Private Information and Dynamic Bargaining in Supply Chains: An Experimental Study

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Problem Definition: We conduct a controlled human-subjects experiment in a two-tier supply chain where a supplier’s per unit production cost may be private information while bargaining with a buyer.

Academic/Practical Relevance: Academically, studies on supply chain contracting usually assume either full information or highly structured bargaining. We consider private information with dynamic, unstructured, bargaining. In practice, a buyer may not know their supplier’s cost exactly and interact with its supplier in a back-and-forth bargaining environment. Thus, understanding how a supplier’s private cost information affects both supply chain outcomes and bargaining is new to the literature and relevant to practice.

Methodology: We employ insights from mechanism design to generate restrictions on the space of agreements and solve for a specific bargaining solution under private information to generate precise predictions. These predictions are then tested through a human-subjects experiment.

Results: While all suppliers should earn 50% of the supply chain surplus under both full and private information, we show that suppliers (i.e., risk holders in our study) consistently earn less than 50% of supply chain expected profits. The effect is most pronounced for high-cost suppliers under private information, who earn disproportionately low shares of supply chain profits (12.83% to 29.59%). We show that this latter result is largely due to (a) retailers making aggressive opening wholesale price offers when bargaining under private information and (b) final agreed upon wholesale prices being anchored on these low-opening offers.

Managerial Implications: Our results suggest that inventory risk holders should be made aware of the need to be adequately compensated for their risk exposure. This is particularly true for high-cost suppliers, who actually suffer from having their costs as private information. Further, although private information does not generate more disagreement, negotiations do take longer, which can be costly to firms.

Key words: behavioral operations; supply chains; bargaining; private information

1. Introduction
Private information is ubiquitous in many supply chain settings where a manufacturer or retailer wishes to contract with one or more suppliers to procure a product. For example, the buyer and supplier may have different beliefs or forecasts about demand. Even more commonly, the buyer may not know the supplier’s cost structure. Indeed, an executive for a large durable goods manufacturer
recently told us, when discussing his company’s procurement practices, “I usually don’t know my supplier’s cost structure exactly, but I have a rough estimate of what it might be.”

Understanding how private information affects the contracting process is, therefore, important from both an academic and practical perspective. In an environment in which there are many potential suppliers, the use of auctions as a procurement strategy for dealing with private information is well-studied in operations management (for a survey of the experimental literature, see Elmaghraby and Katok 2019). In this paper, our interest lies in those situations in which the set of suppliers is small (e.g., because the product is specialized). In particular, we focus on the case of a single buyer and supplier who meet to negotiate a contract, and study how private information affects the outcome of such interactions.

In studying the interactions between buyer-supplier dyads, the supply chain literature often considers a highly structured form of bargaining, such as having a powerful proposer make an ultimatum offer to the responding party. In the presence of private information, this proposal is often extended to include a menu of contracts from which the responder chooses which contract, if any, to accept (as in, e.g., Corbett et al. 2004). Using the tools of mechanism design, these menus of contracts are carefully designed to screen the player types with private information in an incentive compatible manner so that each supplier type accepts the contract that was specifically intended for that type. These approaches are not without merit. First, from a practical perspective, there are business-to-business (B2B) relationships where one party has considerable bargaining power over the other. Second, at a more abstract level, such frameworks often yield clean, testable, theoretical predictions. However, not all negotiations take this form in practice. Instead, two companies may have relatively equal bargaining power and partake in a more dynamic, unstructured, back-and-forth negotiation. Such situations are the focus of our paper.

In this study, we investigate supply chain contracting in a dynamic unstructured bargaining environment where supplier costs may be private or full information. Because negotiations are conducted by human managers, we employ a combination of theory and human-subjects experiments and address the following research questions. In an unstructured bargaining environment, (1) What is the effect of private supplier cost information on supply chain outcomes (e.g., efficiency, distribution of profits, and contract terms)? (2) How does private supplier cost information affect the bargaining dynamics (e.g., negotiating times, opening offers, concession patterns, and agreements)?

We operationalize the more natural bargaining (between players with equal bargaining power) by allowing both parties to make unlimited contract offers and send limited feedback over a fixed
amount of time. One advantage of this setting is that, in a human-subjects experiment, we can observe more than just agreed upon terms. For instance, we are able to track each offer made by either party while negotiating, along with any feedback sent, over time. We focus exclusively on wholesale price contracts such that the two parties negotiate a wholesale price and stocking quantity simultaneously. We also assume that the supplier incurs the cost of any unsold inventory. This closely matches a drop-shipping, vendor-managed inventory, or e-commerce environment. Randall et al. (2006) estimate that between 23% and 33% of e-retailers use drop-shipping, and the United States Census estimates that sales by e-retailers totaled $389.1 billion in 2016 (United States Census Bureau 2016).

We begin by deriving theoretical predictions under full and private information regarding the supplier’s cost. We refer to any buying firm in a B2B relationship (e.g., manufacturers, retailers, distributors, assemblers, etc) as ‘retailers’ for simplicity. In order to provide heterogeneity amongst suppliers we assume that ‘higher quality’ suppliers have lower per-unit production costs. Similarly, for retailers, we assume that ‘higher quality’ retailers have higher per-unit selling prices. Regardless of the production cost or selling price, the quality of the product and demand distribution remain the same (i.e., a low production cost is not associated with low quality and a high selling price is not associated with low demand). Regarding the supplier’s cost details, under full information we rely on the Nash bargaining solution (Nash 1950) to generate theoretical predictions. Under private information, we first use insights from mechanism design to see how incentive compatibility restricts the set of possible contracts.\(^1\) From the set of incentive compatible contracts we go further and adapt the solution concept from Myerson (1984), which seeks to generalize the full information Nash bargaining solution, to generate more precise predictions.

Under full and private information we generate point predictions including supply chain efficiency, distribution of profits, wholesale prices, and quantities. While the solution concepts employed are general, in some cases we derive results for the experimental parameters in order to derive clear, testable predictions. Under private information, we show that incentive compatibility requires that quantities are decreasing in suppliers’ cost. Interestingly, we are able to show that incentive compatibility need not generate inefficiencies. That is, there exist incentive compatible mechanisms in which suppliers would truthfully reveal their private information and, in which the supply chain is coordinated for all supplier cost types. This stands in contrast to the typical mechanism design results in which inefficiency is a necessary consequence of providing incentives.

\(^1\) Recent work by Camerer et al. (2019), in a more abstract, divide a pie bargaining framework, has shown the potential for such a approach.
for truthful revelation of information. That being said, when we focus on the Myerson bargaining solution, for the parameters of the experiment, we show that the supply chain is coordinated only for the lowest-cost supplier. Another important theoretical insight from the Myerson bargaining solution is that, for our experimental parameters, all supplier types benefit from their cost information being private. This means that when a supplier's cost information is unknown to retailers, they can use this private information to their advantage while bargaining and always earn weakly higher expected profits compared to the full information case. This is one of the key theoretical predictions that we seek to test in our experiment.

We formulate a set of experimental hypotheses based on our theoretical predictions and test them through a controlled human-subjects experiment. We accomplish this through a $2 \times 1$ design which manipulates whether the supplier's cost information is known or not by the retailer while bargaining. Our experiments yield a number of insights pertaining to supply chain outcomes and bargaining dynamics. Of them, one important result is that suppliers earn less than 50% of the total supply chain expected profit under both full and private information. This is not entirely surprising in the full information case, as past experimental bargaining studies have shown that inventory risk holders (suppliers in our study) often fail to be sufficiently compensated for incurring such risk. However, what is of more interest is that high-cost suppliers, under private information, earn a disproportionately low share of total supply chain expected profits: between 12.83% and 29.59%. Theory predicts that they should earn at least 50%. Upon further examination, our data suggest that this is largely due to the bargaining dynamics under private information. Retailers' first wholesale price offers to suppliers, under private information, are virtually identical to their first offers to the lowest-cost suppliers under full information. In short, under private information, retailers act as if they are bargaining with the lowest-cost supplier (such that their initial offers would give higher-cost suppliers negative expected profit).

We also show that final agreed upon terms are anchored on such opening offers. As a consequence, under private information, high-cost suppliers end up with an inordinately low wholesale price, and hence a low share of the overall expected profits. In addition, our data suggest that these aggressive wholesale price opening offers by retailers do not increase the likelihood of disagreement under private information (as if suppliers do not blame retailers for making such low-opening offers). Lastly, another important insight from our experiments is that bargaining appears to take longer under private information, which can be costly in practice.

We organize the rest of this paper as follows. In the next section we summarize the most relevant literature to our study. In §3 we detail the theoretical framework for our setting under full and
private information. In §4 we outline our experimental design and provide point predictions for the theory laid out in §3. When then present our results in §5 in two subsections: supply chain outcomes and bargaining dynamics. We then end with a discussion of our results and managerial insights in §6.

2. Related Literature

The literature most related to our work includes supply chain research that considers wholesale price contracts, unstructured dynamic bargaining processes, and/or private information. Because of the breadth of some of these topics, for brevity, we highlight a subset of important works and then refer the reader to resources which provide more comprehensive summaries.

In regards to wholesale price contracting from a theoretical standpoint, Lariviere and Porteus (2001) consider wholesale price contracts in a two-stage supply chain and investigate how aspects like demand variability affect prices and the distribution of profits. Tomlin (2003) demonstrates how price-only contracts can allocate total supply chain profit between a manufacturer and a supplier who can both invest in capacity. Bernstein et al. (2006) identify how wholesale price contracts can coordinate a supply chain with a single supplier and multiple retailers. For a summary of the theoretical features of supply chain contracts please see Cachon (2003).

Experimentally, some papers which investigate supply chain contracting include Ho and Zhang (2008), who study how framing a fixed fee can affect overall supply chain efficiency and Kalkanci et al. (2011), who demonstrate how simple price-only contracts can perform well in a setting where the retailer has accurate information regarding demand. Katok et al. (2014) study wholesale price contracts where supply chain partners have fairness concerns. Davis et al. (2014) investigate wholesale price contracts in three alternative inventory risk arrangements, while Zhang et al. (2015) compare buy-back and revenue-sharing contracts under alternative overage and underage costs with loss-averse suppliers. For a comprehensive summary of the experimental supply chain contracting literature we refer the interested reader to Chen and Wu (2019).

A vast majority of the works mentioned above assume that one party in the supply chain makes an ultimatum offer to the other party. Some studies have extended this setting by allowing for a more natural bargaining process. Theoretically, an important framework for solving these problems under full information is the Nash bargaining solution (Nash 1950). Experimentally, the only supply chain papers that we are aware of which deviate from one-shot offers are Haruvy et al. (2014), Leider and Lovejoy (2016), Davis and Leider (2018) and Davis and Hyndman (2019a). Haruvy et al. (2014) extend the ultimatum offers scenario by permitting only one party to make multiple offers. Leider
and Lovejoy (2016) consider back-and-forth bargaining in a three-stage supply chain with chat box communication. Davis and Leider (2018) allow for unstructured bargaining and evaluate which contracts are best at alleviating under-investment in capacity by suppliers. Davis and Hyndman (2019a) also consider unstructured bargaining and study which contract terms should be included in a wholesale-price contract negotiation under full information. In many ways, our work can be considered an extension of Davis and Hyndman (2019a), with a critical difference being that we investigate one-sided private information, which is directly relevant to practice.

The supply chain literature frequently assumes full information of price, demand, and cost parameters (e.g., Cachon (2004)). There have certainly been some deviations from this, especially in a shot-shot offer setting. For example, some studies have examined a setting where the retailer may have private knowledge about consumer demand. Thus the issue of sharing forecast information is relevant (e.g., Cachon and Lariviere (2001) from a theoretical perspective and Ozer et al. (2011) from an experimental perspective). In a private information setting, Corbett et al. (2004) adopt a mechanism design framework in which a powerful supplier offers menus of contracts to screen buyer cost-types. More relevant to our work are those papers in supply chain management which consider private information combined with a more natural bargaining interaction between two parties. Theoretically, one paper which satisfies this is Feng et al. (2015), who investigate multiple alternating offers where both parties are impatient and the buyer has private information about their type. They show how quantity distortion and information rents may or may not be avoided depending on the patience of the parties involved.

There is also work in experimental economics pertaining to bargaining and private information. Mitzkewitz and Nagel (1993) experimentally study the classic ultimatum game with private information such that the receiver does not know the size of the total pie. They then manipulate whether the proposer offers an amount to the receiver (i.e., the receiver only knows their own earnings) or an amount for themselves (i.e., the receiver only knows what the proposer earns). Closer to our setting, a number of studies allow pairs to partake in an unstructured bargaining environment. For instance, a number of experiments consider pairs bargaining over lottery tickets (e.g., Roth and Malouf (1979), Roth et al. (1981), Roth and Murnighan (1982)) and find that participants differ in their focal points for fair outcomes. In particular, some participants consider an equitable outcome one where each party receives the same number of lottery tickets (usually the participant who receives higher earnings from winning the lottery) whereas others consider an equitable outcome one which equalizes earnings (preferred by the participant who receives lower earnings from winning the lottery). Roth et al. (1988) demonstrate a robust behavioral result in that bargaining pairs
often come to agreements during the final seconds of a negotiation, which they deem the “deadline effect.” More recently, Camerer et al. (2019) take a machine-learning approach to analyzing short (10 second) unstructured negotiations. For summaries on bargaining in economics please see Roth (1985), Roth (1995), Muthoo (1999), and Camerer (2003, Ch. 4).

Overall, we believe our work extends the existing supply chain literature in two important dimensions: (1) we consider a more natural back-and-forth bargaining process between retailers and suppliers which allows for multiple offers and limited feedback, and (2) we evaluate private versus full information with respect to the supplier’s cost.

3. Theoretical Background

In this section we provide a theoretical analysis for the bargaining institutions that we will test in the lab. The basic framework consists of a set of retailers indexed by their per-unit selling price, \( p_1 > p_2 > \ldots > p_n \) and a set of suppliers indexed by their per-unit cost of production, \( c_1 < c_2 < \ldots < c_n < p_n \). We assume that the sets of possible prices for retailers and costs for suppliers are common knowledge. Underlying demand, \( D \), is drawn uniformly from \( [a, b] \) where \( 0 \leq a < b < \infty \), but the actual realization of demand is unknown at the time of bargaining.

We implement an unstructured bargaining protocol in which a retailer – with unit selling price \( p \) – simultaneously negotiates a wholesale price, \( w \), and order quantity, \( q \), with a supplier – with unit cost \( c \). We assume that the supplier bears the risk of unsold inventory, which means that both parties’ payoffs are subject to random demand realizations.

We consider two settings which differ as to whether the supplier’s cost is full or private information. For the full information case we provide a more general analysis. For the private information case we present a general approach to solving the problem, and provide some general insights based on the notion of incentive compatibility, but, due to the highly computational nature of the specific bargaining solution, some predictions are based on the parameters in our experiment. Specifically, in our experiment, we consider markets of three retailers and three suppliers. We chose this market size in an attempt to mimic a somewhat realistic setting with heterogeneity among parties, while also keeping the game relatively straightforward for human participants. The possible selling prices are 10, 11, or 12 and exactly one retailer had each selling price. Similarly, the possible costs for suppliers are 3, 4, or 5 and exactly one supplier had each unit cost. In each period, retailer-supplier dyads are randomly formed, so that there are 9 possible retailer-supplier combinations. We chose to draw prices and costs without replacement to ensure an even number of heterogeneous observations in our data collection. Additionally, demand for each retailer-supplier pair is uniformly distributed over \( [0, 100] \). We will provide more details regarding our experimental design in the next section.
3.1. Bargaining with Full Information

Under full information the supplier’s cost, \( c \), is common knowledge while bargaining. Because of our unstructured bargaining protocol, the relevant theoretical lens for the full information case is the Nash bargaining solution (Nash 1950). Denote by \( \pi_i(w,q) \) the expected profits for firm \( i \in \{r(\text{retailer}), s(\text{supplier})\} \), from an agreement with wholesale price, \( w \), and order quantity, \( q \). The expected profits can be expressed as:

\[
\pi_r(w,q) = \frac{p - w}{b - a} \int_a^b \min\{q,x\}dx; \quad \pi_s(w,q) = \frac{w}{b - a} \int_a^b \min\{q,x\}dx - cq. \tag{1}
\]

The disagreement payoff is 0 for both players. The Nash bargaining solution is the solution to:

\[
\max_{w,q} \frac{\pi_r(w,q) \cdot \pi_s(w,q)}{s.t. \quad c \leq w \leq p \text{ and } a \leq q \leq b.}
\]

Since the full information bargaining environment is identical to Davis and Hyndman (2019a), we state without proof the following result:

**Proposition 1.** When bargaining under full information:

(i) The supply chain is coordinated, \( q^* = a + (b - a)(p - c)/p \).

(ii) Expected profits for the retailer and supplier are split equally, 50%/50%.

(iii) The wholesale price is \( w^* = \frac{p(3ac^2 + ap^2 - 3bc^2 + 2bp + bp)}{2(a^2 + ap^2 - bc^2 + bp)} > \frac{p + c}{2} \).

Note that the agreed wholesale price, \( w^* \), under full information is strictly greater than the mid-point between \( c \) and \( p \) (i.e., \( (p+c)/2 \)). This follows because the supplier bears the inventory risk. Therefore, to equalize the expected payoffs of the retailer and supplier, the wholesale price must increase beyond the midpoint between the retailer’s price and the supplier’s cost.

3.2. Bargaining with Private Information

When supplier costs are private information while bargaining (i.e., unknown to retailers), we need a suitable generalization of the Nash bargaining solution. Using insights from mechanism design, Myerson (1984) provides such a generalization that has been largely unexplored in the operations literature. The basic idea is that the players negotiate over “mechanisms,” which consist of a menu of contracts – one for each possible type of supplier – that are incentive compatible, so that each supplier type truthfully reveals her type.\(^2\) From the set of individually rational and incentive compatible mechanisms, the Myerson (1984) solution then seeks to maximize a weighted sum of

\(^2\)To be sure, in actual bargaining, players do not actually negotiate over mechanisms, but the underlying assumption is that the unstructured bargaining process provides an indirect mechanism to implement the bargaining solution.
the retailer’s and supplier’s expected profits. The solution must also respect so-called *warrant conditions*, which are the minimum amounts that each player type “warrants” in a fair division. The final complication is that the weights must be derived as part of the solution.

While we will leave most details deriving the Myerson (1984) bargaining solution to the appendix, it is instructive to look at the incentive compatibility constraints. Let \( \mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\} \) denote a mechanism, where \( (\gamma_i, w_i, q_i) \) denotes a contract intended for supplier type \( c_i \). The wholesale price and order quantity are \( (w_i, q_i) \) and \( \gamma_i \in [0, 1] \) is the probability of agreement. Given the assumptions that demand is uniform over \([0, 100]\), we know that supplier expected profits, conditional on agreement, are

\[
\pi_s(w, q, c) = \left(\frac{w}{200}\right)(200q - q^2) - c_i q_i
\]

Then, a mechanism is incentive compatible if:

\[
\gamma_i \left(\frac{w_i}{200}\right)(200q_i - q^2) - c_i q_i \geq \gamma_j \left(\frac{w_j}{200}\right)(200q_j - q^2) - c_j q_j
\]

for all \( i = 1, 2, 3 \) and all \( j \neq i \).

Focusing just on incentive compatibility, we now state several preliminary results, the proofs of which can be found in the Appendix.

**Lemma 1.** Let \( \mathcal{M} \) be an incentive compatible mechanism. Then \( \gamma_1 q_1 \geq \gamma_2 q_2 \geq \gamma_3 q_3 \).

Thus, Lemma 1 shows that the “expected quantity” is decreasing in the supplier’s cost. \(^3\)

Although disagreement is possible in an incentive compatible mechanism, our next result shows that disagreement need not occur under private information. The underlying intuition is that since players negotiate over both a quantity (which determines the size of the pie) and a wholesale price (which determines the distribution of the pie), it is possible to construct an alternative mechanism which generates the same expected profits but avoids disagreement. Specifically,

**Lemma 2.** Given any incentive compatible mechanism, \( \mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\} \), there exists an alternative mechanism, \( \bar{\mathcal{M}} = \{(1, \bar{w}_i, \bar{q}_i), i = 1, 2, 3\} \), such that disagreement never happens, which is also incentive compatible and generates the same expected profits for each supplier type and the retailer.

Therefore, our analysis proceeds by assuming that \( \gamma_i = 1 \) for all \( i \). Note that an immediate corollary of Lemmas 1 and 2 is that \( q_1 \geq q_2 \geq q_3 \).

Of course, even though there is no disagreement, it is generally the case that inefficiencies arise due to private information. This is because we may need to distort the quantities away from full efficiency for higher-cost suppliers in order to induce truth-telling. However, we can show that incentive compatibility does not necessarily lead to inefficiency:

\(^3\)To be sure, this is not a strong restriction, since the quantity that coordinates the supply chain is also decreasing in the supplier’s cost.
Proposition 2. There exist incentive compatible mechanisms in which the supply chain is coordinated for all possible supplier types. That is, $q_i = 100\left(\frac{p-c_i}{p}\right)$ for all $i$.

This result shows that if inefficiency arises, it must be due to the properties of the bargaining solution and not merely because of incentive compatibility. To this end, we now provide a brief discussion of Myerson’s (1984) bargaining solution. Recall that $\pi_s(w, q, c_i)$ denotes the expected profits of supplier type $c_i$ when faced with the contract $(w, q)$, while $\pi_r(w, q, p)$ denotes the expected profits of a retailer with selling price $p$ facing the contract $(w, q)$. The general approach consists of solving:

$$\max_{\lambda_i, q_i, w_i \geq 0} \frac{1}{3} \sum_{i=1}^{3} \lambda_i \pi_s(w_i, q_i, c_i) + \frac{1}{3} \sum_{i=1}^{3} \pi_r(w_i, q_i, p)$$

s.t. $\pi_s(w_i, q_i, c_i) \geq \pi_s(w_{i+1}, q_{i+1}, c_i), \ i = 1, 2.$

That is, we maximize a weighted sum of the supplier’s and retailer’s expected profits subject to incentive compatibility constraints. The first complicating factor is that the solution must also determine the weights, $\lambda_i$, that we apply to each supplier type $i$’s profits. That is, the bargaining solution need not weight each supplier type equally. Without loss of generality, we can take $\lambda_3 = 1 - \lambda_1 - \lambda_2$.

One might find it odd that the private information extension of the Nash bargaining solution – which involves solving an additive optimization problem – is so different from the complete information Nash bargaining solution – which involves solving a multiplicative optimization problem. An earlier extension by Harsanyi and Selten (1972) proposed a multiplicative version. However, as discussed in Myerson (1984), this necessarily violates a probability invariance axiom. We refer the interested reader to these papers for further details.

We provide more details in Appendix A; here, we outline the steps to obtain the solution. Letting $\alpha_i$ denote the Lagrange multiplier on supplier type $i$’s incentive compatibility constraint and substituting in the expressions for expected profits, the Lagrangean can be written as:

$$L = \frac{1}{3} \left(3(\lambda_1 + \alpha_1) \left(\frac{w_1}{200} (200q_1 - q_1^2) - c_1q_1\right) + \frac{p-w_1}{200} (200q_1 - q_1^2)\right)$$

$$+ \frac{1}{3} \left(3(\lambda_2 + \alpha_2) \left(\frac{w_2}{200} (200q_2 - q_2^2) - c_2q_2\right) - 3\alpha_1 \left(\frac{w_2}{200} (200q_2 - q_2^2) - c_1q_2\right) + \frac{p-w_2}{200} (200q_2 - q_2^2)\right)$$

$$+ \frac{1}{3} \left(3(1 - \lambda_1 - \lambda_2) \left(\frac{w_3}{200} (200q_3 - q_3^2) - c_3q_3\right) - 3\alpha_2 \left(\frac{w_3}{200} (200q_3 - q_3^2) - c_2q_3\right) + \frac{p-w_3}{200} (200q_3 - q_3^2)\right)$$

4 Since there is only one retailer type, there are no weights applied to the retailer’s payoff, beyond taking expectations over the type of supplier she is matched with.
Observe that the wholesale price is a linear transfer between the retailer and the supplier. Therefore, we can impose the constraints that \( \lambda_1 + \alpha_1 = \frac{1}{3} \) and \( \lambda_2 + \alpha_2 - \alpha_1 = \frac{1}{3} \). This temporarily obviates the need to solve for \( w_i \) in the optimization problem and allows us to focus on \( q_i \). We will return to solve for the wholesale prices in the last step of the problem. Notice also that each line of the above equation represents the total virtual surplus if supplier type \( i \) interacts with the retailer.

The first step is to find the optimal quantities for each supplier cost type as a function of the \( \lambda \)'s and \( \alpha \)'s. Second, using the expressions for \( q_i \) and also the relationship between \( \lambda \) and \( \alpha \), we can write the Lagrangean as a function of \( c_i, p \) and the \( \lambda \)'s. Doing so yields:

\[
\mathcal{L} = \frac{50}{3} \left( \frac{(p - c_1)^2}{p} + \frac{(p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2))^2}{p} + \frac{(p + c_2(2 - 3\lambda_1 - 3\lambda_2) - 3c_3(1 - \lambda_1 - \lambda_2))^2}{p} \right)
\]

where again, each of the three terms represents the total surplus assuming that given supplier cost type is drawn.

The third step imposes further restrictions on the solution. Namely, we must ensure that the warrant conditions are satisfied. In particular, the warrant conditions dictate the virtual utility, \( W_i^* \), that each supplier type \( i \) warrants (i.e., “deserves” in a bargaining solution). This is akin to the standard Nash bargaining solution, but with private information corresponds to half the total virtual surplus generated by the interaction between the retailer and the particular supplier cost type. In particular, we must solve:

\[
(\lambda_1 + \alpha_1)W_1 = \frac{150}{2}\frac{3}{3} \left( \frac{(p - c_1)^2}{p} \right)
\]

\[
(\lambda_2 + \alpha_2)W_2 - \alpha_1 W_1 = \frac{150}{2}\frac{3}{3} \left( \frac{(p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2))^2}{p} \right)
\]

\[
(1 - \lambda_1 - \lambda_2)W_3 - \alpha_2 W_2 = \frac{150}{2}\frac{3}{3} \left( \frac{(p + c_2(2 - 3\lambda_1 - 3\lambda_2) - 3c_3(1 - \lambda_1 - \lambda_2))^2}{p} \right)
\]

for \( W_i^* \), \( i = 1, 2, 3 \).

The final step is to find values of \( \lambda_i \) and \( w_i \) such that:

\[
\pi_s(w_i, q_i, c_i) \geq W_i^*, \text{ with equality if } \lambda_i > 0,
\]

\[
\pi_s(w_i, q_i, c_i) \geq \pi_s(w_{i+1}, q_{i+1}, c_i), \text{ for } i = 1, 2 \text{ and with equality if } \alpha_i > 0.
\]

With three supplier cost types and two incentive compatibility constraints this is, potentially, a system of five equations in five unknown variables: \( (w_1, w_2, w_3, \lambda_1, \lambda_2) \). Moreover, one must check boundary conditions on the \( \lambda \)'s and \( \alpha \)'s, making it necessary to consider seven different systems of equations to find the valid solution. Given the parameters of our experiment, the bargaining solution involves \( \lambda_1 = \lambda_2 = 0 \), and the incentive constraints on the \( c_1 \) and \( c_2 \) supplier types are binding (the equilibrium contract parameters are provided in Table 1b and are discussed when we review our experimental design). We can summarize these results as:
Proposition 3. When bargaining under private information and given the parameters of our experiment:

(i) The supply chain is coordinated only for the lowest cost supplier ($c_1$).

(ii) All suppliers benefit from private information and earn at least half of the expected supply chain profits.

(iii) The wholesale price is higher and the order quantity is lower under private information than under full information.

When $\lambda_1 = \lambda_2 = 0$, it means that the bargaining solution only places weight on the highest-cost supplier type. Moreover, in the bargaining solution, this supplier’s expected profits are equal to the expected profits of the retailer. However, from the retailer’s perspective, she has a chance to bargain with lower-cost suppliers, where she will earn more, this means that she will receive less than half of the supply chain profits when matched with the highest-cost supplier.

That all supplier types strictly benefit from private information is a function of both the particular bargaining solution and the parameters that we implement in the experiment. There exist other parameterizations in which not all suppliers earn information rents under the bargaining solution. Moreover, if we abstract away from Myerson’s bargaining solution and focus instead on simply incentive compatible mechanisms for the parameters that we implement, there exist mechanisms in which all, some or no supplier types earn information rents.

4. Experimental Design

In our experiment, participants were assigned a role of supplier or retailer and placed into a group of six, three retailers and three suppliers. Both roles and groups remained fixed for the duration of the experiment. In every round, each retailer was randomly assigned a selling price per unit, $p \in \{10, 11, 12\}$, without replacement. Therefore, while a specific retailer’s price could vary from round to round, in every round one retailer had $p = 10$, another $p = 11$, and the third $p = 12$. Supplier costs were assigned in a similar fashion where, in every round, each supplier was randomly assigned a production cost per unit, $c \in \{3, 4, 5\}$, without replacement. The possible prices and costs were common knowledge to both parties. As mentioned previously, we opted for market sizes of six in an attempt to mimic a somewhat realistic setting while keeping the game relatively straightforward for participants, and we draw prices and costs without replacement to ensure a relatively even collection of different observations.

One such set of parameters is $p \in \{10, 11, 12\}$ and $c \in \{3, 6.5, 8.5\}$. In this case $\lambda_1 > 0$ and the lowest-cost supplier earns no information rent.
Each round began by randomly assigning retailers and suppliers into pairs. Each pair would then bargain over contract terms for a product with uncertain demand. Regardless of the retailer’s selling price and supplier’s production cost, demand for the product was always a random draw from the discrete uniform distribution on \{1, 2, \ldots, 100\}. If the two parties came to an agreement while bargaining, demand would be realized, and retailers would satisfy demand by sourcing product directly from the supplier, such that the supplier incurred the cost of any unsold inventory.

For our unstructured bargaining we followed a protocol similar to Davis and Leider (2018) and Davis and Hyndman (2019a). Specifically, each retailer-supplier pair was given five minutes to negotiate a contract which consisted of two terms, a wholesale price, \(w\), and a quantity, \(q\). During this time, retailers and suppliers could make as many offers as they desired at any point in time. If either party chose to accept the most recent offer of the other player, then demand would be realized and participants would receive feedback that included realized profits. If a pair was unable to reach an agreement after five minutes then both players would receive a profit of zero.

While bargaining, we allowed participants to provide feedback about the most recent offer received. In particular, they could ‘reject’ either of the proposed terms through a button for each contract term, which they could click at any time for currently valid proposal. This feedback would then be displayed on the proposer’s screen. Note that a participant could later accept the offer even if they signaled disapproval with it, so long as a more recent offer was not received. We opted for this type of feedback to simulate a more natural bargaining process, while also allowing us to monitor offers and feedback. Lastly, to reduce complexity in the experiment, we provided participants with a decision support tool. With this tool, they could enter hypothetical values for \(w\) and \(q\), which would generate a graph showing the profit for both players as a function of demand.

Consistent with our theory section, our experimental design consists of two treatments: one where supplier’s costs were common knowledge while bargaining (full information) and one where the supplier’s cost information was unknown to retailers while bargaining (private information). Each treatment consisted of six rounds and included 48 participants across three sessions. Thus eight markets of six participants in each treatment. The experimental software was programmed in z-Tree (Fischbacher 2007), and all sessions took place in the experimental laboratory at a large northeast university. Sessions took roughly 60 minutes with earnings varying considerably: average $38, maximum $78, and minimum $7 (participants were compensated for all rounds of decisions). Therefore, participants had clear incentives to take the task seriously. Sample instructions and screenshots are available upon request.
### Table 1 Experimental Predictions

<table>
<thead>
<tr>
<th></th>
<th>Efficiency (%)</th>
<th>Supplier Share (%)</th>
<th>Wholesale Price (w)</th>
<th>Quantity (q)</th>
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<td>58.33</td>
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<tr>
<td>Average</td>
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<td>63.43</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Efficiency (%)</th>
<th>Supplier Share (%)</th>
<th>Wholesale Price (w)</th>
<th>Quantity (q)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>p = 11</td>
<td>p = 12</td>
<td>p = 10</td>
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<tr>
<td>c = 3</td>
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<td></td>
<td>60.88</td>
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<td>70.00</td>
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<td></td>
<td>7.89</td>
<td>8.58</td>
<td>9.23</td>
<td>75.00</td>
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<td>65.87</td>
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<td>57.41</td>
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<td></td>
<td>8.59</td>
<td>9.06</td>
<td>9.58</td>
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<td></td>
<td>30.00</td>
<td>36.36</td>
<td>41.67</td>
<td>30.00</td>
</tr>
<tr>
<td>Average</td>
<td>95.37</td>
<td>59.78</td>
<td>8.76</td>
<td>54.29</td>
</tr>
</tbody>
</table>

Note: The supplier’s share under private information is based on the *ex ante* expected profits.

### 4.1. Predictions and Hypotheses

In Tables 1a and 1b we provide point predictions (given the experimental parameters) based on our theoretical analysis of the Nash bargaining solution under full information and Myerson’s generalization under private information. Table 1a depicts the point predictions when the suppliers’ costs are full information while bargaining, whereas Table 1b illustrates the point predictions when the suppliers’ costs are private information while bargaining. A combination of these metrics and our propositions in §3 lead us to the following experimental hypotheses:

**Hypothesis 1.** Under full information:

(i) 100% efficiency is achieved for every c and p combination.

(ii) Retailers and suppliers earn 50%/50% splits of total supply chain expected profit.

**Hypothesis 2.** Under private information:

(i) 100% efficiency is only achieved for the pair with the lowest cost supplier.

(ii) Suppliers earn at least 50% of the total supply chain expected profit.

(iii) The agreed wholesale price is always higher compared to full information.

To be sure, these predictions are generated from underlying theoretical models which may or may not govern actual behavior. In the full information case, we know from Davis and Hyndman (2019a), that (due to risk/loss aversion) full efficiency is not generally achieved. More importantly, due to superficial fairness, when suppliers bear the risk of unsold inventory, suppliers typically earn less than 50% of the supply chain expected profits. Therefore, if these earlier results replicate to the wider parameter space that we consider, it should not be surprising to see less than 100%
efficiency and suppliers earning less than 50% of the supply chain expected profits. Note, however, that our full information treatments are not simply a replication of Davis and Hyndman (2019a). The reason is because we consider several (nine to be precise) price/cost pairs, while that paper considered only one. This matters because, for example, for the same wholesale price and quantity, the risk to the supplier is increasing with its cost. This could influence their bargaining behavior and also suggests that suppliers may be impacted differentially, in terms of profits, depending on their cost.

Regarding Hypothesis 2, there is no similar experimental study in which to benchmark behavior. However, it is possible that suppliers’ inability to negotiate sufficiently high wholesale prices under full information will transfer over to the private information case. Therefore, suppliers may not earn more than 50% of the supply chain expected profits. Moreover, while the Myerson solution predicts that efficiency is only 100% for the lowest-cost supplier, Proposition 2 showed that efficiency need not vary across supplier types. Finally, it is possible that private information generates other interesting bargaining dynamics, which could lead us to reject our hypotheses. Thus, we believe that an experimental investigation is a particularly fruitful exercise.

5. Results

We present our experimental results in two subsections. In §5.1 we investigate how our data compares to the predictions and hypotheses from §4.1. In §5.2, because the bargaining solutions do not provide details pertaining to the process itself, we analyze the bargaining dynamics in our data. For all hypothesis tests we use $t$–tests where a group of six is an independent observation. Also, we run all regressions with random effects and clustered standard errors at the group level.

Before proceeding to our detailed results, we provide a summary of our main insights. First, supply chain efficiency is relatively high, and similar, between full and private information. Second, contrary to theory, suppliers earn less than 50% of the total supply chain expected profits under both full and private information. This effect is especially pronounced for high-cost suppliers ($c = 5$) under private information, where suppliers only earn between 12.83% and 29.59% of total expected profits. Third, under both full and private information, stocking quantities are anchored on mean demand, and wholesale prices are set too low compared to theory (wholesale prices are also similar between the two information conditions). Turning to the bargaining dynamics, fourth, pairs take more time to come to an agreement under private information, even though agreement rates are the same between the two conditions. Fifth, final agreed contract terms are anchored on opening offers and, moreover, under private information, retailers make aggressive opening offers (i.e., as if they were bargaining with the lowest-cost supplier).
5.1. Outcomes and Hypotheses

Before evaluating our experimental hypotheses, we briefly comment on agreement rates in our experiment. While both our full and private information theory predict that disagreement should never occur, it is plausible that disagreements are more frequent under private information due to retailers trying to learn their supplier’s cost and supplier’s trying to earn information rents. However, we observe that pairs came to a bargaining agreement 90.28% of the time under full information and 93.06% of the time under private information ($p = 0.525$). This result validates Lemma 2 and shows that players don’t use disagreement as a tool for separating supplier cost types. Therefore, unless otherwise noted, we will report outcomes conditional on agreement.

Efficiency. Beginning with supply chain efficiency (Table 2), observed average efficiency is 91.34% under full information, and is below 100% for all nine combinations of $c$ and $p$. This is consistent with past bargaining studies on full information, where wholesale price contracts in which both the price and quantity are negotiated have been shown to achieve roughly 90% efficiency (Davis and Hyndman 2019a). Therefore, we reject Hypothesis 1(i), but confirm previous results in the literature on efficiency under full information. Under private information, average efficiency, at 92.67%, is actually higher (but not significantly so) than under full information. Just looking at the overall average, we can reject that efficiency is the same as the 95.41% predicted by Myerson’s bargaining solution ($p = 0.014$). However, more than that, Hypothesis 2(i) is also rejected because there is no (downward) trend in efficiency as the supplier’s cost increases.

Table 2 Efficiency (%), Conditional on Agreement

<table>
<thead>
<tr>
<th></th>
<th>Full Info</th>
<th>Private Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p = 10$</td>
<td>$p = 11$</td>
<td>$p = 12$</td>
</tr>
<tr>
<td>$c = 3$</td>
<td>91.70†</td>
<td>90.31†</td>
</tr>
<tr>
<td></td>
<td>(2.77)</td>
<td>(2.26)</td>
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<tr>
<td>$c = 4$</td>
<td>93.46†</td>
<td>89.12†</td>
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<tr>
<td></td>
<td>(2.64)</td>
<td>(5.25)</td>
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<tr>
<td>$c = 5$</td>
<td>92.75†</td>
<td>94.60‡</td>
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<tr>
<td></td>
<td>(1.94)</td>
<td>(1.71)</td>
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<tr>
<td>Overall</td>
<td>91.34†</td>
<td>92.67†</td>
</tr>
<tr>
<td>Average</td>
<td>(0.95)</td>
<td>(0.82)</td>
</tr>
</tbody>
</table>

Note: Standard errors across groups are reported in parentheses. Significance of t-tests versus the normative theory given by † $p < 0.01$, ‡ $p < 0.05$, and * $p < 0.10$.

Distribution of Profits. The normative theory predicts a 50%/50% split between the two parties in the full information treatments. Figure 1a depicts the supplier’s share of total supply
chain expected profit under full information. From it, we find that suppliers earn 36.89% across all nine combinations of $c$ and $p$, which is significantly less than 50% ($p < 0.01$). In addition, the supplier’s share varies based on the specific combination of $c$ and $p$, such that the minimum share is 25.99% and the maximum share is 46.89%. This result is generally consistent with past findings on bargaining in supply chains under full information which have shown that the risk holder, the supplier in this case, earns less than half of the expected supply chain profit. Hence we reject Hypothesis 1(ii).

Turning to private information, depicted in Figure 1b, the normative prediction is that suppliers should earn at least 50% of the total supply chain expected profit. However, the average observed supplier share across all $c$ and $p$ is only 33.56%, which is significantly less than 50% ($p < 0.01$). Further, the supplier’s share of profits are somewhat extreme for certain combinations of $c$ and $p$. For example, while low cost suppliers ($c = 3$) earn only slightly less than 50% of the total expected profit, high cost suppliers ($c = 5$) earn far below this benchmark. Specifically, under private information, high cost suppliers earn only 12.82%, 29.59%, and 18.71% of the total supply chain expected profits, depending on the selling price of their retailer. Therefore, we also reject Hypothesis 2(ii). We summarize these results as follows:

**Result 1** Suppliers earn less than 50% of total supply chain expected profits under both full and private information. This result is most pronounced for high-cost suppliers under private information, where suppliers earn a disproportionately low share of overall profits.

**Order Quantities and Wholesale Prices.** To gain a better understanding as to what is driving our efficiency and profit results, we now focus on the agreed upon contract quantities and wholesale prices. Tables 3a and 3b illustrate these two terms in our experiment. Regarding quantities, one can see a number of deviations with respect to the predictions in Tables 1a and 1b. Compared to the normative benchmarks, the observed quantities are closer to the mean demand of 50. This could indicate an anchoring bias that drives many efficiencies below their predictions. To show this anchoring effect, we define the variable:

$$\Delta Q^A = \begin{cases} Q - Q_{br}, & Q_{br} \leq 50 \\ Q_{br} - Q, & Q_{br} > 50 \end{cases}$$

6 One observation was removed before creating this figure, where a participant’s supplier share was -100% of the supply chain expected profit, which occurred in the first period.
Figure 1  Supplier Share (%) of Supply Chain Expected Profit, Conditional on Agreement

(a) Full Information

(b) Private Information

where $Q_{br}$ represents the supplier’s optimal quantity given the agreed wholesale price. Absent anchoring, the value should equal zero, while evidence of mean anchoring would be represented by a positive value. Unsurprisingly, we find that the overall value of this term is 7.43 across both treatments. However, digging deeper, we see that the result is more nuanced than anchoring in traditional, single-person, newsvendor settings. In our setting, because the retailer is not exposed to inventory risk, her expected profits are strictly increasing in the order quantity. Therefore, when bargaining, she should try to push the agreement to higher order quantities. Indeed, if we consider separately those cases where $Q_{br} < 50$ and $Q_{br} > 50$, then we see very strong evidence of anchoring in the former case (11.77 on average), but almost no evidence in the latter case (1.45 on average). This suggests that the retailer is able to exacerbate any anchoring bias that the supplier may have for low order quantities and mitigate the bias for high optimal order quantities.

Turning to wholesale prices, in Tables 3a and 3b, one can see that wholesale prices are set too low relative to the normative predictions. On average, under full information, wholesale prices are too low by 0.77 on average (predicted 8.41 versus observed 7.64), and under private information, are too low by 1.19 on average (predicted 8.76 versus observed 7.57). Further, for nearly every combination of $c$ and $p$, the wholesale price is significantly different – and lower – than the normative predictions under both full and private information ($17 t$–tests $p < 0.05$, and one $p = 0.102$).

Comparing wholesale prices under full versus private information directly to each other, we find that there is no significant difference for any of the nine combinations of $c$ and $p$. Even more, in only

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7 Strictly speaking, in the bargaining solution, the order quantity need not be a best response to the wholesale price. For example, in the full information case, the order quantity is set to maximize channel profit, which is different from the quantity that would maximize the supplier’s expected profits given the agreed wholesale price. A similar figure, based upon the theoretical predictions is qualitatively similar.
Table 3 Quantities and Wholesale Prices, Conditional on Agreement

<table>
<thead>
<tr>
<th></th>
<th>(a) Full Information</th>
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<th>(b) Private Information</th>
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<tbody>
<tr>
<td></td>
<td>Quantity (q)</td>
<td>Wholesale Price (w)</td>
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<td></td>
<td>p = 10</td>
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<td>p = 12</td>
</tr>
<tr>
<td>c = 3</td>
<td></td>
<td>57.31†</td>
<td>55.50†</td>
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<td></td>
<td>(3.18)</td>
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<td>56.20</td>
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<td>(1.59)</td>
<td>(0.09)</td>
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Note: Standard errors across groups are reported in parentheses. Significance of t-tests versus the normative theory given by † p < 0.01, ‡ p < 0.05, and * p < 0.10.

three of nine comparisons are wholesale prices higher under private information than under full information. Therefore, we can reject Hypothesis 2(iii). These wholesale price results can directly account for our earlier insight showing that suppliers earn less than theory predicts and that high-cost suppliers, under private information, earn the lowest shares.

Below, we will examine the bargaining process to understand how participants arrived at such agreements. Until then, we summarize the discussion as follows:

Result 2 Under both full and private information, stocking quantities are biased towards the mean demand. Regarding wholesale prices, under both full and private information, wholesale prices are significantly lower than the normative predictions. Also, there is no difference in average wholesale prices between full and private information.

5.2. Bargaining Dynamics

In an effort to understand how participants arrived at such contract terms and outcomes, we now turn our attention to bargaining dynamics. Specifically, we provide results on the bargaining duration, the anchoring effect of first offers, the concession process over time, and how initial offers influence agreement rates.

Bargaining Duration. Recall that pairs came to an agreement while bargaining 90.28% under full information, and 93.06% under private information. While the agreement rates are similar between the two information conditions, we observe differences as to how long these negotiations took. Figure 2 shows a histogram for the time to reach an agreement (in seconds), between full and private information. First, there is clearly a deadline effect in both conditions – under private information 37% of agreements are reached in the last 10 seconds, while under full information,
24% of agreements are reached in the last 10 seconds. This is consistent with Roth et al. (1988). Second, one can see that pairs came to an agreement faster under full information, with an average of 207.2 seconds, versus private information, with an average of 241.7 seconds. While this did not have a meaningful consequence in our experiment, in practice, longer negotiations can certainly incur additional costs. Thus we have:

**Result 3** *Bargaining takes longer when the supplier’s cost is private information.*

ANCHORING. Past studies have shown that first offers can have an anchoring effect on negotiations (Galinsky and Mussweiler 2001), ultimately influencing the final agreement that is reached. Our data allow us to analyze opening offers and determine if there is a similar effect in our experiments. Table 4 depicts two random effects regressions with first offers for wholesale prices as the dependent variable for retailers and suppliers. In both models, $c = 3$ and $p = 10$ under full information are the baseline. For the full information case, it is unsurprising to see both the suppliers’ and retailers’ first offers are higher the higher the supplier’s cost and the higher the retailer’s price.

Continuing in Table 4, the main distinction between retailers and suppliers arises when we consider private information. Suppliers’ first wholesale price offers under private information are statistically indistinguishable from those under full information, as the coefficients on the three $\text{PrivateInfo}$ terms are insignificant for the supplier. The implication is that suppliers do not appear to exploit their private information by proposing a higher wholesale price. Therefore, upon observing the opening wholesale price, retailers can update their belief about the type of supplier they are matched with. In contrast, for retailers, their first offer under private information is
Table 4  The Effects on Opening Wholesale Price Offers by Role

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<thead>
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<th>Suppliers</th>
<th>Retailers</th>
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<tr>
<td>$c = 4$</td>
<td>0.511* (0.289)</td>
<td>0.371 (0.236)</td>
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<tr>
<td>$c = 5$</td>
<td>0.538† (0.093)</td>
<td>0.981† (0.099)</td>
</tr>
<tr>
<td>$p = 11$</td>
<td>0.836† (0.127)</td>
<td>0.484† (0.092)</td>
</tr>
<tr>
<td>$p = 12$</td>
<td>1.174† (0.166)</td>
<td>0.681† (0.191)</td>
</tr>
<tr>
<td>PrivateInfo</td>
<td>0.192 (0.268)</td>
<td>-0.066 (0.304)</td>
</tr>
<tr>
<td>$(c = 4) \times \text{PrivateInfo}$</td>
<td>-0.095 (0.319)</td>
<td>-0.471 (0.297)</td>
</tr>
<tr>
<td>$(c = 5) \times \text{PrivateInfo}$</td>
<td>0.225 (0.176)</td>
<td>-0.965‡ (0.148)</td>
</tr>
<tr>
<td>Period</td>
<td>0.068‡ (0.026)</td>
<td>0.020 (0.039)</td>
</tr>
<tr>
<td>Constant</td>
<td>7.037† (0.213)</td>
<td>5.841‡ (0.234)</td>
</tr>
</tbody>
</table>

Note: The dependent variable is the first wholesale price offer, by role. Standard errors, corrected for clustering at the session level, in parentheses. Significance given by † $p < 0.01$, ‡ $p < 0.05$, and * $p < 0.10$.

virtually identical to the opening offer made to a $c = 3$ supplier under full information. Specifically, under full information for retailers, the coefficient on $c = 4$ is 0.371 and for $c = 5$ it is 0.981. However, under private information, the coefficients on the interaction terms (-0.471 for $c = 4$ and -0.965 for $c = 5$) completely wash away these effects. This means that under private information, retailers begin bargaining as if they are negotiating with the lowest cost supplier.

Result 4 Suppliers’ first offers for wholesale prices are the same between full and private information, for a given supplier cost and retailer price. However, retailers first wholesale price offers under private information are similar to their opening offers made to the lowest cost supplier under full information (i.e., their opening offers are more aggressive under private information).

We now investigate whether final agreed upon contract terms are anchored on opening offers. If true, then we have a reasonable understanding as to why high cost suppliers earn a disproportionately small share of the supply chain expected profits under private information. To this end, Table 5 shows a series of random effects regressions with agreed upon contract terms as the dependent variable by supplier and retailer. For both the wholesale price and order quantity, the final agreements are indeed significantly and positively associated with each party’s first offer, providing the following result:

Result 5 Final agreements, for both the wholesale price and the order quantity, are significantly anchored on first offers.

Concession Process. Because players negotiate over both the wholesale price and order quantity simultaneously, we can also evaluate the expected profits of each offer to both players and get a better understanding as to how opening offers translate into final terms. Figure 3 depicts
the supplier’s average share of the total supply chain expected profit, by offer number, for those negotiations in which a player made at least five offers and an agreement was eventually reached.

We provide six plots, one for each supplier cost type under full and private information. In all six plots there is a clear concession pattern over time. What is especially striking are the retailers’ offers (white columns) when a supplier has a relatively higher cost, \( c = 4 \) or \( c = 5 \). For both costs, retailers make initial offers that would leave the supplier with a negative share of expected total profits. This effect is especially pronounced under private information (Figure 3f): even after five offers the retailer is providing the supplier with a negative share. In addition, suppliers are offering to retain less than half of the expected supply chain profits after their second offer when \( c = 5 \) under private information (0.479).

Both Table 5 and Figure 3 clearly show both the importance of first offers and concessions on the bargaining outcome. One important caveat to anchoring is that aggressive opening offers could also reduce the likelihood that the players are able to reach an agreement. In Table 6, we report the results of a random effects logit regression where the dependent variable is an indicator for whether an agreement was reached and the explanatory variables are the opening offers of suppliers and retailers as well as indicators for retailer price and supplier cost parameters. Under full information, we see that the higher is the retailer’s opening wholesale price (i.e., the less aggressive it is), the higher is the likelihood of agreement. However, under private information, there is no such effect. Thus, under private information, we see that retailers make more aggressive opening offers (Table 4), which lead to less favorable agreements for suppliers (Table 5) without increasing the likelihood of disagreement (Table 6).
Figure 3  The Concession Process within a Bargaining Round: Supplier’s Share of Expected Supply Chain, Conditional on Agreement

(a) Full Information $c = 3$

(b) Private Information $c = 3$

(c) Full Information $c = 4$

(d) Private Information $c = 4$

(e) Full Information $c = 5$

(f) Private Information $c = 5$

Note: Includes subject-periods in which 5 or more offers were made.
Table 6  The Effects on Agreements: First Offers

<table>
<thead>
<tr>
<th></th>
<th>Full Information</th>
<th>Private Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retailer Wholesale Price</td>
<td>0.873† (0.320)</td>
<td>0.082 (0.210)</td>
</tr>
<tr>
<td>Retailer Quantity</td>
<td>−0.005 (0.013)</td>
<td>−0.026 (0.022)</td>
</tr>
<tr>
<td>Supplier Wholesale Price</td>
<td>−0.447 (0.436)</td>
<td>−0.748 (0.480)</td>
</tr>
<tr>
<td>Supplier Quantity</td>
<td>−0.031 (0.024)</td>
<td>0.020 (0.043)</td>
</tr>
<tr>
<td>$p = 4$</td>
<td>−0.762 (1.240)</td>
<td>−0.415 (0.774)</td>
</tr>
<tr>
<td>$c = 5$</td>
<td>−2.071* (1.187)</td>
<td>1.910 (2.156)</td>
</tr>
<tr>
<td>$p = 11$</td>
<td>−1.248 (0.775)</td>
<td>−0.318 (1.212)</td>
</tr>
<tr>
<td>$p = 12$</td>
<td>0.787 (1.668)</td>
<td>−0.209 (1.159)</td>
</tr>
<tr>
<td>Constant</td>
<td>3.681 (3.854)</td>
<td>9.964* (5.565)</td>
</tr>
</tbody>
</table>

Note: The dependent variable is an indicator for whether or not an agreement was reached. Standard errors, corrected for clustering at the session level, in parentheses. Significance given by † $p < 0.01$, ‡ $p < 0.05$, and †† $p < 0.10$.

6. Conclusion

In practice it is common for buyers in a B2B setting to have only a rough estimate, or distribution, of their supplier’s cost. Further, many companies negotiate with one another in a more equitable back-and-forth bargaining environment. In this study we investigate such private supplier cost information in a two-stage supply chain with dynamic unstructured bargaining. We first examine this setting theoretically and find that, given our experimental parameters, suppliers should benefit from their private cost information while bargaining.

Despite this theoretical benefit, our human-subjects experiment shows that certain types of suppliers are actually disadvantaged under private information. In particular, high-cost suppliers under private information earn the lowest share of overall supply chain expected profits. Through our experimental data, we are able to determine that this is driven by a number of behavioral bargaining tendencies by buyers and suppliers, rather than, say, due to social preferences. Indeed, fairness concerns cannot be the main driver because the result that high-cost suppliers earn less than half the surplus holds under full information, where we would expect a 50-50 norm to hold for all price/cost pairs. Instead, we see that under private information, buyers make opening wholesale prices offers that are similar to their initial offers to the lowest-cost supplier under full information and final agreements are anchored on opening offers. A combination of these two results leave high-cost suppliers with a sufficiently low wholesale price and a low share of the overall supply chain expected profits. Lastly, under private information, retailers appear able to hide behind a veil of ignorance. Specifically, aggressive opening offers by retailers do not increase the chance of disagreement like they do under full information.

Our study provides a number of insights for managers in practice. First, our results show that, even under full information, high-cost suppliers earn a significantly smaller share of total supply
chain profits. This suggests that high-cost suppliers are unsuccessful in their efforts to negotiate a sufficiently large wholesale price in order to compensate for the higher risk that they face, owing to their higher cost. Managers would do well to make sure that those negotiating contracts are able to properly evaluate the profits and risk associated with any proposal made and received.\footnote{While we gave subjects substantial decision support capabilities (cf., Figure B.1), our results suggest that more robust support or training may be necessary, particularly for inventory risk holders.}

Second, while most suppliers are reluctant to share their private cost information with buyers, our work indicates that such an action may be beneficial for certain types of suppliers. In particular, high-cost suppliers earn a higher expected profit when their costs are known by retailers. Therefore, high-cost suppliers may consider (truthfully) communicating its private costs to a buyer. Second, private information does not necessarily lead to a higher rate of disagreement, however, it does lead to longer negotiation times. Thus, in practice, where longer negotiations can require additional expenses, both parties may benefit from a supplier’s cost being full information, in the hopes of coming to an agreement in an efficient manner. Both of these recommendations could foster further collaborative interactions between buyers and suppliers and yield additional benefits.\footnote{That is, there could be operational gains from cost transparency. For more thorough investigations on the effects of transparency in operations, please see Buell et al. (2016) for services, Mohan et al. (2017) for retail.}

Of course, once one introduces the possibility for truthful information disclosure, the timing matters. Our results suggest that, for a given retailer, the high-cost supplier would earn more if it disclosed its cost. Thus, one interesting avenue for future research would be to study just such an environment in which disclosure happens after the pairs have been formed but either before or during bargaining. However, if disclosure occurs before matching, then the high-cost player faces a tension: for a given retailer she will earn more during bargaining, but by disclosing her high cost, she reveals that she is a less desirable partner. Thus, it may reduce her chances of matching with a high-price/quality retailer, which reduces the potential size of the pie. Thus, disclosure could mean extracting a larger share of a smaller pie. Davis and Hyndman (2019b) study this tension between matching and disclosure in supply chains.

Beyond the issue of disclosure, we believe there are a number of opportunities for future research. For instance, while we go beyond highly structured negotiations, it would be natural to extend this further and allow for either chat-box communication or even face-to-face negotiations, especially with private information. Unstructured communication would give suppliers the ability to communicate their cost (but in a non-credible way). It would be interesting to see how this effects bargaining and if cheap-talk communication is as effective as truthful information disclosure. Another
interesting avenue for research is to consider the possibility for long-term relationships in which the same parties bargain in a repeated environment.

Acknowledgments
We thank Anyan Qi for fruitful discussions. We also thank seminar participants at Duke University, the University of Virginia, Stanford University, INCAE Business School, Baruch College, the 2018 INFORMS Conference, the 2018 Bargaining: Experiments, Empirics, and Theory Conference, and the 2018 Behavioral Operations Conference, for their helpful comments. We gratefully acknowledge the financial support of Cornell University.

References


**Appendix**

**A. Details and Proofs: Bargaining with Private Information**

**A.1. Proofs**

For this analysis we specialize to the case of $a = 0$ and $b = 100$, to avoid any extraneous algebra. The expected profits of the retailer can be written as:

$$\pi_r(p, c, w, q) = \frac{p - w}{200} (200q - q^2),$$

while the expected profits of the supplier can be written as:

$$\pi_s(p, c, w, q) = \frac{w}{200} (200q - q^2) - cq.$$

**Lemma 1.** Let $\mathcal{M}$ be an incentive compatible mechanism. Then $\gamma_1 q_1 \geq \gamma_2 q_2 \geq \gamma_3 q_3$. 

Proof: Observe that incentive compatibility requires:

\[ \gamma_i \left( \left( \frac{w_i}{200} \right) (200q_i - q_i^2) - c_i q_i \right) \geq \gamma_i \left( \left( \frac{w_j}{200} \right) (200q_j - q_j^2) - c_j q_j \right) \]

\[ \geq \gamma_i \left( \left( \frac{w_j}{200} \right) (200q_j - q_j^2) - c_j q_j \right) \]

This means that, for \( j > i \):

\[ \gamma_i q_i (c_j - c_i) \geq \gamma_j q_j (c_j - c_i). \]

Hence,

\[ (\gamma_i q_i - \gamma_j q_j) (c_j - c_i) \geq 0, \]

which, upon recognizing that \( c_j - c_i > 0 \) for \( j > i \), completes the proof. Q.E.D.

Lemma 2. Given any incentive compatible mechanism, \( \mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\} \), there exists an alternative mechanism, \( \mathcal{M} = \{(\bar{w}_i, \bar{q}_i), i = 1, 2, 3\} \), such that disagreement never happens which is also incentive compatible and generates the same expected profits for each supplier type and the retailer.

Proof: Given the mechanism, \( \mathcal{M} \), the expected profits of the type \( i \) supplier and of the retailer (conditional on matching with this supplier) are:

\[ \pi_i = \gamma_i \left( \left( \frac{w_i}{200} \right) (200q_i - q_i^2) - c_i q_i \right) \]
\[ \pi_i = \gamma_i \left( \left( \frac{p - w_i}{200} \right) (200q_i - q_i^2) \right). \]

Therefore, to find the alternative mechanism with no disagreement, we must solve the following system of equations:

\[ \left( \frac{w_i}{200} \right) (200\bar{q}_i - \bar{q}_i^2) - c_i \bar{q}_i = \pi_i \]
\[ \left( \frac{p - w_i}{200} \right) (200\bar{q}_i - \bar{q}_i^2) = \pi_i. \]

Note that a solution to this system is guaranteed because, by varying \( \bar{q}_i \) from zero to the efficient quantity, any channel profit level that was possible under \( \mathcal{M} \) is obtainable. Furthermore, by varying \( \bar{w}_i \), from \( c_i \) to \( p \), any division of profits between the retailer and supplier is achievable. One can show that:

\[ \bar{q}_i = \frac{-\sqrt{4p(200c_i \gamma_i q + \gamma_i p q_i^2 - 200 \gamma_i p q_i) + (200p - 200c_i)^2 - 200c_i + 200p} \}}{2p}. \]

It remains to be seen that the new mechanism preserves incentive compatibility. It is sufficient to show that (i.e., that expected profits from misreporting are lower in the new mechanism):

\[ \gamma_i (\left( \frac{w_i+1}{200} \right) (200q_{i+1} - q_{i+1}^2) - c_i q_{i+1}) \geq \left( \frac{w_{i+1}}{200} \right) (200\bar{q}_{i+1} - \bar{q}_{i+1}^2) - c_i \bar{q}_{i+1} \].

10 As will become apparent, the solution for \( \bar{w}_i \) is not necessary so we omit it, also because it is particularly messy.
By adding and subtracting $\gamma_{i+1}c_{i+1}q_{i+1}$ to the left-hand side and then substituting for the payoff equivalent contract, we can simplify the above inequality to:

$$\gamma_{i+1}q_{i+1} \geq \bar{q}_{i+1}.$$

Finally, if (for ease of notation) we drop the subscripts, the above expression is equivalent to:

$$\sqrt{10000c^2 + 200cp(\gamma q - 100) + p^2(\gamma(q - 200)q + 10000) + 100c + \gamma pq - 100p} \geq 0.$$

After some algebraic manipulations (taking parts outside the square-root sign to the other side and then squaring both sides), this can be simplified to:

$$(1 - \gamma)\gamma p^2 q^2 \geq 0,$$

and it is easy to see that the above inequality holds. Q.E.D.

**Proposition 2.** There exist incentive compatible mechanisms in which the supply chain is coordinated for all possible supplier types. That is, $q_i = 100(p - c_i)/p$ for all $i$.

**Proof:** One can show that the mechanism is both fully efficient and incentive compatible if the following inequalities hold:

$$w_i \geq \frac{p^2 - c_i^2}{p^2 - c_i} w_j + \frac{2pc_i(c_j - c_i)}{p^2 - c_i^2}$$

$$w_i \leq \frac{p^2 - c_i^2}{p^2 - c_i} w_j + \frac{2pc_i(c_j - c_i)}{p^2 - c_i^2}$$

for $i = 1, 2, j = 2, 3$ and $j \neq i$. Moreover, one can also show that there do exist efficient mechanisms. While it is computationally tedious, if we let $w_3 = \frac{p(p+3c_3)/(p+c_3)}{2(p+c_3)}$ and then take the smallest $w_2$ for the given $w_3$ and the smallest $w_1$ for the given $w_2$, then the above inequalities are all satisfied. Q.E.D.

**A.2. Myerson’s Bargaining Solution (Three Cost Types)**

We can set up the objective function as:

$$\max_{q_i, w_i} = \lambda_1 \pi_s(p, c_1, w_1, q_1) + \lambda_2 \pi_s(p, c_2, w_2, q_2) + (1 - \lambda_1 - \lambda_2) \pi_s(p, c_3, w_3, q_3)$$

$$+ \frac{1}{3} \left( \pi_r(p, c_1, w_1, q_1) + \pi_r(p, c_2, w_2, q_2) + \pi_r(p, c_3, w_3, q_3) \right)$$

subject to the incentive compatibility constraint that the supplier type $c_i$ does not mimic the supplier type $c_{i+1}$ for $i = 1, 2$:

$$\pi_s(p, c_1, w_1, q_1) \geq \pi_s(p, c_1, w_2, q_2)$$

$$\pi_s(p, c_2, w_2, q_2) \geq \pi_s(p, c_2, w_3, q_3).$$

The Lagrangean, rewritten as in the two-type case to collect certain terms, is:

$$\mathcal{L} = \frac{1}{3} \left( 3(\lambda_1 + \alpha_1) \left( \frac{w_1}{200} (200q_1 - q_1^2) - c_1q_1 \right) + \frac{p - w_1}{200} (200q_1 - q_1^2) \right)$$
+ \frac{1}{3} \left( 3(\lambda_2 + \alpha_2) \left( \frac{w_2}{200} (200q_2 - q_3^2) - c_2q_2 \right) - 3\alpha_1 \left( \frac{w_2}{200} (200q_2 - q_3^2) - c_2q_2 \right) + \frac{p-w_2}{200} (200q_2 - q_3^2) \right) \\
+ \frac{1}{3} \left( 3(1-\lambda_1 - \lambda_2) \left( \frac{w_3}{200} (200q_3 - q_3^2) - c_3q_3 \right) - 3\alpha_2 \left( \frac{w_3}{200} (200q_3 - q_3^2) - c_2q_3 \right) + \frac{p-w_3}{200} (200q_3 - q_3^2) \right)

Observe that the linearity in \( w \) implies that \( \lambda_1 + \alpha_1 = \frac{1}{3} \) and \( \lambda_2 + \alpha_2 - \alpha_1 = \frac{1}{3} \). The next step is to optimize with respect to \( q_i \).

This yields:

\[
q_1 = \frac{100(p-w_1 + 3(\lambda_1 + \alpha_1)(w_1-c_1))}{p-w_1 + 3(\lambda_1 + \alpha_1)w_1} \]
\[
q_2 = \frac{100(p-w_2(3(\lambda_2 + \alpha_2 - \alpha_1) - 1) - 3(\lambda_2 + \alpha_2)c_2 + 3\alpha_1 c_1)}{p + w_2(3(\lambda_2 + \alpha_2 - \alpha_1) - 1)} \]
\[
q_3 = \frac{100(p + w_3(3(1-\lambda_1 - \lambda_2) - 3\alpha_2 - 1) - 3(1-\lambda_1 - \lambda_2)c_3 + 3\alpha_2 c_2)}{p + w_3(3(1-\lambda_1 - \lambda_2) - 3\alpha_2 - 1)} .
\]

With these values for quantities and also using the relationship between the \( \alpha \) and \( \lambda \) variables, we obtain the value of the objective function (as a function of the \( \lambda s \)):

\[
\frac{50}{3} \left( \frac{(p-c_1)^2}{p} + \frac{p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2)}{p} + \frac{p + c_2(2 - 3\lambda_1 - 3\lambda_2 - 3c_3(1-\lambda_1 - \lambda_2))}{p} \right)
\]

The warrant conditions imply that:

\[
(\lambda_1 + \alpha_1)W_1 = \frac{150}{2} \left( \frac{(p-c_1)^2}{p} \right) \]
\[
(\lambda_2 + \alpha_2)W_2 - \alpha_1 W_1 = \frac{150}{2} \left( \frac{(p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2))}{p} \right) \]
\[
(1-\lambda_1 - \lambda_2)W_3 - \alpha_2 W_2 = \frac{150}{2} \left( \frac{(p + c_2(2 - 3\lambda_1 - 3\lambda_2) - 3c_3(1-\lambda_1 - \lambda_2))}{p} \right).
\]

This yields:

\[
W_1^* = \frac{25(p-c_1)^2}{p} \]
\[
W_2^* = \frac{25(p^2 + c_1^2(1 - 3\lambda_1) + c_2^2(2 - 3\lambda_1) - 2c_1c_2(1 - 3\lambda_1) - 2c_2p)}{p} \]
\[
W_3^* = \frac{25(c_1^2(3\lambda_1 - 1)(3\lambda_1 + 3\lambda_2 - 2) - 2c_1c_2(3\lambda_1 - 1)(3\lambda_1 + 3\lambda_2 - 2) + c_2^2 (18\lambda_1^2 + 3\lambda_1(9\lambda_2 - 8) + 9\lambda_2^2 - 18\lambda_2 + 8))}{3p(1-\lambda_1 - \lambda_2)}
\]
\[
+ \frac{25(-6c_2c_3(3\lambda_2^2 + 1(6\lambda_2 - 5) + 3\lambda_2^2 - 5\lambda_2 + 2) + 3(\lambda_1 + \lambda_2 - 1)(3c_3^2(\lambda_1 + \lambda_2 - 1) + 2c_3p - p^2))}{3p(1-\lambda_1 - \lambda_2)} .
\]

It remains to solve for \( \lambda_1, \lambda_2, w_1, w_2 \) and \( w_3 \). To do this, we use the expressions for \( W_i \), where we impose that \( W_i \) is greater than or equal to the expected profits for supplier type \( i \) (with equality if \( \lambda_i \) is interior) and the incentive compatibility constraints (which must be satisfied with equality if \( \alpha_i > 0 \)). Specifically, the solution must satisfy:

\[
\pi_i(w_i, q_i, c_i) \geq W^*_i, \text{ with equality if } \lambda_i > 0, \\
\pi_i(w_i, q_i, c_i) \geq \pi_i(w_{i+1}, q_{i+1}, c_i), \text{ for } i = 1, 2 \text{ and with equality if } \alpha_i > 0.
\]

This leads to many cases to consider.
Using the values that we implemented in the experiment, the relevant case is $\lambda_1 = \lambda_2 = 0$. In this case, we have:

$$w_1 = \frac{p(-2x_1^2 + 32x_1x_2 + 8x_2x_3 + 3(-9x_3^2 + 2x_3p + p^2))}{6(p^2 - c_2^2)}$$

$$w_2 = \frac{p(2x_1^2 + 8x_1x_2 + 4x_2x_3 + 3(-9x_3^2 + 2x_3p + p^2))}{6(-c_2^2 + 4x_3 - 4c_2x_3 + 4c_3x_3)}$$

$$w_3 = \frac{p(2x_1^2 - 4x_1x_2 + 8x_2x_3 + 3(-9x_3^2 + 2x_3p + p^2))}{6(-4c_2^2 + 12c_2x_3 - 9c_3^2 + p^2)}$$

Upon substituting for prices for the retailer prices ($p \in \{10, 11, 12\}$) and supplier costs ($c_1 = 3$, $c_2 = 4$ and $c_3 = 5$) that we implemented, the precise numerical predictions are depicted in Table A.1.

**Table A.1  Equilibrium Predictions Under Private Information (Three Cost Types)**

<table>
<thead>
<tr>
<th>Suppliers Profit</th>
<th>Wholesale Price ($w$)</th>
<th>Quantity ($q$)</th>
</tr>
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<tbody>
<tr>
<td>$p = 10$</td>
<td>$p = 11$</td>
<td>$p = 12$</td>
</tr>
<tr>
<td>$c = 3$</td>
<td>149.17</td>
<td>178.79</td>
</tr>
<tr>
<td>$c = 4$</td>
<td>99.17</td>
<td>124.24</td>
</tr>
<tr>
<td>$c = 5$</td>
<td>69.17</td>
<td>87.88</td>
</tr>
</tbody>
</table>
B. Sample Experimental Screenshot

Figure B.1 Screenshot of the Private Information Treatment