality.

contracting – either simultaneously or sequentially – matters and also how this assembly system compares to a dyadic supply chain in which the OEM sources both inputs from the same supplier.

We provide theoretical results for both the case in which the OEM is powerful and can make take-it-or-leave-it offers to suppliers (*mechanism design*) and for the case of more balanced bargaining power between the OEM and suppliers (*dynamic bargaining*), with the latter case being a novel contribution to the literature. Our experiment then sought to test the predictions generated by our theoretical analysis, many of which are borne out with some deviations. As discussed in the previous section, we believe that bounded rationality and fairness concerns are able to explain the key findings. Indeed, we believe that future research could extend our work by explicitly aiming to investigate these behavioral drivers in an assembly system, in order to gain further insights.

Our analysis generates managerial insights regarding how managers should approach negotiating with suppliers and, if possible, building their supply chain. For one, we found that when the OEM has considerable bargaining power in the assembly system, it prefers to contract with suppliers sequentially; when the OEM has relatively equal bargaining power, it weakly prefers to contract with suppliers simultaneously. A second important managerial finding is that both the OEM, when it is able to potentially sole-source inputs, and the supply chain suffer when moving from a dyadic supply chain to an assembly system. In particular, we showed that disagreements are more common and both OEM and supply chain profits, conditional on agreement, are lower in an assembly system.

Our paper is not without limitations. First, we assumed that suppliers are symmetric. It would be interesting to consider supplier heterogeneity. For example, while Apple likely has significant power over many of its suppliers, its relationship with Samsung is almost surely more balanced. Investigating such a setting might be an exciting, and challenging, avenue for future work. Second, in our dyadic setting we assumed that only one supplier could provide the required inputs. It would be interesting to explore competition among suppliers, where multiple suppliers can provide all required inputs for the OEM.

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Appendix. Technical Proofs and Additional Results

A. Dynamic Bargaining in Assembly

A.1. Simultaneous Bargaining

Consider the primal problem and IC/IR constraints in Section 3.1.1. For example, the IR and IC constraints for Supplier 1 are as follows:

$$p(P_{1HH}-c_HQ_{HH})+\bar{p}(P_{1HL}-c_HQ_{HL})\geq 0 \quad (\mathrm{IR}_{1H})$$
$$p(P_{1LH}-c_LQ_{LH})+\bar{p}(P_{1LL}-c_LQ_{LL})\geq 0 \quad (\mathrm{IR}_{1L})$$
$$p(P_{1HH}-c_HQ_{HH})+\bar{p}(P_{1HL}-c_HQ_{HL})\geq p(P_{1LH}-c_HQ_{LH})+\bar{p}(P_{1LL}-c_HQ_{LL}) \quad (\mathrm{IC}_{1H})$$
$$p(P_{1LH}-c_LQ_{LH})+\bar{p}(P_{1LL}-c_LQ_{LL})\geq p(P_{1HH}-c_LQ_{HH})+\bar{p}(P_{1HL}-c_LQ_{HL}) \quad (\mathrm{IC}_{1L})$$

We first reduce the IR and IC constraints following standard procedures. Note that IC_{1L} and IR_{1H} imply IR_{1L}:

$$\begin{aligned}&p(P_{1LH}-c_LQ_{LH})+\bar{p}(P_{1LL}-c_LQ_{LL})\geq p(P_{1HH}-c_LQ_{HH})+\bar{p}(P_{1HL}-c_LQ_{HL})\ (\mathrm{IC}_{1L})\\ \geq&p(P_{1HH}-c_HQ_{HH})+\bar{p}(P_{1HL}-c_HQ_{HL})\geq 0\ (\mathrm{IR}_{1H}).\end{aligned}$$

Next, note that a binding IC_{1L} and monotonicity constraints $Q_{HY}\leq Q_{LY},\ Y\in\{L,H\}$ (MN_1) imply IC_{1H}:

$$\begin{aligned}p(P_{1HH}-c_LQ_{HH})+\bar{p}(P_{1HL}-c_LQ_{HL})=&p(P_{1LH}-c_LQ_{LH})+\bar{p}(P_{1LL}-c_LQ_{LL})\ (\text{binding } \mathrm{IC}_{1L}),\\ p(c_L-c_H)Q_{HH}+\bar{p}(c_L-c_H)Q_{HL}\geq&p(c_L-c_H)Q_{LH}+\bar{p}(c_L-c_H)Q_{LL}\ (\mathrm{MN}_1),\\ \Rightarrow p(P_{1HH}-c_HQ_{HH})+\bar{p}(P_{1HL}-c_HQ_{HL})\geq&p(P_{1LH}-c_HQ_{LH})+\bar{p}(P_{1LL}-c_HQ_{LL})\ (\mathrm{IC}_{1H}).\end{aligned}$$

For the case where IC_{1L} is not binding under the bargaining solution (derived in Proposition A.1), one may verify that IC_{1H} is still satisfied. As a result, all IC and IR constraints in the primal problem can be replaced by the IR constraint for the OEM IR_o, and IR_{iH}, IC_{iL}, MN_i; $i=1,2$.

Let us temporarily ignore the IR and MN constraints and verify them later. Also note that the requirement of $\bar{\lambda}_i=1-\lambda_i$ follows from the common assumptions of independent supplier types and transferrable utilities (i.e., payments) among stakeholders; see Section 4 of Myerson (1984a). Let the shadow price of Supplier i's IC_{iL} constraint be α_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, its virtual utility equals its profit.

$$\begin{aligned}v_o(\mathbf{P},\mathbf{Q})\doteq&p^2[(a-Q_{HH}/2)Q_{HH}-P_{1HH}-P_{2HH}]+\bar{p}p[(a-Q_{LH}/2)Q_{LH}-P_{1LH}-P_{2LH}]+\\&p\bar{p}[(a-Q_{HL}/2)Q_{HL}-P_{1HL}-P_{2HL}]+\bar{p}^2[(a-Q_{LL}/2)Q_{LL}-P_{1LL}-P_{2LL}]\\ v_{1LY}(\mathbf{P},\mathbf{Q},\lambda,\alpha)\doteq&\frac{\bar{\lambda}_1+\alpha_1}{\bar{p}}(P_{1LY}-c_LQ_{LY})\\ v_{1HY}(\mathbf{P},\mathbf{Q},\lambda,\alpha)\doteq&\frac{1}{p}[\lambda_1(P_{1HY}-c_HQ_{HY})-\alpha_1(P_{1HY}-c_LQ_{HY})]\\ v_{2XL}(\mathbf{P},\mathbf{Q},\lambda,\alpha)\doteq&\frac{\bar{\lambda}_2+\alpha_2}{\bar{p}}(P_{2XL}-c_LQ_{XL})\end{aligned}$$

$$v_{2XH}(\mathbf{P},\mathbf{Q},\lambda,\alpha) \doteq \frac{1}{p}[\lambda_2(P_{2XH}-c_HQ_{XH})-\alpha_2(P_{2XH}-c_LQ_{XH})]$$

The Lagrange dual of the primal problem can be presented using the virtual utilities as follows:

$$\begin{aligned}\min_{\alpha_i}\max_{\mathbf{P},\mathbf{Q}}\ & v_o(\mathbf{P},\mathbf{Q})+\bar{p}pv_{1LH}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+p^2v_{1HH}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+\bar{p}^2v_{1LL}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+p\bar{p}v_{1HL}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+\\ & p\bar{p}v_{2HL}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+p^2v_{2HH}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+\bar{p}^2v_{2LL}(\mathbf{P},\mathbf{Q},\lambda,\alpha)+\bar{p}pv_{2LH}(\mathbf{P},\mathbf{Q},\lambda,\alpha)\\ s.t.\ & \alpha_i+p-\lambda_i=0;\ \alpha_i\geq 0,\ i=1,2.\end{aligned}$$

We note that the objective function is the expected total virtual utilities of the assembly system. The constraint $\alpha_i+p-\lambda_i=0$ ensures the dual problem to be bounded (or equivalently, for the primal problem to be feasible). Solving the problem, we find that the optimal shadow prices $\alpha_i^*=\lambda_i-p$; $i=1,2$. The optimal sourcing quantities Q^*_{XY} are as follows:

$$\begin{aligned}Q^*_{HH}&=a-2c_H-\frac{(\lambda_1-p)\Delta}{p}-\frac{(\lambda_2-p)\Delta}{p}, & Q^*_{LL}&=a-2c_L,\\ Q^*_{LH}&=a-c_L-c_H-\frac{(\lambda_2-p)\Delta}{p}, & Q^*_{HL}&=a-c_H-\frac{(\lambda_1-p)\Delta}{p}-c_L.\end{aligned} \tag{A-1}$$

It is trivial to verify that the monotonicity constraints MN$_i$'s are satisfied. The corresponding optimal objective value is

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

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 Δ_{1X} be the conditional expected virtual utility of the assembly system when Supplier 1's type is X as follows:

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

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 stakeholder-type 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.

$$W_{1L}=\frac{\Delta_{1L}}{3},\quad \frac{1}{p}\cdot[\lambda_1W_{1H}-(\lambda_1-p)W_{1L}]=\frac{\Delta_{1H}}{3}.$$

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

$$W^*_{1L}=\frac{\Delta_{1L}}{3},\quad W^*_{1H}=\frac{p\Delta_{1H}}{3\lambda_1}+\frac{\lambda_1-p}{\lambda_1}\cdot\frac{\Delta_{1L}}{3}.$$

The next proposition shows the complete bargaining solution and its proof details the analysis.

Proposition A.1 **(Simultaneous bargaining solution)**.
Let $\overline{a} \doteq 2c_L + \frac{(5+4p)\Delta}{4p}$ *and* $\underline{a} \doteq 2c_L + \frac{(5+4p)\Delta}{4}$. *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* λ_i *in equations* (A-1) *by the corresponding values below.*

Case 1: $a \le \underline{a}$. *In this case,* $\lambda_1 = \lambda_2 = \lambda^* \doteq p$. *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: $\underline{a} < a < \overline{a}$. *In this case,* $\lambda_1 = \lambda_2 = \lambda^* \doteq \frac{4p(a-2c_L)}{(5+4p)\Delta}$. *The expected payments for a supplier with type* L *and* H *respectively are*

$$P_L^* = \frac{a-2c_L}{6(4p+5)^2}[a(16p+25) + 4c_L(22p+25) - 16p^2(a-2c_L)],$$
$$P_H^* = \frac{a-2c_L}{6(4p+5)^2}[a(16p+25) + 4c_L(2p+5) - 16p^2(a-2c_L)].$$

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

$$P_L^* = \frac{(a-2c_L)(a+4c_L)}{6} + \Delta\frac{a-5c_L}{3} - 2\Delta^2\frac{1+p}{3p},$$
$$P_H^* = \frac{a^2+2ac_L-4c_L^2}{6} - \frac{2c_L^2}{3p} + \Delta\frac{pa-(3+5p)c_L}{3p} - 2\Delta^2\frac{1+p}{3p}.$$

Proof. We complete the derivation of the bargaining solutions as follows. Recall that P_{iX} denotes the expected payment to Supplier i when its 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 λ_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 $\lambda_i \in (p,1)$.

$$\begin{aligned}
&P_{1L} - c_L(a-2c_L) + c_L\Delta\lambda_2 = W_{1L}^*,\\
&P_{1H} - c_H\left(a - c_H - \frac{(\lambda_1-p)\Delta}{p} - c_L\right) + c_H\Delta\lambda_2 = W_{1H}^*,\\
&P_{2L} - c_L(a-2c_L) + c_L\Delta\lambda_1 = W_{2L}^*,\\
&P_{2H} - c_H\left(a - c_H - \frac{(\lambda_2-p)\Delta}{p} - c_L\right) + c_H\Delta\lambda_1 = W_{2H}^*,\\
&P_{1L} - c_L(a-2c_L) = P_{1H} - c_L\left(a - c_H - \frac{(\lambda_1-p)\Delta}{p} - c_L\right),\\
&P_{2L} - c_L(a-2c_L) = P_{2H} - c_L\left(a - c_H - \frac{(\lambda_2-p)\Delta}{p} - c_L\right).
\end{aligned}$$

Thus we obtain the following solutions on λ_i's and P_{iX}^*'s.

$$\lambda_1^* = \lambda_2^* = \frac{4p(a-2c_L)}{(5+4p)\Delta},$$

$$P_{1L}^* = P_{2L}^* = \frac{a-2c_L}{6(4p+5)^2}[a(16p+25)+4c_L(22p+25)-16p^2(a-2c_L)],$$
$$P_{1H}^* = P_{2H}^* = \frac{a-2c_L}{6(4p+5)^2}[a(16p+25)+4c_L(2p+5)-16p^2(a-2c_L)].$$

Defining the following critical values, where $\overline{a} \geq \underline{a}$:

$$\overline{a} \doteq 2c_L + \frac{(5+4p)\Delta}{4p},$$
$$\underline{a} \doteq 2c_L + \frac{(5+4p)\Delta}{4},$$

we note that when $\underline{a} < a < \overline{a}$, 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: $a \leq \underline{a}$ and $a \geq \overline{a}$. We focus on the symmetric solutions where $\lambda_1 = \lambda_2$ and $P_{1X} = P_{2X}$ due to the *ex ante* symmetry of the two suppliers.

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

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

We next solve for the warranted claims:

$$W_L^* = \frac{\Delta_L}{3},\ W_H^* = \frac{\Delta_H}{3}.$$

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

$$P_L^* = c_L(a-2c_L) - c_L\Delta p + \frac{p}{6}(a-c_L-c_H)^2 + \frac{\bar{p}}{6}(a-2c_L)^2,$$
$$P_H^* = c_H(a-c_H-c_L) - c_H\Delta p + \frac{p}{6}(a-2c_H)^2 + \frac{\bar{p}}{6}(a-c_H-c_L)^2.$$

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

$$P_L^* - c_L(a-2c_L) > P_H^* - c_L(a-c_H-c_L).$$

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.

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

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

We next solve for the warranted claim:

$$W_L^* = \frac{\Delta_L}{3},\ W_H^* = \frac{p\Delta_H}{3} + \frac{\bar{p}\Delta_L}{3}.$$

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

$$\begin{aligned} P_L^* &= \frac{(a-2c_L)(a+4c_L)}{6} + \Delta\frac{a-5c_L}{3} - 2\Delta^2\frac{1+p}{3p},\\ P_H^* &== \frac{a^2+2ac_L-4c_L^2}{6} - \frac{2c_L^2}{3p} + \Delta\frac{pa-(3+5p)c_L}{3p} - 2\Delta^2\frac{1+p}{3p}. \end{aligned}$$

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

$$\begin{aligned} \Delta_L(\varepsilon) =& \frac{p}{2}\left[a - c_L - c_H - \frac{(\bar{p}-\varepsilon)\Delta}{p}\right]^2 + \frac{\bar{p}}{2}\left[a - 2c_L\right]^2,\\ \Delta_H(\varepsilon) =& \frac{p}{2}\left[a - 2c_H - \frac{2(\bar{p}-\varepsilon)\Delta}{p}\right]^2 + \frac{\bar{p}}{2}\left[a - c_H - \frac{(\bar{p}-\varepsilon)\Delta}{p} - c_L\right]^2. \end{aligned}$$

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

$$W_L^*(\varepsilon) = \frac{\Delta_L(\varepsilon)}{3},\ W_H^*(\varepsilon) = \frac{p\Delta_H(\varepsilon)}{3(1-\varepsilon)} + \frac{\bar{p}-\varepsilon}{1-\varepsilon}\cdot\frac{\Delta_L(\varepsilon)}{3},\ W_O^*(\varepsilon) = \frac{\bar{p}\Delta_L(\varepsilon)+p\Delta_H(\varepsilon)}{3}.$$

We note that

$$\lim_{\varepsilon\to 0} W_L^*(\varepsilon) = W_L^*,\ \lim_{\varepsilon\to 0} W_H^*(\varepsilon) = W_H^*,\ \lim_{\varepsilon\to 0} W_O^*(\varepsilon) = \frac{\bar{p}\Delta_L + p\Delta_H}{3}.$$

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. □

A.2. Sequential Bargaining

Second-stage bargaining. We focus on cases where only the more efficient types' IC constraints may be binding, and temporarily ignore the IR and less efficient types' IC constraints. The primal bargaining problem becomes

$$\begin{aligned} \max_{\substack{\mathbf{w_{2H}},\mathbf{f_{2H}},\\ \mathbf{w_{2L}},\mathbf{f_{2L}}}}\ & \bar{\lambda}_o\left\{p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2} - f_{1L}^\dagger - f_{2LH}\right] + \bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2} - f_{1L}^\dagger - f_{2LL}\right]\right\} +\\ & \lambda_o\left\{p\left[\frac{(a-w_{1H}^\dagger-w_{2HH})^2}{2} - f_{1H}^\dagger - f_{2HH}\right] + \bar{p}\left[\frac{(a-w_{1H}^\dagger-w_{2HL})^2}{2} - f_{1H}^\dagger - f_{2HL}\right]\right\} +\\ & \bar{\lambda}_2\{p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})+f_{2HL}] + \bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})+f_{2LL}]\}+\\ & \lambda_2\{p[(w_{2HH}-c_H)(a-w_{1H}^\dagger-w_{2HH})+f_{2HH}] + \bar{p}[(w_{2LH}-c_H)(a-w_{1L}^\dagger-w_{2LH})+f_{2LH}]\}\\ \text{s.t. }& p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})+f_{2HL}] + \bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})+f_{2LL}]\\ & \geq p[(w_{2HH}-c_L)(a-w_{1H}^\dagger-w_{2HH})+f_{2HH}] + \bar{p}[(w_{2LH}-c_L)(a-w_{1L}^\dagger-w_{2LH})+f_{2LH}] \qquad (\text{IC}_{2L})\\ & p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2} - f_{1L}^\dagger - f_{2LH}\right] + \bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2} - f_{1L}^\dagger - f_{2LL}\right]\\ & \geq p\left[\frac{(a-w_{1L}^\dagger-w_{2HH})^2}{2} - f_{1L}^\dagger - f_{2HH}\right] + \bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2HL})^2}{2} - f_{1L}^\dagger - f_{2HL}\right] \qquad (\text{IC}_{OL}) \end{aligned}$$

Let the shadow price of Supplier 2's IC constraint be α_2 and the shadow price of the OEM's IC constraint be α_o. The Lagrange dual problem is as follows:

$$\begin{aligned}
\min_{\alpha_2,\alpha_o} \max_{\substack{\mathbf{w_{2H}},\mathbf{f_{2H}},\\ \mathbf{w_{2L}},\mathbf{f_{2L}}}} \ & \bar{\lambda}_o\left\{p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2}-f_{1L}^\dagger-f_{2LH}\right]+\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2}-f_{1L}^\dagger-f_{2LL}\right]\right\}+\\
& \lambda_o\left\{p\left[\frac{(a-w_{1H}^\dagger-w_{2HH})^2}{2}-f_{1H}^\dagger-f_{2HH}\right]+\bar{p}\left[\frac{(a-w_{1H}^\dagger-w_{2HL})^2}{2}-f_{1H}^\dagger-f_{2HL}\right]\right\}+\\
& \bar{\lambda}_2\{p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})+f_{2HL}]+\bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})+f_{2LL}]\}+\\
& \lambda_2\{p[(w_{2HH}-c_H)(a-w_{1H}^\dagger-w_{2HH})+f_{2HH}]+\bar{p}[(w_{2LH}-c_H)(a-w_{1L}^\dagger-w_{2LH})+f_{2LH}]\}+\\
& \alpha_2\left\{\begin{array}{l} p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})+f_{2HL}]+\bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})+f_{2LL}]- \\ p[(w_{2HH}-c_L)(a-w_{1H}^\dagger-w_{2HH})+f_{2HH}]-\bar{p}[(w_{2LH}-c_L)(a-w_{1L}^\dagger-w_{2LH})+f_{2LH}]\end{array}\right\}+\\
& \alpha_o\left\{\begin{array}{l} p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2}-f_{1L}^\dagger-f_{2LH}\right]+\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2}-f_{1L}^\dagger-f_{2LL}\right]- \\ p\left[\frac{(a-w_{1L}^\dagger-w_{2HH})^2}{2}-f_{1L}^\dagger-f_{2HH}\right]-\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2HL})^2}{2}-f_{1L}^\dagger-f_{2HL}\right]\end{array}\right\}\\
\text{s.t. } & \alpha_2+p-\lambda_2=0;\ \alpha_o+p-\lambda_o=0;\ \alpha_2\geq 0;\ \alpha_o\geq 0.
\end{aligned}$$

For the problem to be feasible, we require $\lambda_o \geq p$ and $\lambda_2 \geq p$. Observing $\alpha_2+p-\lambda_2=0$ and $\alpha_o+p-\lambda_o=0$ (conditions to ensure boundedness of the dual), the Lagrange function can be simplified into

$$\begin{aligned}
& \bar{\lambda}_o\left\{p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2}-f_{1L}^\dagger\right]+\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2}-f_{1L}^\dagger\right]\right\}+\\
& \lambda_o\left\{p\left[\frac{(a-w_{1H}^\dagger-w_{2HH})^2}{2}-f_{1H}^\dagger\right]+\bar{p}\left[\frac{(a-w_{1H}^\dagger-w_{2HL})^2}{2}-f_{1H}^\dagger\right]\right\}+\\
& \bar{\lambda}_2\{p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})]+\bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})]\}+\\
& \lambda_2\{p[(w_{2HH}-c_H)(a-w_{1H}^\dagger-w_{2HH})]+\bar{p}[(w_{2LH}-c_H)(a-w_{1L}^\dagger-w_{2LH})]\}+\\
& \alpha_2\left\{\begin{array}{l} p[(w_{2HL}-c_L)(a-w_{1H}^\dagger-w_{2HL})]+\bar{p}[(w_{2LL}-c_L)(a-w_{1L}^\dagger-w_{2LL})]- \\ p[(w_{2HH}-c_L)(a-w_{1H}^\dagger-w_{2HH})]-\bar{p}[(w_{2LH}-c_L)(a-w_{1L}^\dagger-w_{2LH})]\end{array}\right\}+\\
& \alpha_o\left\{p\left[\frac{(a-w_{1L}^\dagger-w_{2LH})^2}{2}\right]+\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL})^2}{2}\right]-p\left[\frac{(a-w_{1L}^\dagger-w_{2HH})^2}{2}\right]-\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2HL})^2}{2}\right]\right\}
\end{aligned}$$

Solving the dual yields

$$\begin{aligned}
w_{2HH}^\dagger &= c_H+\frac{(\lambda_2-p)\Delta}{p}+\frac{(\lambda_o-p)(w_{1H}^\dagger-w_{1L}^\dagger)}{p}, & w_{2LL}^\dagger &= c_L,\\
w_{2HL}^\dagger &= c_L+\frac{(\lambda_o-p)(w_{1H}^\dagger-w_{1L}^\dagger)}{p}, & w_{2LH}^\dagger &= c_H+\frac{(\lambda_2-p)\Delta}{p}.
\end{aligned}$$

We next derive the condition that guarantees the equitable share of profits among the stakeholders. Let Δ_{oX} (resp., Δ_{2X}) be the conditional expected virtual utility of the OEM and Supplier 2 when the OEM's (resp., Supplier 2's) type is X as follows:

$$\begin{aligned}
\Delta_{oL} \doteq & p\left[\frac{(a-w_{1L}^\dagger-w_{2LH}^\dagger)^2}{2}-f_{1L}^\dagger\right]+\bar{p}\left[\frac{(a-w_{1L}^\dagger-w_{2LL}^\dagger)^2}{2}-f_{1L}^\dagger\right]+\bar{p}(w_{2LL}^\dagger-c_L)(a-w_{1L}^\dagger-w_{2LL}^\dagger)+\\
& p\left(w_{2LH}^\dagger-\frac{\lambda_2}{p}c_H+\frac{\lambda_2-p}{p}c_L\right)(a-w_{1L}^\dagger-w_{2LH}^\dagger) \qquad \text{(A-3)}\\
\Delta_{oH} \doteq & \frac{\lambda_o}{p}\left\{p\left[\frac{(a-w_{1H}^\dagger-w_{2HH}^\dagger)^2}{2}-f_{1H}^\dagger\right]+\bar{p}\left[\frac{(a-w_{1H}^\dagger-w_{2HL}^\dagger)^2}{2}-f_{1H}^\dagger\right]\right\}-
\end{aligned}$$

$$\frac{\lambda_o - p}{p}\left\{p\left[\frac{(a-w_{1L}^\dagger - w_{2HH}^\dagger)^2}{2} - f_{1L}^\dagger\right] + \bar{p}\left[\frac{(a-w_{1L}^\dagger - w_{2HL}^\dagger)^2}{2} - f_{1L}^\dagger\right]\right\} +$$
$$\bar{p}(w_{2HL}^\dagger - c_L)(a-w_{1H}^\dagger - w_{2HL}^\dagger) + p\left(w_{2HH}^\dagger - \frac{\lambda_2}{p}c_H + \frac{\lambda_2 - p}{p}c_L\right)(a - w_{1H}^\dagger - w_{2HH}^\dagger) \tag{A-4}$$

$$\Delta_{2L} \doteq \bar{p}\left[\frac{(a-w_{1L}^\dagger - w_{2LL}^\dagger)^2}{2} - f_{1L}^\dagger\right] + \lambda_o\left[\frac{(a-w_{1H}^\dagger - w_{2HL}^\dagger)^2}{2} - f_{1H}^\dagger\right] - (\lambda_o - p)\left[\frac{(a-w_{1L}^\dagger - w_{2HL}^\dagger)^2}{2} - f_{1L}^\dagger\right] +$$
$$p(w_{2HL}^\dagger - c_L)(a-w_{1H}^\dagger - w_{2HL}^\dagger) + \bar{p}(w_{2LL}^\dagger - c_L)(a - w_{1L}^\dagger - w_{2LL}^\dagger) \tag{A-5}$$

$$\Delta_{2H} \doteq \bar{p}\left[\frac{(a-w_{1L}^\dagger - w_{2LH}^\dagger)^2}{2} - f_{1L}^\dagger\right] + \lambda_o\left[\frac{(a-w_{1H}^\dagger - w_{2HH}^\dagger)^2}{2} - f_{1H}^\dagger\right] - (\lambda_o - p)\left[\frac{(a-w_{1L}^\dagger - w_{2HH}^\dagger)^2}{2} - f_{1L}^\dagger\right] +$$
$$p\left(w_{2HH}^\dagger - \frac{\lambda_2}{p}c_H + \frac{\lambda_2 - p}{p}c_L\right)(a-w_{1H}^\dagger - w_{2HH}^\dagger) + \bar{p}\left(w_{2LH}^\dagger - \frac{\lambda_2}{p}c_H + \frac{\lambda_2 - p}{p}c_L\right)(a - w_{1L}^\dagger - w_{2LH}^\dagger) \tag{A-6}$$

Since both the OEM and Supplier 2 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 1/2 of the conditional expected virtual utility derived above. Let W_{oX} (resp., W_{2X}) denote the warranted claim for the OEM (resp., Supplier 2) of type X. Recall that the optimal shadow prices are $\alpha_2 + p - \lambda_2 = 0$ and $\alpha_o + p - \lambda_o = 0$. The system of equations to solve for the warranted claims is as follows.

$$W_{oL} = \frac{\Delta_{oL}}{2}, \qquad \frac{1}{p}[\lambda_o W_{oH} - (\lambda_o - p)W_{oL}] = \frac{\Delta_{oH}}{2},$$
$$W_{2L} = \frac{\Delta_{2L}}{2}, \qquad \frac{1}{p}[\lambda_2 W_{2H} - (\lambda_2 - p)W_{2L}] = \frac{\Delta_{2H}}{2}.$$

Thus, the warranted claims are

$$W_{oL}^\dagger = \frac{\Delta_{oL}}{2}, \qquad W_{oH}^\dagger = \frac{p\Delta_{oH}}{2\lambda_o} + \frac{(\lambda_o - p)\Delta_{oL}}{2\lambda_o},$$
$$W_{2L}^\dagger = \frac{\Delta_{2L}}{2}, \qquad W_{2H}^\dagger = \frac{p\Delta_{2H}}{2\lambda_2} + \frac{(\lambda_2 - p)\Delta_{2L}}{2\lambda_2}.$$

We observe that when $\lambda_o = p$ and $\lambda_2 = 1$ (and correspondingly $\alpha_o = 0$ and $\alpha_2 = 1 - p$), the second stage bargaining leads to the same wholesale price for Supplier 2 as in simultaneous bargaining. We next show the conditions under which such an outcome constitute as a bargaining solution for the second stage in two steps. In the derivation, the λ_o (resp., λ_2) in Equations (A-3)-(A-6) is replaced by p (resp., 1).

Step 1: We derive the expressions for $f_{2H}^\dagger$ and $f_{2L}^\dagger$ using the warranted condition for Supplier 2 of type H, the binding IC constraint for Supplier 2 of type L and the warranted condition for the OEM of type L. The system of equations is as follows:

$$p\left[\left(w_{2HH}^\dagger - c_H\right)\left(a - w_{1H}^\dagger - w_{2HH}^\dagger\right) + f_{2HH}\right] + \bar{p}\left[\left(w_{2LH}^\dagger - c_H\right)\left(a - w_{1L}^\dagger - w_{2LH}^\dagger\right) + f_{2LH}\right] = W_{2H}^\dagger,$$
$$p[(w_{2HL}^\dagger - c_L)(a - w_{1H}^\dagger - w_{2HL}^\dagger) + f_{2HL}] + \bar{p}[(w_{2LL}^\dagger - c_L)(a - w_{1L}^\dagger - w_{2LL}^\dagger) + f_{2LL}] =$$
$$p[(w_{2HH}^\dagger - c_L)(a - w_{1H}^\dagger - w_{2HH}^\dagger) + f_{2HH}] + \bar{p}[(w_{2LH}^\dagger - c_L)(a - w_{1L}^\dagger - w_{2LH}^\dagger) + f_{2LH}],$$
$$p\left[\frac{(a - w_{1L}^\dagger - w_{2LH}^\dagger)^2}{2} - f_{1L}^\dagger - f_{2LH}\right] + \bar{p}\left[\frac{(a - w_{1L}^\dagger - w_{2LL}^\dagger)^2}{2} - f_{1L}^\dagger - f_{2LL}\right] = W_{oL}^\dagger;$$

Solving the system of equations yields

$$f_{2H}^\dagger = p f_{2HH}^\dagger + \bar{p} f_{2LH}^\dagger$$

$$
\begin{aligned}
=&\frac{(a-c_L)^2}{4}+\frac{(4-3p)\Delta^2}{4p^2}-\frac{(2-p)\Delta}{2p}(a-c_L-pw_{1H}^{\dagger}-\bar{p}w_{1L}^{\dagger})\\
&-\frac{p}{2}\left[f_{1H}^{\dagger}+w_{1H}^{\dagger}\left(a-c_L-w_{1H}^{\dagger}/2\right)\right]-\frac{\bar{p}}{2}\left[f_{1L}^{\dagger}+w_{1L}^{\dagger}\left(a-c_L-w_{1L}^{\dagger}/2\right)\right],\\
f_{2L}^{\dagger}=&pf_{2HL}^{\dagger}+\bar{p}f_{2LL}^{\dagger}\\
=&\frac{(a-c_L)^2}{4}-\frac{3\Delta^2}{4p}+\frac{\Delta}{2}(a-c_L-pw_{1H}^{\dagger}-\bar{p}w_{1L}^{\dagger})\\
&-\frac{p}{2}\left[f_{1H}^{\dagger}+w_{1H}^{\dagger}\left(a-c_L-w_{1H}^{\dagger}/2\right)\right]-\frac{\bar{p}}{2}\left[f_{1L}^{\dagger}+w_{1L}^{\dagger}\left(a-c_L-w_{1L}^{\dagger}/2\right)\right].
\end{aligned}
$$

Step 2: It is easy to verify that the warranted condition for OEM of type H is satisfied with equality:

$$
p\left[\frac{(a-w_{1H}^{\dagger}-w_{2HH}^{\dagger})^2}{2}-f_{1H}^{\dagger}-f_{2HH}^{\dagger}\right]+\bar{p}\left[\frac{(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger})^2}{2}-f_{1H}^{\dagger}-f_{2HL}^{\dagger}\right]=W_{oH}^{\dagger}.
$$

Since $a\geq\bar{a}$, under the first-stage bargaining outcome to be derived below, it can be verified that the warranted condition for Supplier 2 of type L is satisfied with inequality as follows:

$$
f_{2L}+p\left(w_{2HL}^{\dagger}-c_L\right)\left(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger}\right)+\bar{p}\left(w_{2LL}^{\dagger}-c_L\right)\left(a-w_{1L}^{\dagger}-w_{2LL}^{\dagger}\right)\geq W_{2L}^{\dagger}.
$$

However, we note that in order to satisfy the OEM's IC constraint, i.e.,

$$
\begin{aligned}
&p\left[\frac{(a-w_{1L}^{\dagger}-w_{2LH}^{\dagger})^2}{2}-f_{1L}^{\dagger}-f_{2LH}^{\dagger}\right]+\bar{p}\left[\frac{(a-w_{1L}^{\dagger}-w_{2LL}^{\dagger})^2}{2}-f_{1L}^{\dagger}-f_{2LL}^{\dagger}\right]\\
\geq\,&p\left[\frac{(a-w_{1L}^{\dagger}-w_{2HH}^{\dagger})^2}{2}-f_{1L}^{\dagger}-f_{2HH}^{\dagger}\right]+\bar{p}\left[\frac{(a-w_{1L}^{\dagger}-w_{2HL}^{\dagger})^2}{2}-f_{1L}^{\dagger}-f_{2HL}^{\dagger}\right]
\end{aligned}
$$

we need

$$
f_{1L}^{\dagger}-f_{1H}^{\dagger}\geq\frac{1}{2}(w_{1H}^{\dagger}-w_{1L}^{\dagger})(2a-2c_H-w_{1H}^{\dagger}-w_{1L}^{\dagger}),\qquad(\mathrm{IC}_{OL}').
$$

First-stage bargaining. Again by focusing on cases where only the more efficient types' IC constraints may be binding, and temporarily ignore the IR and less efficient type' IC constraints, the first-stage primal bargaining problem becomes

$$
\begin{aligned}
\max_{\mathbf{w_1},\mathbf{f_1}}\;&\bar{p}p\left[\frac{(a-w_{1L}-w_{2LH}^{\dagger})^2}{2}-f_{1L}+\left(w_{2LH}^{\dagger}-\frac{1}{p}c_H+\frac{\bar{p}}{p}c_L\right)(a-w_{1L}-w_{2LH}^{\dagger})\right]+\\
&\bar{p}^2\left[\frac{(a-w_{1L}-w_{2LL}^{\dagger})^2}{2}-f_{1L}+(w_{2LL}^{\dagger}-c_L)(a-w_{1L}-w_{2LL}^{\dagger})\right]+\\
&p^2\left[\frac{(a-w_{1H}-w_{2HH}^{\dagger})^2}{2}-f_{1H}+\left(w_{2HH}^{\dagger}-\frac{1}{p}c_H+\frac{\bar{p}}{p}c_L\right)(a-w_{1H}-w_{2HH}^{\dagger})\right]+\\
&p\bar{p}\left[\frac{(a-w_{1H}-w_{2HL}^{\dagger})^2}{2}-f_{1H}+(w_{2HL}^{\dagger}-c_L)(a-w_{1H}-w_{2HL}^{\dagger})\right]+\\
&\bar{\lambda}_1\{p[(w_{1L}-c_L)(a-w_{1L}-w_{2LH}^{\dagger})+f_{1L}]+\bar{p}[(w_{1L}-c_L)(a-w_{1L}-w_{2LL}^{\dagger})+f_{1L}]\}+\\
&\lambda_1\{p[(w_{1H}-c_H)(a-w_{1H}-w_{2HH}^{\dagger})+f_{1H}]+\bar{p}[(w_{1H}-c_H)(a-w_{1H}-w_{2HL}^{\dagger})+f_{1H}]\}\\
\text{s.t. }\;&p[(w_{1L}-c_L)(a-w_{1L}-w_{2LH}^{\dagger})+f_{1L}]+\bar{p}[(w_{1L}-c_L)(a-w_{1L}-w_{2LL}^{\dagger})+f_{1L}]\\
&\geq p[(w_{1H}-c_L)(a-w_{1H}-w_{2HH}^{\dagger})+f_{1H}]+\bar{p}[(w_{1H}-c_L)(a-w_{1H}-w_{2HL}^{\dagger})+f_{1H}]\qquad(\mathrm{IC}_{1L})\\
&f_{1L}-f_{1H}\geq\frac{1}{2}(w_{1H}-w_{1L})(2a-2c_H-w_{1H}-w_{1L}),\qquad(\mathrm{IC}_{OL}')
\end{aligned}
$$

We temporarily ignore (IC_{1L}) and will verify it later on. Let α_o' be the shadow price of the constraint of (IC_{OL}'). The Lagrange dual problem is

$$\begin{aligned}\min_{\alpha_o'}\max_{\mathbf{w_1},\mathbf{f_1}}\ & \bar{p}p\left[\frac{(a-w_{1L}-w_{2LH}^{\dagger})^2}{2}-f_{1L}+\left(w_{2LH}^{\dagger}-\frac{1}{p}c_H+\frac{1-p}{p}c_L\right)(a-w_{1L}-w_{2LH}^{\dagger})\right]+\\
& \bar{p}^2\left[\frac{(a-w_{1L}-w_{2LL}^{\dagger})^2}{2}-f_{1L}+(w_{2LL}^{\dagger}-c_L)(a-w_{1L}-w_{2LL}^{\dagger})\right]+\\
& p^2\left[\frac{(a-w_{1H}-w_{2HH}^{\dagger})^2}{2}-f_{1H}+\left(w_{2HH}^{\dagger}-\frac{1}{p}c_H+\frac{1-p}{p}c_L\right)(a-w_{1H}-w_{2HH}^{\dagger})\right]+\\
& p\bar{p}\left[\frac{(a-w_{1H}-w_{2HL}^{\dagger})^2}{2}-f_{1H}+(w_{2HL}^{\dagger}-c_L)(a-w_{1H}-w_{2HL}^{\dagger})\right]+\\
& \bar{\lambda}_1\{p[(w_{1L}-c_L)(a-w_{1L}-w_{2LH}^{\dagger})+f_{1L}]+\bar{p}[(w_{1L}-c_L)(a-w_{1L}-w_{2LL}^{\dagger})+f_{1L}]\}+\\
& \lambda_1\{p[(w_{1H}-c_H)(a-w_{1H}-w_{2HH}^{\dagger})+f_{1H}]+\bar{p}[(w_{1H}-c_H)(a-w_{1H}-w_{2HL}^{\dagger})+f_{1H}]\}+\\
& \alpha_o'\left\{f_{1L}-f_{1H}-\frac{1}{2}(w_{1H}-w_{1L})(2a-2c_H-w_{1H}-w_{1L})\right\}\\
\text{s.t. }\ & \alpha_o'=\lambda_1-p;\alpha_o'\geq 0.\end{aligned}$$

Solving the problem yields

$$w_{1H}^{\dagger}=c_H,\quad w_{1L}^{\dagger}=c_L.$$

We next verify that it is a bargaining solution when $\lambda_1=1$. Note that when $\lambda_1=1$, (IC_{OL}') is binding. It can be verified that Supplier 1's IC constraint is not binding as it is implied by (IC_{OL}'). It follows that the conditional virtual utility when Supplier 1 is of type L (resp., H) is

$$\begin{aligned}\Delta_{1L}\doteq & p\left[\frac{(a-w_{1L}^{\dagger}-w_{2LH}^{\dagger})^2}{2}+\left(w_{2LH}^{\dagger}-\frac{1}{p}c_H+\frac{1-p}{p}c_L\right)(a-w_{1L}^{\dagger}-w_{2LH}^{\dagger})\right]+\\
& \bar{p}\left[\frac{(a-w_{1L}^{\dagger}-w_{2LL}^{\dagger})^2}{2}+(w_{2LL}^{\dagger}-c_L)(a-w_{1L}^{\dagger}-w_{2LL}^{\dagger})\right]\\
\Delta_{1H}\doteq & p\left[\frac{(a-w_{1H}^{\dagger}-w_{2HH}^{\dagger})^2}{2}+\left(w_{2HH}^{\dagger}-\frac{1}{p}c_H+\frac{1-p}{p}c_L\right)(a-w_{1H}^{\dagger}-w_{2HH}^{\dagger})\right]+\\
& \bar{p}\left[\frac{(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger})^2}{2}+(w_{2HL}^{\dagger}-c_L)(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger})\right]+\\
& \frac{1}{p}[p(w_{1H}^{\dagger}-c_H)(a-w_{1H}^{\dagger}-w_{2HH}^{\dagger})+\bar{p}(w_{1H}^{\dagger}-c_H)(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger})]\end{aligned}$$

Thus, we obtain the warranted claims for Supplier 1 as follows.

$$W_{1L}^{\dagger}=\frac{\Delta_{1L}}{3},\quad W_{1H}^{\dagger}=\frac{\Delta_{1H}}{3}.$$

Solve the following system of equations for fixed payments

$$\begin{aligned}& f_{1L}-f_{1H}-\frac{1}{2}(w_{1H}^{\dagger}-w_{1L}^{\dagger})(2a-2c_H-w_{1H}^{\dagger}-w_{1L}^{\dagger})=0\\
& f_{1H}+(w_{1H}^{\dagger}-c_H)[p(a-w_{1H}^{\dagger}-w_{2HH}^{\dagger})+\bar{p}(a-w_{1H}^{\dagger}-w_{2HL}^{\dagger})]=W_{1H}^{\dagger}\end{aligned}$$

yields Supplier 1's fixed payments:

$$f_{1L}^{\dagger}=\frac{1}{3}\left[p\frac{(a-2c_H-\frac{\bar{p}}{p}\Delta)^2}{2}+\bar{p}\frac{(a-c_H-c_L)^2}{2}\right]+\frac{1}{2}\Delta(2a-3c_H-c_L);$$

$$f_{1H}^{\dagger} = \frac{1}{3}\left[p\frac{(a-2c_H-\frac{\bar{p}}{p}\Delta)^2}{2} + \bar{p}\frac{(a-c_H-c_L)^2}{2}\right].$$

It is easy to verify that Supplier 1's profit when the type is L is higher than the warranted claim.

B. Mechanism Design in Assembly

In this appendix, we present relevant formulations and key intermediate steps in the analysis from Hu and Qi (2018) without providing technical details of the analyses, and focus on contrasting dynamic bargaining and mechanism design institutions and deriving testable hypotheses for our subsequent experiments. Once again we present the two-part tariff implementations of the optimal mechanisms.

B.1. Simultaneous Mechanism Design

The formulation of the simultaneous mechanism design problem is as follows, where $\mathbf{w},\mathbf{f} \doteq w_{ix_i}, f_{ix_i}, i = 1,2, x_i = H,L$, and $\bar{p} \doteq 1-p$. The formulation allows the principal (OEM) to maximize its expected profit subject to IR and IC constraints of all supplier types.

$$\begin{aligned}
\max_{\mathbf{w},\mathbf{f}}\ & pp[(a-w_{1H}-w_{2H})^2/2 - f_{1H} - f_{2H}] + \bar{p}\bar{p}[(a-w_{1L}-w_{2L})^2/2 - f_{1L} - f_{2L}] \\
& + p\bar{p}[(a-w_{1H}-w_{2L})^2/2 - f_{1H} - f_{2L}] + \bar{p}p[(a-w_{1L}-w_{2H})^2/2 - f_{1L} - f_{2H}] \\
\text{s.t. } & (w_{1H}-c_H)(a-w_{1H}-pw_{2H}-\bar{p}w_{2L}) + f_{1H} \geq 0 && (\text{IR}_{1H}) \\
& (w_{2H}-c_H)(a-w_{2H}-pw_{1H}-\bar{p}w_{1L}) + f_{2H} \geq 0 && (\text{IR}_{2H}) \\
& (w_{1L}-c_L)(a-w_{1L}-pw_{2H}-\bar{p}w_{2L}) + f_{1L} \geq 0 && (\text{IR}_{1L}) \\
& (w_{2L}-c_L)(a-w_{2L}-pw_{1H}-\bar{p}w_{1L}) + f_{2L} \geq 0 && (\text{IR}_{2L}) \\
& (w_{1H}-c_H)(a-w_{1H}-pw_{2H}-\bar{p}w_{2L}) + f_{1H} \geq (w_{1L}-c_H)(a-w_{1L}-pw_{2H}-\bar{p}w_{2L}) + f_{1L} && (\text{IC}_{1H}) \\
& (w_{2H}-c_H)(a-w_{2H}-pw_{1H}-\bar{p}w_{1L}) + f_{2H} \geq (w_{2L}-c_H)(a-w_{2L}-pw_{1H}-\bar{p}w_{1L}) + f_{2L} && (\text{IC}_{2H}) \\
& (w_{1L}-c_L)(a-w_{1L}-pw_{2H}-\bar{p}w_{2L}) + f_{1L} \geq (w_{1H}-c_L)(a-w_{1H}-pw_{2H}-\bar{p}w_{2L}) + f_{1H} && (\text{IC}_{1L}) \\
& (w_{2L}-c_L)(a-w_{2L}-pw_{1H}-\bar{p}w_{1L}) + f_{2L} \geq (w_{2H}-c_L)(a-w_{2H}-pw_{1H}-\bar{p}w_{1L}) + f_{2H} && (\text{IC}_{2L}).
\end{aligned}$$

The problem is analyzed in Section 4 of Hu and Qi (2018) and the result adapted to our notation and special setting is presented in Proposition 4.

B.2. Sequential Mechanism Design

The sequential mechanism design problem needs to be analyzed in two stages in reverse. The second-stage mechanism design problem adopts the *Rothschild-Stiglitz-Wilson (RSW)* formulation, following the analysis framework of Maskin and Tirole (1992), where we use subscript $2XY$, $X,Y = H,L$ to denote the contract intended for Supplier 2 of type Y given Supplier 1 of type X, and define $\mathbf{w_{2X}},\mathbf{f_{2X}} \doteq w_{2XH}, w_{2XL}, f_{2XH}, f_{2XL}, X = H,L$. The contract terms for Supplier 1, w_{1X}, f_{1X}, $X = H,L$, are treated as constants in this stage. Recall that in this stage, the OEM is equipped with the private information of Supplier 1, and thus is an *informed principal.*

$$\begin{aligned}
&\max_{\mathbf{w_{2H}},\mathbf{f_{2H}}}\ p[(a-w_{1H}-w_{2HH})^2/2 - f_{1H} - f_{2HH}] + \bar{p}[(a-w_{1H}-w_{2HL})^2/2 - f_{1H} - f_{2HL}] \\
&\max_{\mathbf{w_{2L}},\mathbf{f_{2L}}}\ p[(a-w_{1L}-w_{2LH})^2/2 - f_{1L} - f_{2LH}] + \bar{p}[(a-w_{1L}-w_{2LL})^2/2 - f_{1L} - f_{2LL}]
\end{aligned}$$

$$
\begin{aligned}
\text{s.t. } & (w_{2HH}-c_H)(a-w_{1H}-w_{2HH})+f_{2HH}\ge 0 && (\mathrm{IR}_{2HH})\\
& (w_{2HL}-c_L)(a-w_{1H}-w_{2HL})+f_{2HL}\ge (w_{2HH}-c_L)(a-w_{1H}-w_{2HH})+f_{2HH} && (\mathrm{IC}_{2HL})\\
& (w_{2LH}-c_H)(a-w_{1L}-w_{2LH})+f_{2LH}\ge 0 && (\mathrm{IR}_{2LH})\\
& (w_{2LL}-c_L)(a-w_{1L}-w_{2LL})+f_{2LL}\ge (w_{2LH}-c_L)(a-w_{1L}-w_{2LH})+f_{2LH} && (\mathrm{IC}_{2LL})\\
& p[(a-w_{1H}-w_{2HH})^2/2-f_{1H}-f_{2HH}]+\bar{p}[(a-w_{1H}-w_{2HL})^2/2-f_{1H}-f_{2HL}]\\
& \ge p[(a-w_{1H}-w_{2LH})^2/2-f_{1H}-f_{2LH}]+\bar{p}[(a-w_{1H}-w_{2LL})^2/2-f_{1H}-f_{2LL}] && (\mathrm{IC}_{MH})\\
& p[(a-w_{1L}-w_{2LH})^2/2-f_{1L}-f_{2LH}]+\bar{p}[(a-w_{1L}-w_{2LL})^2/2-f_{1L}-f_{2LL}]\\
& \ge p[(a-w_{1L}-w_{2HH})^2/2-f_{1L}-f_{2HH}]+\bar{p}[(a-w_{1L}-w_{2HL})^2/2-f_{1L}-f_{2HL}] && (\mathrm{IC}_{ML})
\end{aligned}
$$

We want to highlight constraints (IC_{MH}) and (IC_{ML}), which require that the informed principal (OEM) makes an offer consistent with its (i.e., Supplier 1's) private information; in other words, these constraints guarantee credible signaling of the OEM's type. In general, signaling is costly due to such additional constraints, and thus optimal sequential mechanisms generally yield lower profits for the OEM than optimal simultaneous mechanisms.

Lemma 2 of Hu and Qi (2018) presents the following second-stage mechanism: the OEM of type X offers the menu $\{(w^Q_{2XH}, f^Q_{2XH}), (w^Q_{2XL}, f^Q_{2XL})\}$ to Supplier 2, $X=H,L$ where

$$
\begin{aligned}
w^Q_{2LL} &= w^Q_{2HL} = c_L, \quad w^Q_{2LH} = w^Q_{2HH} = c_L+\Delta/p,\\
f^Q_{2LL} &= \Delta(a-c_L-w_{1L})-\Delta^2/p, \quad f^Q_{2LH} = -\Delta(a-c_L-w_{1L})\bar{p}/p+\Delta^2\bar{p}/p^2,\\
f^Q_{2HL} &= \Delta(a-c_L-w_{1H})-\Delta^2/p, \quad f^Q_{2HH} = -\Delta(a-c_L-w_{1H})\bar{p}/p+\Delta^2\bar{p}/p^2.
\end{aligned}
$$

Notably, this second-stage mechanism naturally satisfies constraints (IC_{MH}) and (IC_{ML}), suggesting cost-free signaling in this particular problem.

Based on the second-stage mechanism, the first-stage problem is formulated as the following mechanism design problem, where $\mathbf{w_1}, \mathbf{f_2} \doteq w_{1H}, w_{1L}, f_{1H}, f_{1L}$:

$$
\begin{aligned}
\max_{\mathbf{w_1},\mathbf{f_1}} \; & pp[(a-w_{1H}-w^Q_{2HH})^2/2-f_{1H}-f^Q_{2HH}]+p\bar{p}[(a-w_{1H}-w^Q_{2HL})^2/2-f_{1H}-f^Q_{2HL}]\\
& +\bar{p}p[(a-w_{1L}-w^Q_{2LH})^2/2-f_{1L}-f^Q_{2LH}]+\bar{p}\bar{p}[(a-w_{1L}-w^Q_{2LL})^2/2-f_{1L}-f^Q_{2LL}]\\
\text{s.t. } & (w_{1H}-c_H)[a-w_{1H}-pw^Q_{2HH}-\bar{p}w^Q_{2HL}]+f_{1H}\ge 0 && (\mathrm{IR}_{1H})\\
& (w_{1L}-c_L)[a-w_{1L}-pw^Q_{2LH}-\bar{p}w^Q_{2LL}]+f_{1L}\ge 0 && (\mathrm{IR}_{1L})\\
& (w_{1H}-c_H)[a-w_{1H}-pw^Q_{2HH}-\bar{p}w_{2HL}]+f_{1H}\ge (w_{1L}-c_H)[a-w_{1L}-pw^Q_{2LH}-\bar{p}w^Q_{2LL}]+f_{1L} && (\mathrm{IC}_{1H}),\\
& (w_{1L}-c_L)[a-w_{1L}-pw^Q_{2LH}-\bar{p}w^Q_{2LL}]+f_{1L}\ge (w_{1H}-c_L)[a-w_{1H}-pw^Q_{2HH}-\bar{p}w_{2HL}]+f_{1H} && (\mathrm{IC}_{1L}).
\end{aligned}
$$

Solving the problem, we obtain Proposition 5, which is a special case of Proposition 3 in Hu and Qi (2018).

C. Benchmark: Dyadic Supply Chain with the Integrated Supplier

In this appendix, we present the formulation and detailed analysis for the benchmark dyadic supply chain.

C.1. Mechanism Design

The formulation of the OEM offering an optimal menu of two-part tariff contracts to the supplier who may have three different types is as follows, with the IR and IC constraints simplified following standard procedures into the IR constraint for the least efficient type, the local downward IC constraints, and the monotonicity constraints.

$$\begin{aligned}
\max_{\mathbf{w},\mathbf{f}}\ & p^2[(a-w_{HH})^2/2-f_{HH}]+2p\bar{p}[(a-w_{HL})^2/2-f_{HL}]+\bar{p}^2[(a-w_{LL})^2/2-f_{LL}] \\
\text{s.t. } & (w_{HH}-2c_H)(a-w_{HH})+f_{HH}\geq 0 && (\text{IR}_{HH}) \\
& (w_{HL}-c_H-c_L)(a-w_{HL})+f_{HL}\geq (w_{HH}-c_H-c_L)(a-w_{HH})+f_{HH} && (\text{IC}_{HL}) \\
& (w_{LL}-2c_L)(a-w_{LL})+f_{LL}\geq (w_{LH}-2c_L)(a-w_{LH})+f_{LH} && (\text{IC}_{LL}) \\
& w_{HH}\geq w_{HL}\geq w_{LL}. && (\text{MN})
\end{aligned}$$

Following standard mechanism design procedures, we ignore the monotonicity constraints and let the remaining IR and IC constraints be binding to solve for the contract terms, and then verify that the monotonicity constraints are satisfied. The optimal contract terms are

$$\begin{aligned}
& w_{LL}^M=2c_L,\quad w_{HL}^M=c_L+c_H+\frac{1-p}{2p}\Delta,\quad w_{HH}^M=2c_H+\frac{1-p^2}{p^2}\Delta, \\
& f_{LL}^M=2(a-2c_L)\Delta-\frac{3p^2+p+2}{2p^2}\Delta^2, \\
& f_{HL}^M=(a-2c_L)\frac{3p-1}{2p}\Delta-\frac{5p^2+3}{4p^2}\Delta^2, \\
& f_{HH}^M=-\left(a-c_L-c_H-\frac{\Delta}{p^2}\right)\frac{1-p^2}{p^2}\Delta.
\end{aligned}$$

The optimal mechanism yields the expected profit for the OEM

$$\Pi^M=(a-2c_L)(a-2c_L-4\Delta)/2+\frac{2+p+p^2(5-p\bar{p})}{4p^2}\Delta^2,$$

and the expected profit for the supplier

$$\pi^M=(a-2c_L)2\bar{p}\Delta-\frac{(1-p^2)(2+p+p^2)}{2p^2}\Delta^2.$$

Comparing the profits above with those derived using the optimal mechanisms in Propositions 4 and 5 yields Proposition 7.

C.2. Dynamic bargaining

The formulation of the OEM bargaining with a supplier who may have three different types is as follows, with the constraints simplified similar to that in Appendix A.1. We temporarily ignore the IR and MN constraints. The primal bargaining problem is

$$\begin{aligned}
\max_{\mathbf{P},\mathbf{Q}}\ & p^2[(a-Q_{HH}/2)Q_{HH}-P_{HH}]+2p\bar{p}[(a-Q_{HL}/2)Q_{HL}-P_{HL}]+\bar{p}^2[(a-Q_{LL}/2)Q_{LL}-P_{LL}]+ \\
& (1-\lambda_{HH}-\lambda_{HL})(P_{LL}-2c_LQ_{LL})+\lambda_{HL}[P_{HL}-(c_H+c_L)Q_{HL}]+\lambda_{HH}(P_{HH}-2c_HQ_{HH}) \\
\text{s.t. } & \text{IC}_{LL} \text{ and } \text{IC}_{HL}.
\end{aligned}$$

We similarly use λ_{HH} (resp., λ_{HL}) to denote weights of the supplier-type HH's (resp., HL's) profits and α_{LL} (resp., α_{HL}) represents the shadow price of constraint IC$_{LL}$ (resp., IC$_{HL}$). We have the following Lagrange dual problem:

$$\begin{aligned}\min_{\alpha_{LL},\alpha_{HL}} \max_{\mathbf{P},\mathbf{Q}} \;& p^2[(a-Q_{HH}/2)Q_{HH}-P_{HH}]+2p\bar{p}[(a-Q_{HL}/2)Q_{HL}-P_{HL}]+\bar{p}^2[(a-Q_{LL}/2)Q_{LL}-P_{LL}]+\\ & (1-\lambda_{HH}-\lambda_{HL})(P_{LL}-2c_LQ_{LL})+\lambda_{HL}[P_{HL}-(c_H+c_L)Q_{HL}]+\lambda_{HH}(P_{HH}-2c_HQ_{HH})+\\ & \alpha_{LL}[P_{LL}-2c_LQ_{LL}-P_{HL}+2c_LQ_{HL}]+\alpha_{HL}[P_{HL}-(c_H+c_L)Q_{HL}-P_{HH}+(c_H+c_L)Q_{HH}]\\ \text{s.t. } & \alpha_{LL}=\lambda_{HH}+\lambda_{HL}-2p+p^2,\;\alpha_{HL}=\lambda_{HH}-p^2,\;\alpha_{LL}\geq 0,\;\alpha_{HL}\geq 0.\end{aligned}$$

Rearranging the Lagrange function using $\alpha_{LL}=\lambda_{HH}+\lambda_{HL}-2p+p^2$ and $\alpha_{HL}=\lambda_{HH}-p^2$ yields

$$\begin{aligned}& p^2\left[(a-Q_{HH}/2)Q_{HH}-2c_HQ_{HH}-\frac{(\lambda_{HH}-p^2)(c_H-c_L)Q_{HH}}{p^2}\right]+\\ & 2p\bar{p}\left[(a-Q_{HL}/2)Q_{HL}-(c_H+c_L)Q_{HL}-\frac{(\lambda_{HH}+\lambda_{HL}-2p+p^2)(c_H-c_L)Q_{HL}}{2p\bar{p}}\right]+\\ & \bar{p}^2\left[(a-Q_{LL}/2)Q_{LL}-2c_LQ_{LL}\right].\end{aligned}$$

The optimal sourcing quantities are

$$\begin{aligned}Q^*_{HH}&=a-2c_H-\frac{(\lambda_{HH}-p^2)(c_H-c_L)}{p^2},\\ Q^*_{HL}&=a-(c_H+c_L)-\frac{(\lambda_{HH}+\lambda_{HL}-2p+p^2)(c_H-c_L)}{2p\bar{p}},\\ Q^*_{LL}&=a-2c_L.\end{aligned}$$

The system total expected virtual utility is

$$\frac{p^2}{2}\left[a-2c_H-\frac{(\lambda_{HH}-p^2)(c_H-c_L)}{p^2}\right]^2+p\bar{p}\left[a-(c_H+c_L)-\frac{(\lambda_{HH}+\lambda_{HL}-2p+p^2)(c_H-c_L)}{2p\bar{p}}\right]^2+\frac{\bar{p}^2}{2}\left(a-2c_L\right)^2.$$

Let Δ_X be the conditional expected virtual utility of the system when the supplier's type is X, namely

$$\begin{aligned}\Delta_{HH}&=\frac{1}{2}\left[a-2c_H-\frac{(\lambda_{HH}-p^2)(c_H-c_L)}{p^2}\right]^2,\\ \Delta_{HL}&=\frac{1}{2}\left[a-(c_H+c_L)-\frac{(\lambda_{HH}+\lambda_{HL}-2p+p^2)(c_H-c_L)}{2p\bar{p}}\right]^2,\\ \Delta_{LL}&=\frac{1}{2}\left(a-2c_L\right)^2.\end{aligned}$$

Now we solve for the warranted claims. Let W_X denote the warranted claim for the supplier when the supplier's type is X. We have

$$\begin{aligned}&\frac{1}{p^2}[\lambda_{HH}W_{HH}-(\lambda_{HH}-p^2)W_{HL}]=\frac{\Delta_{HH}}{2},\\ &\frac{1}{2p\bar{p}}[(\lambda_{HL}+\lambda_{HH}-p^2)W_{HL}-(\lambda_{HH}+\lambda_{HL}-2p+p^2)W_{LL}]=\frac{\Delta_{HL}}{2},\\ &W_{LL}=\frac{\Delta_{LL}}{2}.\end{aligned}$$

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

$$W^*_{HH}=\frac{\Delta_{HH}p^2\left(\lambda_{HH}+\lambda_{HL}-p^2\right)+2\Delta_{HL}p\bar{p}\left(\lambda_{HH}-p^2\right)+\Delta_{LL}\left(\lambda_{HH}-p^2\right)\left(\lambda_{HH}+\lambda_{HL}-2p+p^2\right)}{2\lambda_{HH}\left(\lambda_{HH}+\lambda_{HL}-p^2\right)},$$

$$W_{HL}^* = \frac{2\Delta_{HL}\bar{p}p + \Delta_{LL}(\lambda_{HH} + \lambda_{HL} - 2p + p^2)}{2\,(\lambda_{HH} + \lambda_{HL} - p^2)},$$

$$W_{LL}^* = \frac{\Delta_{LL}}{2}.$$

Note that while the problem is numerically solvable, the solutions are algebraically cumbersome and intractable. Thus, we provide the key steps to compute the bargaining solution below, which is used to derive the bargaining solution of the dyadic supply chain for the experiment design in the main paper.

To obtain the bargaining solution, we need to find compatible λ's, which guarantee the warranted conditions are satisfied, i.e., the profit of the supplier of each type is greater than or equal to their respected warranted claim, and also the IC constraint is satisfied. Take the case of $\lambda_{HH} \in (p^2, 1)$ and $\lambda_{HL} + \lambda_{HH} \in (2p - p^2, 1)$ for example. In this case, the λ's for all three types are strictly between 0 and 1, indicating that the three warranted conditions should hold with equality; the α's for both IC constraints is also strictly positive, indicating that the two IC constraints should hold with equality too. Thus, we have a system of five equations with five unknowns:

$$P_{HH} - 2c_H Q_{HH}^* = W_{HH}^*, \tag{WC$_{HH}$}$$

$$P_{HL} - (c_H + c_L)Q_{HL}^* = W_{HL}^*, \tag{WC$_{HL}$}$$

$$P_{LL} - 2c_L Q_{LL}^* = W_{LL}^*, \tag{WC$_{LL}$}$$

$$P_{LL} - 2c_L Q_{LL}^* = P_{HL} - 2c_L Q_{HL}^*, \tag{IC$_{LL}$}$$

$$P_{HL} - (c_H + c_L)Q_{HL}^* = P_{HH} - (c_H + c_L)Q_{HH}^*. \tag{IC$_{HL}$}$$

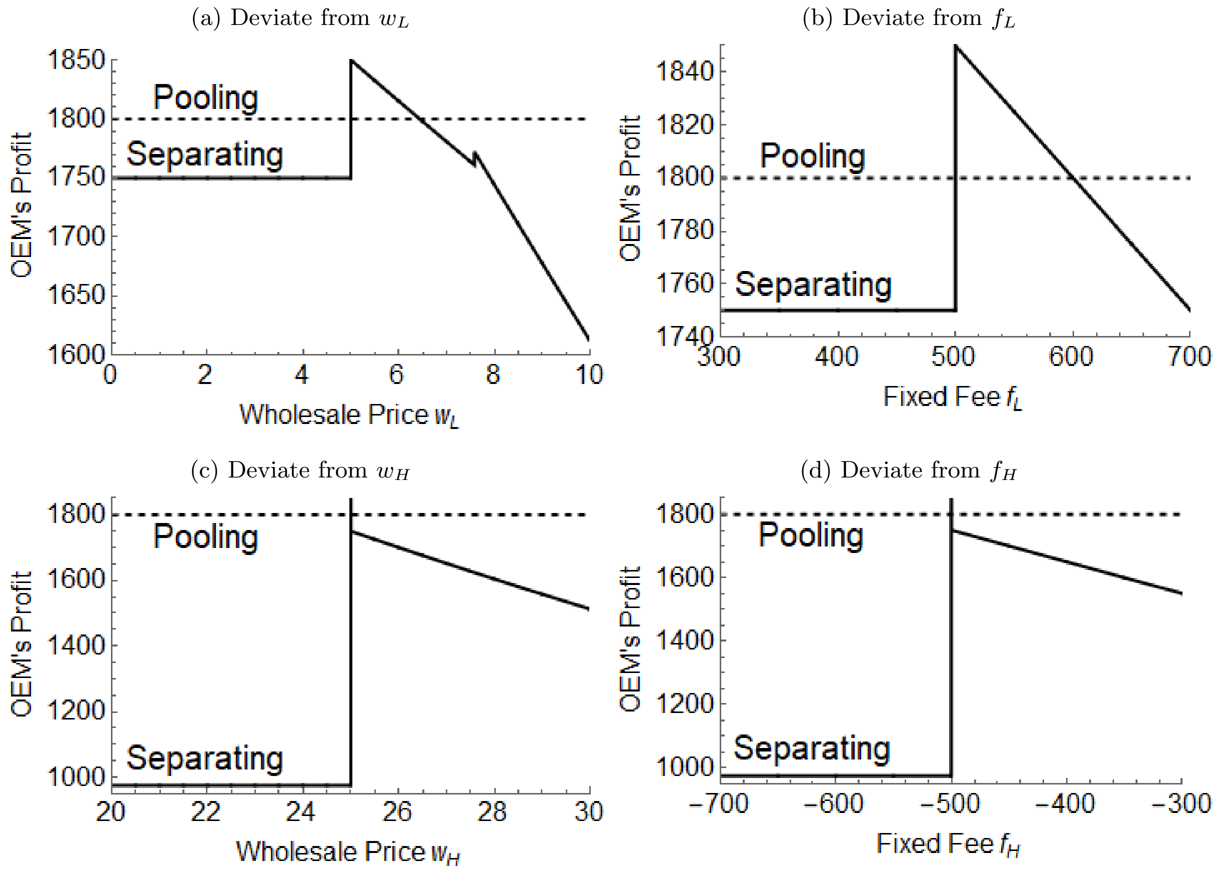
If the solution satisfies that $\lambda_{HH}^* \in (p^2, 1)$ and $\lambda_{HL}^* + \lambda_{HH}^* \in (2p - p^2, 1)$, then one set of bargaining solution is obtained. If not, we start considering different cases where the λ^*'s may take the boundary values, corresponding to scenarios where the warranted condition may hold with inequality (if the corresponding $\lambda = 0$) or the IC constraint may hold with inequality (if the corresponding $\alpha = 0$). Then, drop the corresponding WC or IC equations and solve the system of remaining equations. Again, we need to check the solution satisfies the range of λ^*'s as specified by each scenario. Under the set of parameters in our experiment design, the bargaining solution satisfies that $\lambda_{LL}^* = 0$, $\lambda_{HL}^* = 0.095$, and $\lambda_{HH}^* = 0.905$.

D. Discussion on the Impact of Bounded Rationality

In this appendix, we illustrate that the optimal separating contract may not be robust when the OEM is subject to bounded rationality in deciding the contract parameters. We further argue that the pooling contract may be preferred compared to the separating contract under bounded rationality. We note that the suppliers are mostly rational in choosing the contract that maximizes their profit as observed in our experiment, so we assume the supplier is rational in the discussion below.

In Figure D.1, we employ a numerical example for a dyadic supply chain calibrated with the parameters used in our experimental design to show the observations. The supplier has two cost types: $c_L = 5$ w.p. 0.5 and $c_H = 15$ w.p. 0.5. The market clearing price is $a - Q/2$ where $a = 75$. Under this set of parameter, the optimal separating contract menu is $(w_L^*, f_L^*, w_H^*, f_H^*) = (5, 500, 25, -500)$ resulting in the OEM's profit of 1850, and the optimal pooling contract is $(w_p^*, f_p^*) = (15, 0)$ resulting in the OEM's profit of 1800.

Figure D.1 OEM's Profit Under the Optimal Pooling Contract and the Separating Contract with Errors



Note: Each of the four figures above plots the OEM's profit under the optimal pooling contract (dashed line) and the OEM's profit when deviating from the optimal separating contract in one parameter fixing the other three parameters as those in the optimal separating contract (solid line). Parameter: $a = 75$, $c_L = 5$, $c_H = 15$, $p = 0.5$.

Each of the four figures shows the OEM's profit under the optimal pooling contract as well as the OEM's profit under the (optimal) separating contract when it makes mistake in offering one of the four parameters *ceteris paribus*: (a) wholesale price w_L, (b) fixed fee f_L, (c) wholesale price w_H, and (d) fixed fee f_H. We note that as the OEM deviates from offering the contractual terms under the optimal separating contract, the resulting contract may not be "separating" since both types of the supplier may prefer the same contract. Nevertheless, for convenience, we still name such a contract as *separating contract (subject to errors of the OEM)*.

We first observe from Figure D.1 (a) that if the OEM offers a wholesale price w_L (intended for the supplier with type c_L) less than the optimal value w_L^*, there is a sharp drop in the OEM's profit. This is because the supplier type c_L prefers the contract (w_H^*, f_H^*) intended for the supplier type c_H to (w_L, f_L^*). Thus, both types of suppliers choose the same contract term and the contract is *de facto* a pooling one, leading to a lower profit of the OEM than that under the optimal pooling contract. If the OEM offers a wholesale price $w_L > w_L^*$, then as long as such deviation is sufficiently small ($w_L < 6.41$), the contract remains a separating contract and results in a higher profit of the OEM. However, if the deviation is moderately large ($w_L > 6.41$), the OEM will earn a higher profit under the optimal pooling contract. The small jump in OEM's profit under the separating contract near $w_L = 7.59$ is due to the supplier type c_H also switches to choose (w_L, f_L^*). The observation from Figure D.1 (b) is similar.

We next observe from Figure D.1 (c) that if the OEM offers a wholesale price w_H (intended for the supplier type c_H) less than the optimal value w_H^*, there is a significant drop in the OEM's profit. This is due to the supplier type c_H rejecting such a contract and not participating. If the OEM offers a $w_H > w_H^*$, the OEM's profit also drops significantly since the supplier type c_L prefers (w_H, f_H^*) to (w_L^*, f_L^*). Again the separating contract is *de facto* pooling and results in a lower profit of the OEM than that under the optimal pooling contract. The observation from Figure D.1 (d) is similar. In summary, if the OEM deviates to pay the supplier type c_H less, it suffers due to the rejection of such a supplier; if the OEM deviates to pay the supplier type c_H more, it also suffers due to the supplier type c_L choosing the contract term not intended for such a supplier.

These observations above, together with the fact that the pooling contract is cognitively simpler to design than the separating contract, may make the pooling contract more attractive to the OEMs subject to bounded rationality.

E. Additional Analysis of Experimental Data

In this section, we provide some additional analysis of our data, focusing on a regression-based approach to learning and digging deeper into the drivers of agreement.

E.1. Learning

In Table E.1 we study the evolution of supply chain, OEM and supplier profits over time, including a full set of treatment dummies. The baseline represents the Dyad-Barg institution. As can be seen, there is a significantly positive trend for supply chain profits and OEM profits, while there is no trend for supplier profits. Therefore, the OEM appears to capture all of the gains from learning, which seems reasonable as they face the most complex decision environment.

Table E.1 Learning and Profits

Parameter	Supply Chain		OEM		Suppliers	
Mech	40.738	(35.112)	127.975***	(32.697)	−86.225**	(35.604)
Sim	−41.324	(35.418)	−280.381***	(40.083)	−236.453***	(30.778)
Seq	−68.595*	(41.043)	−306.887***	(54.730)	−232.534***	(34.566)
Mech × Sim	−61.002	(55.475)	−6.855	(60.267)	12.585	(50.714)
Mech × Seq	42.740	(55.719)	107.195	(70.378)	5.749	(44.731)
Period	14.212**	(5.776)	13.992***	(4.861)	0.164	(2.898)
Supplier 2					−12.994	(24.084)
Constant	1369.673***	(36.567)	656.774***	(23.892)	719.847***	(26.382)
Observations	2466		942		1524	
R^2	0.019		0.228		0.143	

Note: Standard errors are corrected for clustering at the session level. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively.

In Table E.2, we look at the agreed contract terms and whether there are any trends. Because of the different support of plausible contract terms, we separately study the dyadic and assembly treatments.

Interestingly, in the dyadic treatments (panel (a)), there is a downward trend in wholesale prices and an increasing trend in the agreed fixed payments. This result is replicated (but at a smaller magnitude given the cost differences between suppliers in dyad and assembly) for the assembly treatments.

Table E.2 Learning and Contract Terms

(a) Dyadic Treatments

Parameter	Wholesale Price		Fixed Payment	
Mech	-2.368	(1.493)	-31.687	(53.599)
Period	-1.051^{***}	(0.215)	21.685^{***}	(6.475)
Constant	38.785^{***}	(1.330)	66.448^{*}	(37.578)
Observations	360		360	
R^2	0.070		0.033	

(b) Assembly Treatments

	Supplier 1				Supplier 2			
Parameter	Wholesale Price		Fixed Payment		Wholesale Price		Fixed Payment	
Mech	-0.522	(0.842)	23.052	(44.092)	-1.188	(0.812)	-56.772	(47.249)
Seq	1.236	(1.259)	90.254^{**}	(35.184)	-2.292^{**}	(1.117)	-16.783	(47.517)
Mech × Seq	-2.080	(1.533)	-88.614^{*}	(50.910)	0.481	(1.448)	13.712	(61.776)
Period	-0.501^{***}	(0.109)	9.291^{**}	(3.860)	-0.289^{***}	(0.109)	7.259^{**}	(3.571)
Constant	20.458^{***}	(0.726)	84.127^{**}	(34.470)	20.331^{***}	(0.635)	155.888^{***}	(35.047)
Observations	582		582		582		582	
R^2	0.060		0.038		0.044		0.027	

Note: Standard errors are corrected for clustering at the session level. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively.

E.2. The Drivers of Agreement

Here we seek to understand the drivers of agreement and disagreement in our dynamic bargaining institution. Specifically, how do things like the difference between final offers, the supplier's cost and the supplier's position in the supply chain (Supplier 1 or Supplier 2) affect the likelihood of agreement? In Table E.3 we present random-effects regressions where the dependent variable is whether an agreement was made in the two dynamic bargaining treatments (we focus only on the assembly setting). The independent variables represent the difference in final contract terms proposed between the OEM and supplier and whether the supplier is high cost, as well as an indicator for Supplier 1. Reiterating a point made in Table 4, negotiating with a high cost supplier decreases the chance of coming to an agreement. Though the direct effect is only marginally significant in the Barg-Seq treatment, there is also an indirect effect. Specifically, the further apart are final wholesale price and fixed payment offers, the less is the chance of agreement. Importantly, it is the case that final offers between the OEM and a high-cost supplier are further apart than are final offers between the OEM and a low-cost supplier. Therefore, disagreement arises due to a divergence between final offers of the OEM and the suppliers, and these differences are generally larger when the supplier has high cost.

While not depicted, we conducted a similar set of random effects regressions for whether an OEM contract offer was accepted by a supplier in the two (Assembly) mechanism design treatments. We find once again

Table E.3 The Drivers of Agreement in the Dynamic Bargaining Institution

Parameter	Barg-Seq		Barg-Sim	
Final Offer: $w^{Sup} - w^{OEM}$	-0.017^{***}	(0.002)	-0.013^{**}	(0.005)
Final Offer: $(F^{Sup} - F^{OEM})/100$	-0.068^{***}	(0.011)	-0.044^{***}	(0.013)
Supplier Cost: 15	-0.078^{*}	(0.042)	-0.054	(0.042)
Supplier 1	-0.025	(0.039)	0.037	(0.027)
Constant	0.999^{***}	(0.036)	0.941^{***}	(0.028)
Observations	333		352	
R^2	0.121		0.086	

Note: Standard errors are corrected for clustering at the session level. *, ** and *** denote significance at the 10%, 5% and 1% level, respectively.

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 6 *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.*