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Horizontal Subcontracting in Procurement Auctions

Nancy Huff
Clemson University, nmvogh@gmail.com

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Nancy Marie Vogh Huff
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Dr. Michael T. Maloney, Committee Chair
Dr. Charles J. Thomas
Dr. Daniel P. Miller
Dr. Raymond D. Sauer

Abstract

A firm submitting a bid in a procurement auction is sometimes also listed as a subcontractor in one or more competing bids. This paper theoretically and empirically examines how such *horizontal* subcontracting affects welfare and price competition. I first specify a model of horizontal subcontracting which endogenizes the roles of the subcontracting firms as well as a negotiated payment for subcontracted work. The model shows that horizontal subcontracting always weakly increases welfare by enabling more efficient allocation of production but has two opposite effects on price competition: an efficiency effect and a strategic effect. The efficiency effect arises when firms use the subcontract to lower production costs and submit lower bids. However, horizontal subcontracting can soften competition by allowing strategic firms to raise each other's opportunity costs of winning the auction, producing higher bids. I find empirical support for the model's implications using detailed data collected from highway procurement auctions in California. I find that strategy-driven horizontal subcontracts yield 6% higher prices relative to efficiency-driven horizontal subcontracts.

Dedication

I dedicate this dissertation to Jared Huff who, over the course of my graduate school endeavors, has been my study partner, best friend, office-mate, and, most importantly, husband. In each of these roles, he has been my chief supporter, sharing both my successes and frustrations. I have been immensely privileged to share this adventure of graduate school with him, and I look forward to all of the new adventures awaiting us.

I would also like to dedicate this dissertation to my parents, Richard and Polly Vogh, who taught me to think deeply and to never be satisfied with a half-done job. Their love and support have made this dissertation possible.

Finally, to the God of all Truth, I give my thanks, for He is the source of everything I am and have. If this dissertation brings any shame, it is mine; if any glory, it is His.

Lead me in your truth and teach me,
for you are the God of my salvation;
for you I wait all the day long.
Psalm 25:5

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Chapter 1

Introduction

Government construction projects are frequently contracted through procurement auctions. The government typically announces a project well in advance of the auction to allow interested contractors time before bidding to determine their costs of completing the project. Part of this determination includes reaching agreements with subcontractors to perform a portion of the work. Occasionally, a firm bidding in a procurement auction (called a "prime contractor") is also listed as a subcontractor in one or more competing bids for the same project. In this paper I examine the implications of such *horizontal* subcontracting relationships by developing a complete-information auction model that endogenizes the subcontracting decisions between rival prime contractors. I then empirically assess the model's implications using data collected from highway procurement auctions in California.

The model shows that horizontal subcontracting has two opposite effects on competition: an efficiency effect and a strategic effect. The efficiency effect arises when firms allocate a subset of production to a rival with lower costs on that component, resulting in lower overall production costs and inducing firms to submit more competitive bids. However, forward-looking contractors can use a horizontal subcontract to strategically raise their rivals' costs, increasing the resulting bids in the auction. For the prime hired as a subcontractor by a rival (called the subbing prime), a horizontal subcontracting arrangement raises its opportunity cost of winning the auction, because it must forgo any profit from subcontracting. For the prime contractor that hires its rival as a subcontractor (called the hiring prime), a horizontal subcontracting arrangement can raise its cost of winning directly by requiring the hiring firm to pay its rival more for subcontracted work than it costs the hiring firm to produce that work in-house or with a non-prime subcontractor. Although this second result seems counterintuitive, the hiring firm is willing to increase its production cost when the gains from softened competition outweigh the additional cost.

The incentive firms have to raise their rivals' costs is well established in the literature. For example, Salop and Scheffman (1983) discuss firms' incentive to restrict input supply or engage in costly investments to raise their rivals' costs and gain market share. A key difference of this present paper is the voluntary nature of the cost increases. For horizontal subcontracting to raise the participating firms' costs, both must agree to the subcontract. Neither the hiring firm nor the subbing firm can be forced to accept higher costs.

The overall effect of horizontal subcontracting on competition is ambiguous, but the model identifies two main types of horizontal subcontracts with differing effects on competition. In the first type, the subbing firm is expected to bid below the hiring firm in the auction; in the second type, the hiring firm is expected to bid below its subcontractor in the auction. When the subbing firm dominates (i.e., the subbing firm underbids the hiring firm in the auction), any efficiency gains from the subcontract are written in a losing bid. Therefore, the sole advantage of this type of horizontal subcontract is to strategically soften competition. When the hiring firm dominates, the subcontract is a part of the pair's more competitive bid. Consequently, the motive for this subcontract could be cost savings. However, weakening competition cannot be ruled out as a motive for these subcontracting pairs. Even though the effect of hiring-firm-dominant subcontracts on competition is uncertain, on average these subcontracts should lower prices relative to subbing-firm-dominant subcontracts.

I test these model implications using data on California Department of Transportation (Caltrans) highway projects with at least one horizontal subcontract. Caltrans has become a common source of data for many researchers, due in part to the availability of detailed lists of task-level bids from all bidders on each project, as well as a list of subcontractors on each bid and the assigned tasks of each these subcontractors.[1] I use the the task-level bids as a proxy for the costs of hiring primes and their subcontractors. I find that the presence of a subbing-firm-dominant subcontract raises the auction price by nearly 6% percent, compared to a hiring-firm-dominant subcontract. In addition, subbing-firm-dominant subcontracts are associated with higher markups on subcontracted work, which is consistent with the theoretical prediction that these firms are more likely to use the

[1]See for example, Bajari, Houghton, and Tadelis (2006), Marion (2009), Miller (2010), and Marion (2011).

horizontal subcontract to raise their rivals' costs to soften competition.

These results have significant implications for procurers who may be suspicious of the "air of collusion" surrounding horizontal subcontracting. The instinctive response to ban horizontal subcontracting is costly because horizontal subcontracting produces both a strategic incentive to raise rivals' costs and an efficiency incentive to lower costs. Therefore a ban on horizontal subcontracting to prevent anti-competitive behavior would also prevent efficient horizontal subcontracts from forming. This paper provides insights into the motivations and mechanisms of horizontal subcontracting so that procurers may consider more effective responses to horizontal subcontracting.

1.1 Related research

Empirical analysis of horizontal subcontracting is still very new, and to my knowledge the only other paper that addresses this issue is the recent work by Marion (2011). He also develops a model of horizontal subcontracting and tests it using a rich data set from the California Department of Transportation. Marion shows that horizontal subcontractors typically bid lower as a result of being cost advantaged; however, subcontracting for additional rivals on the same project raises the subcontractor's own bid for the project. Marion attributes the higher bid to increasing opportunity costs: the more rivals the firm supplies, the greater the expected profit from subcontracting that is forgone by winning the auction.

My paper and Marion's are similar, but they assume different motivations for horizontal subcontracting. Marion models the subcontracting decision as simple cost minimization; neither the hiring firm nor the subcontracting firm is forward looking. Since the hiring firm hires the subcontractor as long as it is the lowest cost option, horizontal subcontracting can only lower the hiring firm's cost. In contrast, I develop a model that assumes both firms engaged in negotiations consider the impact of any horizontal subcontract on their rival's costs and the resulting bid strategies in the auction. This forward-looking negotiation has important implications for the negotiated subcontract payment; in my model the negotiating firms decide the payment for subcontracted work strategically. Consequently, a hiring firm is willing to accept a horizontal subcontract that raises its costs if doing so increases its expected profits from the auction.

Two papers evaluate horizontal subcontracting in non-auction settings. Kamien, Li, and Samet (1989) model Bertrand competition in which two firms with convex costs compete in prices, then consider whether to subcontract production to the rival. The authors find that both firms benefit if the loser sets the terms of the subcontract in the second stage; however, buyers face the lowest price when the winner sets the terms of the subcontract. Spiegel (1993) looks at *ex ante* and *ex post* horizontal subcontracting under Cournot competition. He shows that when firms have asymmetric convex costs, subcontracting has an ambiguous effect on output; however, subcontracting can improve welfare even if output falls, provided the firms' costs fall sufficiently.

Grimm (2004) theoretically examines horizontal subcontracting in two-stage procurement auctions in which the subcontracting decisions occur after the first contracted is awarded. Specifically, she considers procurement auctions in which a winning contractor may gain a cost advantage for subsequent related auctions. If this is so, then firms' bidding strategies should account for the potential to earn higher profits in the future by winning the present auction. Grimm develops a stylized model of a second-price sealed-bid auction of two related items. The costs of providing the second item are not known until after the first item has been produced. The buyer chooses whether to auction the two items sequentially or as a bundle. If the buyer chooses a bundle auction, the winner of the auction can choose whether to produce the second item or to subcontract it to a rival firm. Grimm finds that the bundle auction results in the lowest expected price. Moreover, restricting the winning firm's ability to subcontract the second item almost never lowers the expected price. However a bundle auction may result in an inefficient allocation, whereas the sequential auction is always efficient.

Another related segment of the literature deals with procurement auctions and non-rival subcontracting. Marechal and Morand (2003) find conditions that characterize when a buyer should use pre- or post-award subcontracting. Wambach (2009) shows that if subcontracting takes place prior to the award of the contract and subcontractors do not compete at multiple firms, then revenue equivalence between first-price sealed-bid (FPSB) auctions and second-price sealed-bid auctions (SPSB) breaks down. This result follows from the intuition that pre-award subcontractors in FPSB auctions take into consideration how their bid affects the competitiveness of "their" prime contractor, lowering the expected price in the FPSB auction below that of the SPSB auction.

Horizontal subcontracting is also related to several other strands in the literature, including split-award auctions and joint-ventures. In split-awards auctions, the buyer (rather than the contractor) can choose to divide production between rival firms. Anton and Yao (1989) find that even though split-award auctions encourage collusion, buyers may still prefer the split-award format relative to a winner-take-all auction if there are sufficient efficiency gains.[2] Joint-ventures involve two firms temporarily cooperating to supply a good to a buyer.[3] Joint-ventures are distinct from horizontal subcontracting since in joint-ventures the firms compete as a single firm, but in horizontal subcontracting the firms compete separately.

The next chapter introduces a two-firm model to characterize the procurement auction with horizontal subcontracting, while chapter 3 adds an independent prime contractor. Chapter 4 provides background on Caltrans auctions and describes the data used to test the model's implications. Chapter 5 presents the empirical results, and chapter 6 concludes. The appendix contains all proofs.

[2]See Anton and Yao (1992), Perry and Sakovics (2003), and Anton, Brusco, and Lopomo (2010) for additional work on split-award auctions.

[3]Hendricks and Porter (1992) empirically evaluate the effects of joint ventures in off-shore oil drilling leases.

Chapter 2

Two-Firm Model

Consider two prime contractors, 1 and 2, competing for a single project with two parts, A and B. Part B can be subcontracted, but part A cannot.[1] Contractor $i \in \{1, 2\}$ has commonly known costs $c_i = c_i^A + c_i^B$, where c_i is the total cost to firm i of producing the project and c_i^j is the cost to firm i of providing part $j \in \{A, B\}$ of the contract.[2] The buyer's valuation of the project, V, is commonly known and strictly exceeds the maximum possible total cost of either firm,[3] to ensure that trade always takes place. The timing of the model is as follows:

1. The buyer announces the project. Firms observe the buyer's valuation and all costs.

2. Firms 1 and 2 negotiate the horizontal subcontracting agreement. Each firm simultaneously chooses one of three subcontracting alternatives: "firm 1 hires firm 2," "firm 2 hires firm 1," or "no subcontracting."[4] In addition, if a firm chooses one of the two options with subcontracting, then the firm must also simultaneously announce a binding payment, t, that the hiring firm pays to its subcontractor if the hiring firm wins the auction in the next stage. If the firms' choices agree, then their choice is realized. If the firms' choices do not agree, then the firms do not subcontract with each other. If the firms agree to a subcontract, then the hiring prime

[1] This assumption is intended to simplify the following analysis. It could be interpreted as reflecting the restriction on how much of the project firms can subcontract.

[2] Non-prime subcontractors are not explicitly considered in this model. However, they could be easily introduced by assuming that c_i^B is the minimum of the cost to firm i of producing part B itself or the cost of hiring an independent subcontractor to perform work on part B in the event that firm i wins the auction.

[3] That is, $V > \max\{c_1^A, c_2^A\} + \max\{c_1^B, c_2^B\}$.

[4] In this paper, I am excluding the possibility of a reciprocal agreement in which both firms agree to subcontract for the other. While such reciprocal agreements are occasionally observed, the vast majority of horizontal subcontracts in the Caltrans data are one-way.

is denoted firm H, and the subbing prime is denoted firm S.[5]

3. Both firms compete in a first-price sealed-bid auction. The winning firm is paid its bid and compensates any subcontractors according to agreements determined in stage 2.

This game is solved using backwards induction, beginning with the auction subgame in the last stage.

2.1 The auction without horizontal subcontracting

If the firms choose not to subcontract, then the final stage is just a standard complete-information first-price sealed-bid auction: the firm with the lowest total cost wins the auction with a bid just below the total cost of the higher-cost firm. Total gains from trade are maximized only if the low-cost firm has the lowest cost on *both* parts of the contract. The low-cost firm earns profit equal to the difference between the total costs of the two firms. The high-cost firm earns zero profit. The buyer earns surplus equal to $V - c_H$ where c_H is the total cost of the high-cost firm. In subsequent sections, the payoffs from this auction without horizontal subcontracting are the baseline against which the effects of horizontal subcontracting are considered.

2.2 The auction with horizontal subcontracting

Assume instead that the firms have agreed to a horizontal subcontract. To solve the auction subgame, take as given the subcontracting payment t and the assignment of the primes to the roles of hiring firm and subbing firm. The two firms' payoffs are

$$\pi_H = \begin{cases} p_H - (c_H^A + t) & \text{if firm } H \text{ wins} \\ 0 & \text{if firm } H \text{ loses} \end{cases} \quad \text{and} \quad \pi_S = \begin{cases} p_S - c_S & \text{if firm } S \text{ wins} \\ t - c_S^B & \text{if firm } S \text{ loses,} \end{cases} \tag{2.1}$$

where p_i is firm i's bid for the project and π_i is firm i's profit.

The Nash equilibrium outcome of this subgame depends only on the relative sizes of the

[5] This is obviously a simplification of a complex negotiation between the two prime contractors. Other approaches could be used such as the bargaining model developed by Rubinstein (1982). Any model which causes the firms to maximize the total size of the pie and divide it amongst themselves produces the same results as the simultaneous announcement approach used in this paper. Advantages of this approach include simplicity and eliminating reliance on questionably legal tactics such as side payments other than direct compensation for work.

non-subcontractable portions of the firms' costs, c_H^A and c_S^A. This unusual result occurs because the subcontracting agreement changes each firm's opportunity cost of winning the auction. The hiring firm's cost of winning is now the production cost of part A plus the payment to the subbing firm:

$$\tilde{c}_H(t) = c_H^A + t. \tag{2.2}$$

The subbing firm's cost of winning the auction is more complex. By winning the auction as a prime, firm S pays the production cost $c_S^A + c_S^B$ *and* forgos the profit it could have earned as a subcontractor, $t - c_S^B$. Since the subbing firm pays the production cost c_S^B regardless of whether it wins or loses, its opportunity cost of winning the auction is now

$$\tilde{c}_S(t) = c_S^A + t. \tag{2.3}$$

The auction with subcontracting can therefore be characterized as a standard first-price sealed-bid auction as described in section 2.1, with respective costs $\tilde{c}_H$ and $\tilde{c}_S$ for firms H and S. The winning firm is the one with lower $\tilde{c}_i$, and that comparison follows solely from the comparison of c_i^A.

If $c_H^A < c_S^A$, then the hiring firm wins the auction with price $p_H = c_S^A + t - \epsilon$, where ϵ represents the smallest incremental change in price.[6] The subbing firm bids its cost $p_S = c_S^A + t$. The resulting payoffs of the first-price sealed-bid auction when $c_H^A < c_S^A$ are

$$\pi_S = t - c_S^B \qquad \text{and} \qquad \pi_H = c_S^A - c_H^A - \epsilon. \tag{2.4}$$

Since the subcontract is in the winning bid, the firms share production of the final good and both earn positive profit. If $c_S^A < c_H^A$ instead, then the subbing firm wins the auction with price $p_S = c_H^A + t - \epsilon$. The resulting payoffs of the first-price sealed-bid auction when $c_H^A < c_S^A$ are then

$$\pi_S = c_H^A + t - c_S - \epsilon \qquad \text{and} \qquad \pi_H = 0. \tag{2.5}$$

Since the subcontract is in the losing bid, the subbing firm wins as a prime contractor and does not share production. Consequently, only the subbing firm earns positive profit.

[6] The model results are unchanged if, instead, the firms bid the same price (equal to the high-cost firm's cost) and the buyer employs a tie-breaking rule awarding the contract to the low-cost firm.

2.3 Deciding the payment for subcontracted work

Without loss of generality, define firm 1 as the firm with the lower cost on the non-subcontractable part A, so that $c_1^A < c_2^A$. These definitions imply $\tilde{c}_1 < \tilde{c}_2$, so firm 1 always wins the auction if the firms agree on a subcontract. In stage 2, the prime contractors can choose one of three alternatives: firm 2 hires firm 1 as a subcontractor ("firm 1 is S"), firm 1 hires firm 2 as a subcontractor ("firm 2 is S"), or the firms do not subcontract with each other ("no subcontracting"). For each of the first two options, the firms must also decide how much the hiring firm will pay for subcontracted work.

To solve this subgame, consider first the negotiation of the payment t, conditional on agreeing to a horizontal subcontract. This payment must exceed the subbing firm's costs to produce the subcontracted work, $t > c_S^B$, so that it does not earn negative profit if the hiring firm wins the auction. Equations (2.4) and (2.5) show that the hiring firm's profit is unaffected by the size of t, regardless of who wins the auction. Intuitively, if the hiring firm wins the auction, a \$1 increase in t raises *both* the hiring firm's price ($\tilde{c}_S - \epsilon$) *and* cost ($\tilde{c}_H$) by \$1. If the hiring firm loses the auction, then it earns zero profit regardless of t. So, conditional on the firms agreeing to subcontract in stage 2, the hiring firm will accept any t such that trade still occurs. Counterintuitively, this result implies that the hiring firm is willing to pay its subcontractor *more* than its in-house production cost for the same work.

Equations (2.4) and (2.5) show that the subbing firm's profit increases in t, regardless of who wins the auction. If the hiring firm wins the auction, increasing t increases the subbing firm's revenue from the subcontract. If the subbing firm wins the auction, increasing t increases the hiring firm's cost, hence raising the price at which the subbing firm wins the auction. Therefore, the subbing firm prefers the highest t such that trade occurs.

Since the hiring firm is indifferent to t and the subbing firm prefers higher t, it is Pareto efficient for the firms to set t such that the winning price equals the buyer's value, V.[7] Since $\tilde{c}_1 < \tilde{c}_2$ by definition, firm 1 wins the auction with price $p_1 = c_2^A + t - \epsilon$, regardless of whether the firms choose "firm 1 is S" or "firm 2 is S." Therefore, the joint-profit-maximizing subcontract payment is $t = V - c_2^A + \epsilon$.

Table 2.1 shows the two possible equilibrium outcomes of the auction subgame with hori-

[7] Pareto efficiency here refers only to the payoffs of the two firms. The buyer would obviously prefer a lower t that yields a lower price.

Table 2.1: Auction outcomes, conditional on a horizontal subcontract

	Firm 1 is S (Firm S wins)	Firm 2 is S (Firm H wins)
Winning price, p_1	V	V
Subcontract payment, t	$V - c_2^A$	$V - c_2^A$
Hiring firm's profit, π_H	0	$c_2^A - c_1^A$
Subbing firm's profit, π_S	$V - c_1$	$V - c_2$
Buyer's profit, π_B	0	0

Epsilons have been suppressed for simplicity.

zontal subcontracting. In both cases the winning price is V and the buyer receives no surplus. With only two firms, horizontal subcontracting allows the subbing firm to extract surplus from the buyer by raising the subcontract payment well above the actual costs of production. In fact, the subbing firm earns the same profit from a horizontal subcontract that it would have earned if it faced no competition from any rival prime contractors. The hiring firm's profit from horizontal subcontracting reflects the cost savings generated by the hiring firm. When firm 1 is the hiring firm, it earns profit equal to its cost advantage on part A, the portion it produces. When firm 2 is the hiring firm, the subcontract is not exercised since it is submitted as part of the losing bid, so no cost reductions are realized. Consequently, firm 2 earns no profit as the hiring firm.

2.4 Deciding the horizontal subcontracting roles

Consider now the choice of the three subcontracting alternatives, "firm 1 is S," "firm 2 is S," and "no subcontracting." The firms' profits under each alternative depend on both firms' cost parameters. Table 2.2 presents the three possible combinations of costs. In case A, firm 1 is the low cost prime on both parts of the contract. In case B, firm 2 is the lower cost prime on part B, but firm 1 still has the lower total cost. In case C, firm 2 is the lower cost prime on part B, and firm 2 has the lower total cost. In cases A and B, firm 1 wins the auction regardless of whether there is horizontal subcontracting. By contrast, in case C, firm 1 wins the auction only with horizontal subcontracting. Table 2.3 reports the payoffs to firms 1 and 2 for each of the three alternative strategies, given the cost parameters and $t = V - c_2^A$. Define $\pi_i^{k \text{ is } S}$ as the payoff to firm $i \in \{1, 2\}$ when both firms agree that firm $k \in \{1, 2\}$ is the subcontractor and $\pi_i^{\text{No Sub}}$ as the payoff to firm $i \in \{1, 2\}$ if the firms do

Table 2.2: Two-firm model cost cases

Case	Relative cost on part B	Relative total cost
A	$c_1^B < c_2^B$	$c_1 < c_2$
B	$c_2^B < c_1^B$	$c_1 < c_2$
C	$c_2^B < c_1^B$	$c_2 < c_1$

Firms 1 and 2 are defined such that $c_1^A < c_2^A$. Part B is the project's subcontractable portion.

Table 2.3: Payoffs under various subcontracting alternatives

	Firm 1 is S		Firm 2 is S	No Subcontracting $c_1 < c_2$ (Cases A and B)	No Subcontracting $c_2 < c_1$ (Case C)
π_1	$V - c_1$	$>$	$c_2^A - c_1^A$	$c_2 - c_1$	0
π_2	0	$<$	$V - c_2$	0	$c_1 - c_2$

not agree or both choose "no subcontracting." Given $V > \max\{c_1^A, c_2^A\} + \max\{c_1^B, c_2^B\}$,

$$\pi_i^{i \text{ is } S} > \max\{\pi_i^{k \text{ is } S}, \pi_i^{\text{No Sub}}\} \text{ for } i \neq k. \tag{2.6}$$

Since the subbing firm captures all of the extracted consumer surplus from choosing a high t, each firm strictly prefers to be the subcontractor rather than hire its rival or bid independently. The following propositions characterize the equilibria in each of the three cost cases.

Proposition 2.4.1. *If $c_1 < c_2$ and $c_1^j < c_2^j$ for $j \in \{A, B\}$, then the firms choose either no subcontracting or firm 2 hires firm 1. The outcome is fully efficient.*

Table 2.4 shows the payoff matrix of firms 1 and 2 for case A where firm 1 has the low cost on both parts. The cost parameters of case A imply that $\pi_1^{1 \text{ is } S} > \pi_1^{\text{No Sub}} > \pi_1^{2 \text{ is } S}$ and $\pi_2^{2 \text{ is } S} > \pi_2^{\text{No Sub}} = \pi_2^{1 \text{ is } S} = 0$. As Table 2.4 shows, there are multiple Nash equilibria from this negotiation (shown in bold). However, only $\{1 \text{ is } S, 1 \text{ is } S\}$ (shown in gray) is a Pareto dominant Nash equilibrium.[8] The equilibrium outcome is fully efficient: firm 1 wins the auction and performs all of the work. Since firm 1 is low cost on both parts, total production costs are minimized.

Proposition 2.4.2. *If $c_1 < c_2$ and $c_1^B > c_2^B$ then firm 1 hires firm 2. The outcome is fully efficient.*

[8] Pareto dominance here refers only to the profits of the firms. The buyer would obviously prefer the lower price generated by the auction without subcontracting.

Table 2.4: Negotiating the subcontract, case A

	Firm 2		
Firm 1	1 is S	2 is S	No Sub
1 is S	$\boldsymbol{V - c_1, 0}$	$\boldsymbol{c_2 - c_1, 0}$	$\boldsymbol{c_2 - c_1, 0}$
2 is S	$c_2 - c_1$, 0	$c_2^A - c_1^A$, $V - c_2$	$c_2 - c_1$, 0
No Sub	$c_2 - c_1$, 0	$\boldsymbol{c_2 - c_1, 0}$	$\boldsymbol{c_2 - c_1, 0}$

All Nash equilibria are bolded. The Pareto dominant Nash equilibrium is highlighted in gray.

Table 2.5 shows the payoff matrix of firms 1 and 2 for case B where firm 2 has the low cost on the subcontractable part. The cost parameters imply that $\pi_1^{1 \text{ is } S} > \pi_1^{2 \text{ is } S} > \pi_1^{\text{No Sub}}$ and $\pi_2^{2 \text{ is } S} > \pi_2^{\text{No Sub}} = \pi_2^{1 \text{ is } S} = 0$. Again, there are multiple Nash equilibria (in bold), but none of them dominate. Firm 1 prefers the $\{1$ is S, 1 is $S\}$ equilibrium, and firm 2 prefers the $\{2$ is S, 2 is $S\}$ equilibrium.

Since there is no Pareto dominant Nash equilibrium, I solve for a unique equilibrium by eliminating weakly-dominated strategies. Since no subcontracting is the least profitable option for firm 1, "No Sub" is weakly-dominated by both "1 is S" and "2 is S" for firm 1. As in the previous case, firm 2 only earns profit from being the subcontractor, so "2 is S" is the weakly-dominant strategy for firm 2. The resulting equilibrium is then $\{2$ is S, 2 is $S\}$ where firm 1 hires firm 2 as the subcontractor.

The outcome is for firm 1 to produce part A and firm 2 to produce part B. Since each part is produced by the lowest cost firm, the outcome is fully efficient. In contrast to the previous case, maximum efficiency is only feasible with horizontal subcontracting. Were horizontal subcontracting forbidden, the price would fall—increasing the surplus of the buyer—but total welfare would decrease because total production costs increase.

Proposition 2.4.3. *If $c_1 > c_2$ and $c_1^B > c_2^B$, then firm 1 hires firm 2 as a subcontractor. The outcome is fully efficient.*

In this case, firm 1 wins any auction in which the firms have negotiated a subcontract, but firm 2 wins the auction if a subcontract is not negotiated. Table 2.6 displays the payoff matrix of the negotiation subgame for case C. The cost parameters imply that $\pi_1^{1 \text{ is } S} > \pi_1^{2 \text{ is } S} > \pi_1^{\text{No Sub}}$ and $\pi_2^{2 \text{ is } S} > \pi_2^{\text{No Sub}} > \pi_2^{1 \text{ is } S}$. As Table 2.6 shows, there are multiple Nash equilibria from this

Table 2.5: Negotiating the subcontract, case B

	Firm 2		
Firm 1	1 is S	2 is S	No Sub
1 is S	$\boldsymbol{V - c_1, 0}$	$c_2 - c_1, 0$	$\boldsymbol{c_2 - c_1, 0}$
2 is S	$c_2 - c_1, 0$	$\boldsymbol{c_2^A - c_1^A, V - c_2}$	$c_2 - c_1, 0$
No Sub	$c_2 - c_1, 0$	$c_2 - c_1, 0$	$\boldsymbol{c_2 - c_1, 0}$

All Nash equilibria are bolded. The equilibrium after eliminating weakly-dominated strategies is highlighted in gray.

Table 2.6: Negotiating the subcontract, case C

	Firm 2		
Firm 1	1 is S	2 is S	No Sub
1 is S	$V - c_1, 0$	$0, c_1 - c_2$	$\boldsymbol{0, c_1 - c_2}$
2 is S	$0, c_1 - c_2$	$\boldsymbol{c_2^A - c_1^A, V - c_2}$	$0, c_1 - c_2$
No Sub	$0, c_1 - c_2$	$0, c_1 - c_2$	$\boldsymbol{0, c_1 - c_2}$

All Nash equilibria are bolded. The Pareto dominant Nash equilibrium is highlighted in gray.

negotiation (shown in bold). However, only {2 is S, 2 is S} (shown in gray) is a Pareto dominant Nash equilibrium.[9]

Like the previous case, the outcome in this situation is for firm 1 to produce part A and firm 2 to produce part B. Since each part is produced by the lowest cost firm, the outcome is fully efficient. Again, maximum efficiency is only feasible here with horizontal subcontracting. Were horizontal subcontracting forbidden, the price would fall—increasing the surplus of the buyer—but total welfare would decrease because total production costs increase.

2.5 Summary of the two-firm model

Table 2.7 summarizes the outcomes of the two-firm model in each of the three cost cases. In all cases, the firms negotiate a horizontal subcontract. Compared to an environment in which horizontal subcontracting is not permitted, horizontal subcontracts always soften competition, lead-

[9]Again, Pareto dominance here refers only to the profits of the firms.

Table 2.7: Effect of horizontal subcontracting relative to no subcontracting

	Case A	Case B	Case C
Subbing Prime	Firm 1	Firm 2	Firm 2
Winning Prime	Firm 1	Firm 1	Firm 1
Price	Rises by $V - c_2$	Rises by $V - c_2$	Rises by $V - c_1$
Efficiency	No change	Rises by $c_1^B - c_2^B$	Rises by $c_2^A - c_1^A$
Firm 1's profit	Rises by $V - c_2$	Rises by $c_1^B - c_2^B$	Rises by $c_2^A - c_1^A$
Firm 2's profit	No change	Rises by $V - c_2$	Rises by $V - c_1$
Buyer's profit	Falls by $V - c_2$	Falls by $V - c_2$	Falls by $V - c_1$

ing to higher prices and lower buyer surplus. However, horizontal subcontracting can also increase efficiency by allocating production among the firms with the lower cost on each part. Importantly, even though horizontal subcontracting reduces buyer surplus, it never harms total welfare and may increase total welfare. This result is consistent with the findings of Kamien, Li, and Samet (1989) and Spiegel (1993) who looked at horizontal subcontracting in the context of oligopoly models. In the next chapter, I show that introducing an independent prime can mitigate horizontal subcontracting's competition softening effects without eliminating its efficiency gains.

Chapter 3

Three-Firm Model

Horizontal subcontracting softens competition in the two-firm model because both firms cooperate to extract surplus from the buyer. Introducing an independent prime contractor restricts the hiring and subbing primes' ability to extract surplus, because raising prices through horizontal subcontracting may cause the subcontracting pair to lose the auction to the independent firm.

As before, firm H is the hiring prime, and firm S is the subcontracting prime; for convenience, these two firms are referred to jointly as the "negotiating primes." Let firm I be an exogenously-determined independent prime contractor[1] with costs $c_I = c_I^A + c_I^B$.[2] The timing of the three-firm model is the same as in the two-firm model, except that the independent firm only acts in the auction subgame. All costs are common knowledge, and the independent firm knows the outcome of the subcontracting negotiation at the start of the auction subgame.

3.1 The prime auction without subcontracting

If all three firms bid independently without a horizontal subcontract, then the auction subgame is a standard first-price sealed-bid auction. The lowest-cost firm bids just below the cost of the next-lowest-cost firm, and the other two firms bid their costs. The lowest-cost firm wins the auction and earns profit equal to the difference between the lowest and next-lowest costs. The losing firms earn zero profits. The buyer gains surplus equal to the difference between its value and the

[1]Endogenizing the decision of roles of firms as "independent" or potentially involved in horizontal subcontract negotiation is an interesting question that I leave for future research.

[2]The model can be easily adapted to encompass more than three prime contractors by denoting firm I as the lowest-cost independent firm. The subsequent results are minimally affected by this adaptation.

second-lowest production cost. Total gains from trade are maximized only if the winning firm has the lowest cost on both parts of the contract.

3.2 The prime auction with subcontracting

Assume instead that the negotiating firms have agreed to a horizontal subcontract, with subcontract payment t and assigned roles H, S, and I. The three firms' profits are

$$\pi_I = \begin{cases} p_I - c_I & \text{if } I \text{ wins} \\ 0 & \text{if } I \text{ loses,} \end{cases} \qquad \pi_H = \begin{cases} p_H - (c_H^A + t) & \text{if } H \text{ wins} \\ 0 & \text{if } H \text{ loses,} \end{cases}$$
$$\text{and} \qquad \pi_S = \begin{cases} p_S - c_S & \text{if } S \text{ wins} \\ t - c_S^B & \text{if } H \text{ wins} \\ 0 & \text{if } I \text{ wins,} \end{cases} \tag{3.1}$$

where p_i is firm i's bid for the project.

The best-response functions of the independent firm and the hiring firm are straightforward. The independent firm earns profit only by winning the auction, so the independent firm undercuts its lowest cost rival if that rival's cost exceeds c_I; otherwise, the independent firm bids its cost. The hiring firm's cost is transformed in the same manner as in the two-firm model, so that $\tilde{c}_H = c_H^A + t$. The hiring firm also earns profit only by winning, so it likewise undercuts its lowest-cost rival, unless that rival's cost is below $\tilde{c}_H$.

The relevant costs and best-response function of the subbing firm are more complex. If the independent firm is the subbing firm's lower-cost rival, then the subbing firm's relevant opportunity cost of winning the auction is c_S, as in a standard first-price auction without subcontracting. However, if the hiring firm is the subbing firm's lower-cost rival, then as in the two-firm model, the subbing firm must choose between the profits it could earn from winning and the profits it could earn by subcontracting. Consequently, when $c_H < c_I$, the subbing firm's relevant opportunity cost is $\tilde{c}_S = c_S^A + t$. Formally, the subbing firm's relevant opportunity cost is

$$\tilde{c}_S(t, p_I, p_H) = \begin{cases} c_S & \text{if } p_I < p_H \\ c_S^A + t & \text{if } p_H < p_I, \end{cases} \tag{3.2}$$

and the subbing firm's best-response function is

$$p_S^{BR}(p_I, p_H) = \begin{cases} c_S & \text{if } p_I \leq c_S \\ p_I - \epsilon & \text{if } p_I > c_S \text{ and } p_I < p_H \\ c_S^A + t & \text{if } p_H \leq c_S^A + t \text{ and } p_H < p_I \\ p_H - \epsilon & \text{if } p_H > c_S^A + t \text{ and } p_H < p_I. \end{cases} \tag{3.3}$$

The first two cases presented in equation (3.3) correspond to the independent firm being the subbing firm's relevant competitor, while the last two cases correspond to the hiring firm being the subbing firm's relevant competitor.

Without loss of generality, define firm 1 as the negotiating firm with the lower cost on part A, and firm 2 as the negotiating firm with the higher cost on part A, so $c_1^A < c_2^A$. The independent firm's cost on part A could be higher or lower than c_1^A and c_2^A. As in the two-firm model, this definition of firms 1 and 2 means that in equilibrium, firm 1 bids below firm 2 in any auction in which firms 1 and 2 have written a horizontal subcontract. Formally,

Proposition 3.2.1. *With $c_1^A < c_2^A$, if firms 1 and 2 agree to a horizontal subcontract in Stage 2 (either "1 is S" or "2 is S"), then in equilibrium, $p_1 < p_2$.*

It follows from Proposition 3.2.1 that if firms 1 and 2 have agreed to a horizontal subcontract in Stage 2, firm 2 never wins the auction as prime contractor. Rather, firm I wins if $c_I < \tilde{c}_1$, and firm 1 wins otherwise.

3.3 Deciding the subcontracting arrangement

The relative costs of the three firms can be sorted into the nine cases shown in Table 3.1. These nine cases can be simplified to three broad cases. The first broad case includes cases 1, 4, 8

Table 3.1: Three-firm model cost cases

	Cost Parameters			Outcomes		
Case	Firm I's cost rank	$\min\{c_1^B, c_2^B\}$	Pair's cost rank	Subcontract	Price Effect	Winning Firm
1	$c_I < \{c_1, c_2\}$	c_1^B		"$NoSub$" or "1 is S"	$\Uparrow$	I
2	$c_I < \{c_1, c_2\}$	c_2^B	$c_I < c_1^A + c_2^B$	"$NoSub$" or "2 is S"	$\Downarrow$	I
3	$c_I < \{c_1, c_2\}$	c_2^B	$c_I > c_1^A + c_2^B$	"2 is S"	$\Downarrow$	H
4	$\{c_1, c_2\} < c_I$	c_1^B		"1 is S"	$\Uparrow$	S
5	$\{c_1, c_2\} < c_I$	c_2^B		"2 is S"	$\Uparrow$	H
6	$c_2 < c_I < c_1$	c_2^B		"2 is S"	$=$	H
7	$c_1 < c_I < c_2$	c_2^B		"2 is S"	$=$	H
8	$c_1 < c_I < c_2$	c_1^B	$c_I < c_1^A + c_2^B$	"$NoSub$" or "1 is S"	$=$	$1(S)$
9	$c_1 < c_I < c_2$	c_1^B	$c_I > c_1^A + c_2^B$	"$NoSub$"	$=$	1

The price effect is the effect of horizontal subcontracting on price relative to an auction in which horizontal subcontracting is not permitted.

and 9: $c_1^B < c_2^B$, so firms 1 and 2 cannot use subcontracting to lower the cost of producing the total project. The second broad case includes cases 2, 3, 6, and 7: $c_2^B < c_1^B$, and the independent firm is a low-cost competitor that prevents the negotiating firms from raising the price. The final broad case is case 5: $c_2^B < c_1^B$, and the independent firm provides minimal restriction on price since it has the highest cost. The propositions below summarize the primary outcomes of each of these broad cases.

Proposition 3.3.1. *If $c_1^B < c_2^B$, then firms 1 and 2 either negotiate a subcontract where firm 2 hires firm 1, or they choose not to subcontract. If firms 1 and 2 subcontract, then the winning price is weakly higher than if horizontal subcontracting were not permitted.*

The intuition of Proposition 3.3.1 follows from case A of the two-firm model: firm 1 has lower costs than firm 2 on *both* parts of the project, so the two firms cannot write a horizontal subcontract that lowers the total cost of producing the project. Consequently, firm 1 would never agree to hire firm 2 as a subcontractor, since doing so would only increase firm 1's production cost, resulting in lower profit than firm 1 could receive from bidding independently. In contrast, firm 1 would readily agree to a subcontract in which it is hired by firm 2. This subcontract ("1 is S") allows firm 1 to increase firm 2's cost by charging a high subcontracting payment t. If firm 2 is firm 1's lowest-cost competitor, then the horizontal subcontract allows firm 1 to raise firm 2's cost to c_I and undercut both firms with price $p_1 = c_I - \epsilon$. Absent the horizontal subcontract, firm 1's best price is lower at $p_1 = c_2 - \epsilon$, and firm 1's profit is lower as a result. Even though this subcontract hurts firm 2's competitive position in the auction subgame, it may be willing to accept this higher cost, since it would lose the auction to firm 1 anyway. Although outside the scope of this model, the repeated nature of highway auctions gives rise to several mechanisms by which firm 1 could compensate firm 2 for an otherwise zero-gain agreement. For example, firm 1 could promise to reciprocate on a future project for which their relative cost positions are reversed. Alternatively, firm 1 could offer favorable subcontracting terms on a different project in which it is not competing as a prime contractor.[3]

Since firm 1 has the lower cost on both parts of the project, a horizontal subcontract between firms 1 and 2 cannot generate cost savings. Hence, the only strategic purpose of this horizontal subcontract is to raise the cost of firm 2 to benefit firm 1. From an empirical perspective, this result implies that any horizontal subcontract in which the subbing firm bids below its hiring firm should soften competition and lead to weakly higher prices. The extent to which the subbing firm benefits from softening competition is limited by the cost of the independent prime.

Proposition 3.3.2. *If $c_2^B < c_1^B$ and the independent firm has either the lowest cost or the second lowest cost (i.e., $c_I < \max\{c_1, c_2\}$), then firms 1 and 2 either negotiate a subcontract where firm 1 hires firm 2, or they choose not to subcontract. The winning price is weakly lower than if horizontal subcontracting were not permitted.*

In this broad category, the independent firm is sufficiently low cost that firms 1 and 2 cannot use the horizontal subcontract to soften competition and raise the price. However, since firm 2 has a cost advantage on part B relative to firm 1, the two firms can use a horizontal subcontract to lower the cost of producing the project. The resulting intensified competition generates weakly lower prices that benefit the buyer. In this case, the only party that might be harmed by horizontal subcontracting is the independent firm which now faces more competitive rivals. If firm 1 wins the auction (as the hiring firm), then horizontal subcontracting strictly increases efficiency. If the independent firm wins the auction, then efficiency is unchanged.

Proposition 3.3.3. *If $c_2^B < c_1^B$ and the independent firm has the highest cost (i.e., $c_I > \max\{c_1, c_2\}$), then firms 1 and 2 negotiate a subcontract where firm 1 hires firm 2. The winning price is higher*

[3]One could also imagine firm 1 might offer a side payment to firm 2 in exchange for writing this subcontract. However, such a side payment from a winning firm to a losing firm is questionably legal. Importantly, the theory does not imply that observing this type of subcontract necessarily means that the involved firms are engaging in illegal behavior.

than if horizontal subcontracting were not permitted.

The strategic decisions of firms 1 and 2 are the same in this case as in cases B and C of the two-firm model, except now the independent firm's cost c_I, rather than the buyer's value V, restricts the extent to which the negotiating firms can raise the price. Firm 2 earns zero profit if it hires firm 1, because firm 1 always undercuts firm 2 whenever a subcontract is negotiated. Since the subcontractor captures all of the additional profit that results from raising the subcontracting payment t, firm 2's dominant strategy is to choose "2 is S." If firm 1 agrees, then firm 2 gets the higher profit from subcontracting. If firm 1 disagrees, then the outcome is no subcontracting, which is strictly better for firm 2 than "1 is S" if $c_2 < c_1$ and no worse if $c_2 > c_1$.

Given that firm 2 chooses "2 is S," firm 1's best response is to agree and also choose "2 is S," since hiring firm 2 allows firm 1 to benefit from the resulting cost efficiencies. Since increasing t raises firm 2's cost and firm 1's cost identically, firm 1 is indifferent to the size of t. So the negotiating firms set t such that the winning price equals c_I. Consequently, horizontal subcontracting in this case increases both efficiency and the price.

3.4 Empirical implications

As in the two-firm model, the subbing firm always has the lower cost on the subcontractable part of the project. Consequently, horizontal subcontracting either preserves or enhances the cost efficiency of producing the project. However, given that a subcontract is written, c_H^B cannot be observed directly, because the hiring firm's bid on subcontracted work reflects the subcontracting cost t instead of its original cost c_H^B.[4] Empirical testing of the efficiency implications of horizontal subcontracting are therefore left to future research.

Other implications of the model can be tested using the existing data. For example, the model predicts that the negotiating firm with the lower cost on the non-subcontractable part A of the project (firm 1) is the low bidder of the pair, $p_1 < p_2$. This prediction is testable, and to the extent that it is true, firm 1 can be identified as the lower-priced firm of the negotiating pair.

Identifying firm 1 enables identification of the pair types according to the three broad cases described in section 3.3. Define the lower-priced negotiating firm as the pair's "dominant firm." Then pairs in which firm 2 hires firm 1 ("1 is S") are "subbing-firm dominant," and pairs in which

[4] The data and identification of costs are described in more detail in chapter 4.

Table 3.2: Empirical predictions by pair type

Pair Type	Price & Markup Comparison	Pair Type	Price & Markup Comparison
Subbing dominant	Higher	Subbing dominant	Highest
Hiring dominant	Lower	Hiring dominant, I wins	Middle
		Hiring dominant, H wins	Lowest

firm 1 hires firm 2 ("2 is S") are "hiring-firm dominant." Subbing-firm-dominant pairs correspond to Proposition 3.3.1; the model predicts that the motivation of subbing-firm-dominant pairs is to soften competition, resulting in higher prices and higher markups on subcontracted work. If, instead, the pair is hiring-firm dominant, then the pair corresponds to either Proposition 3.3.2 in which the firms' motivation is to reduce costs to improve their competitive position, or Proposition 3.3.3 in which the firms' motivation is to raise the price. Even though the overall effect of hiring-firm-dominant pairs on competition is ambiguous, the presence of cost-reduction incentives for some pairs implies that hiring-firm-dominant pairs should be more competitive, on average, than subbing-firm-dominant pairs.

Hiring-firm-dominant pairs can be sorted into two additional types based on whether the hiring firm or the independent firm wins the auction. If the hiring firm wins the auction, then the motivation for the horizontal subcontract is still unknown. The hiring firm could have won due to cost savings that improved its competitive position as in case 3, or the hiring firm could have won because the independent firm was already a weak competitor that could not prevent price increases as in case 5. Consequently, the expected direction of competition is still ambiguous in any auction in which the hiring firm wins the auction. However, in case 2, the independent firm wins the auction, even though the hiring firm still bids below the subbing firm. Therefore, any hiring-firm-dominant pair which loses the auction to an independent firm corresponds to Proposition 3.3.2 and should cause prices to fall. The resulting implication is that hiring-firm-dominant pairs in which the hiring firm loses are the most competitive pair type, and subbing-firm-dominant pairs are the least competitive pair type. Table 3.2 summarizes the pair types and their expected effect on price.

3.5 Implications of incomplete information

Solving the model of horizontal subcontracting with incomplete information is challenging for several reasons. First, even if firms have *ex ante* symmetric cost distributions, the possibility of horizontal subcontracting eliminates the cost symmetry between negotiating firms and the independent firm. Asymmetric cost distributions introduce several complications, including an inability to analytically solve for the bidding strategies and thus an inability to analytically solve for prices, payoffs, and welfare.[5] Second, if the negotiating firms are uncertain about each other's costs, then even if the firms choose not to subcontract, the negotiation stage allows them to send signals about their costs. The resulting information content from these signals must be incorporated into the bidding strategies of the negotiating firms, and the independent firm's bidding strategy must reflect its beliefs about the transformed bidding strategies of its rivals. Finally, the independent firm is uncertain about the value of t or even whether its rivals have agreed to a horizontal subcontract. Consequently, the independent firm must also generate beliefs about the subcontract negotiation, and the negotiating firm's strategies in both the negotiation subgame and the auction subgame must be consistent with these beliefs.

Even though a model with incomplete information is challenging to solve, it is possible to generate some intuition about how the firm's behavior differs under incomplete information relative to the complete-information model. The expected profits of the independent firm and hiring firm under incomplete-information are

$$E\pi_i = (p_i - c_i)\Pr[p_i < \min(p_k)] \quad \text{for} \quad i \in \{I, H\}, \quad k \in \{I, H, S\}, \quad \text{and } i \neq k, \tag{3.4}$$

where $p_i - c_i$ is firm i's profit conditional on winning the auction, and $\Pr[p_i < \min(p_k)]$ is the probability that firm i wins the auction. The expected profit of the subbing firm is

$$E\pi_S = (p_S - c_S)\Pr[p_S < \min\{p_H, p_I\}] + \left(t - c_s^B\right)\Pr[p_H < \min\{p_S, p_I\}], \tag{3.5}$$

where $\left(t - c_s^B\right)$ is the subbing firm's profit from the subcontract if the hiring firm wins. Define firms 1 and 2 as the negotiating firms such that $c_1^A < c_2^A$ as before. To eliminate problems with signaling, suppose that firms 1 and 2 have complete information about each other's costs, but firms 1

[5] See Lebrun (1996), Waehrer (1999), and Maskin and Riley (2000) for more on auctions with asymmetric costs.

and 2 know only the distribution of the independent firm's cost, and the independent firm similarly knows only the distributions of costs for firms 1 and 2.[6] Since $c_1^A < c_2^A$ and firms 1 and 2 know each other's costs, firm 1 is still the pair's dominant firm, so conditional on a horizontal subcontract, firm 1's only binding rival is the independent firm. The lowest possible cost of the dominant firm is $c_d = \min\{c_1, c_1^A + c_2^B\}$ where $t = c_S^B$.[7] Increasing t above c_S^B raises the dominant firm's cost above c_d. Define $\Pr(c_d < c_I)$ as the probability that the dominant firm's lowest possible cost is below the independent firm's cost.

If c_d is high relative to the expectation of c_I, then $\Pr(c_d < c_I)$ is low, and the negotiating firms have incentive to horizontally subcontract with a low payment t to decrease $\tilde{c}_1$ and improve the competitive position of the negotiating firms. This result is essentially the same as in the complete-information model in which negotiating firms facing a low-cost independent prime have incentive to horizontally subcontract to lower costs.

If c_d is low relative to the expectation of c_I, then $\Pr(c_d < c_I)$ is high, and the negotiating firms have incentive to charge a higher payment t to raise the winning price. Compared to the complete-information model, however, the negotiating firms' incentive to raise t is mitigated. In the complete-information model, when the independent firm is high cost, raising t increases the subbing firm's profit and does no harm to the hiring firm's profit. With incomplete information, raising t still raises the payoff of the subbing firm and does no harm to the hiring firm's payoff, conditional on the subbing firm having the lowest cost. However, raising t also reduces the probability that that the subbing firm has the lowest cost, lowering the *expected* profit if the subbing firm and the *expected* profit of the hiring firm when the hiring firm is the dominant firm. (Raising t has no effect on the hiring firm's expected profit when firm 2 is the hiring firm, because firm 2's expected profit as the hiring firm is still zero.) Consequently, uncertainty about the independent firm's cost mitigates the competition softening effects of horizontal subcontracting. Importantly the model predictions summarized in Table 3.2 seem like they still may be appropriate with incomplete information.

[6] I.e., the independent firm does not know which of the negotiating firms is the pair's dominant firm or what t is, but it knows that its rivals are engaged in subcontracting negotiations.

[7] c_2 is never the most competitive bid since $c_1^A < c_2^A$ implies $c_1^A + c_2^B < c_2$.

Chapter 4

Data and Background

4.1 California highway procurement auctions

The California Department of Transportation (Caltrans) announces highway construction projects on its website several weeks in advance of a project. The contracts are awarded by means of a first-price sealed-bid auction to contractors that have prequalified to bid on the project.[1] All prime contractors are required to complete at least 30 percent of the project themselves, measured by the value of the original total bid.[2] In addition, the Subletting and Subcontracting Fair Practice Act requires all prime contractors to list as part of their bid all subcontractors performing work costing more than 0.5 percent of the total bid or $10,000, whichever is greater.[3]

Each project auctioned by Caltrans is made up of many individual tasks with a specific quantity q_j for each item j specified in the contract by Caltrans. To bid on the project, each prime contractor submits an individual unit bid p_j for each item in the project. Each prime contractor's total bid is calculated as

$$\boldsymbol{p} = \sum_{j=1}^{J} p_j q_j, \tag{4.1}$$

where J is the total number of items in the project. After all bids are accepted, Caltrans reveals all bids for the project and awards the project to the prime contractor with the lowest total bid, $\boldsymbol{p}$.

[1] Contractors are prequalified according to licensing, equipment, training, and work history.

[2] An exception to this rule are project items that Caltrans denotes as "specialty" items. Subcontracting a specialty item does not count against the subcontracting limit.

[3] The Subletting and Subcontracting Act prohibits contractors from changing subcontractors or hiring additional subcontractors after the contract is awarded, except in exceptional circumstances such as when the subcontractor refuses to perform the contracted work or becomes insolvent.

4.2 Data description

The dataset for this paper includes 75 highway construction projects which represent all awarded contracts in California in 2002 in which at least one prime contractor is listed as a subcontractor for a rival prime contractor on the same project. For each contract, Caltrans reports the location where the work will take place, a brief description of the work to be done, an estimated cost of the project from Caltrans engineers, and information about each bid on the project. Each bid includes the prime contractor's name and address, the total bid amount for the whole project, the bid amounts for each individual item of the project, the list of subcontractors employed by the contractor, and the portion of the project the subcontractor has been employed to perform. In most instances, the subcontracted work is listed as an item number (e.g., items 4 through 6) or a brief description that corresponds to listed tasks (e.g., "asphalt concrete paving") so that subcontractors can be easily assigned to the correct items. On occasion, the listed subcontracted work is less specific (e.g., "bridge work"); in these cases the best attempt has been made to match the subcontractor to the correct item. When the subcontractor is listed as performing a "portion" of an item, I record the subcontractor as performing the entirety of the item, since there is no additional information to determine the fraction of the work for which the subcontractor is actually responsible.

The item-level bids are particularly useful, because they reveal information about the firms' underlying cost structure. For example, even though we cannot directly observe the subbing firm's cost or the price the subbing firm is charging to its rival for its work, these costs must be reflected in the firms' bids on these task. Consequently, the item-level bids are a useful approximation of the unobserved production costs. Define $j \in \{1, 2, ..., J_A\}$ as the non-horizontally subcontracted items and $j \in \{J_A + 1, J_A + 2, ..., J\}$ as the items which are horizontally subcontracted. Then firm i's cost on part A is estimated as

$$\hat{c}_i^A = \sum_{j=1}^{J_A} p_j q_j, \tag{4.2}$$

and firm i's cost on part B is estimated as

$$\hat{c}_i^B = \sum_{j=J_A+1}^{J} p_j q_j. \tag{4.3}$$

For comparison and estimation purposes, these estimated costs are normalized by dividing by the engineer's estimate. For the hiring firm, $\hat{t} = \hat{c}_H^B$ is the estimated payment for horizontally subcontracted work. The estimated markup on horizontally subcontracted work is then calculated as the difference between the hiring firm's estimated cost on horizontally subcontracted items and the subbing firm's estimated cost on the same items, $\hat{t} - \hat{c}_S^B$.

This cost estimate is measured with error for several reasons. First, prime contractors typically mark up their prices above their base cost of the project to earn positive profit. Since Caltrans does not include a separate category for this profit markup, prime contractors must distribute any markup over cost across the item bids so that on average $p_j q_j$ is greater than the actual cost of producing item j. In addition, recognizing that contractual incompleteness often results in changes to the pre-specified quantities q_j, prime contractors have incentive to skew their item-level bids to maximize their expected profits.[4] Bid skewing is a source of error since it distorts the item-level bids so that they are not directly proportional to their costs. To minimize the incentives for bid skewing, Caltrans reserves the right to reject any bid that it considers too unbalanced.[5] Finally, as mentioned above, since subcontractors that are listed as performing only a "portion" of a particular task are treated as producing the entire task, $\hat{c}_i^B$ will tend to be overestimated and $\hat{c}_i^A$ will tend to be underestimated.

The 75 auctions include 542 total bids made up of 25,944 item bids by 202 unique prime contractors. Of the 542 bids, 231 are submitted by firms that either hire a rival as a subcontractor (i.e., bids by hiring firms) or are listed as a subcontractor for a rival (i.e., bids by subbing firms). In total, I observe 155 unique project-pairs, where a "pair" is a single subcontracting arrangement between a hiring prime and a subbing prime.

Table 4.1 shows summary statistics at the project level. An important aspect of Table 4.1 is the large variation in the size of the included projects. The engineer's estimates range from \$78,000 to \$20.8 million. Moreover, the least complex project lists only 4 tasks, and the most complex project lists 221 individual tasks. To make comparisons across projects, it is useful to normalize the bids by dividing by the engineer's estimate.[6] Table 4.1 shows that the average winning bid is about 84% of the engineer's estimate, and the average difference between the highest bid and the lowest bid is about 35% of the engineer's estimate. A typical project in this sample has 7 prime bidders and an 85% chance of a winning bid below the engineer's estimate. Nearly half (36 out of 75 projects)

[4] See Athey and Levin (2001), Bajari, Houghton, and Tadelis (2006), and Miller (2010) for more on bid skewing.

[5] In my sample, Caltrans invalidates bids very infrequently. The few bids in my data where this occurs are dropped.

[6] Regressing the log winning price on the log engineer's estimate yields a coefficient estimate of 1.001 and an R-squared of 0.984. This result suggests that the engineer's estimate explains about 98% of the variance of the winning bid across projects. Increasing the engineer's estimate by 1% increases the winning price by 1%.

Table 4.1: Project-level summary statistics

Variable	Mean	Std. Dev.	Min	Max
Engineer's estimate	2,845,640	4,471,175	78,000	20,840,000
Winning price	2,337,275	3,585,549	43,806.5	15,700,000
Bid range	704,210	999,787	39,504	4,602,881
Cash on table	93,697	163,962	943	1,125,431
Normalized winning price	0.843	0.148	0.474	1.29
Normalized bid range	0.356	0.202	0.030	1.18
Normalized cash on table	0.044	0.041	0.002	0.224
Winning bid < engineer's est.	0.853	0.356	0	1
Number of prime bidders	7.23	2.49	2	14
Number of items	49.5	41.2	4	221
Number of pairs	2.07	1.52	1	8
Number of subbing-dominant pairs	1.19	1.01	0	4
Number of hiring-dominant pairs	0.880	1.28	0	7
Has subbing-dominant pair	0.760	0.430	0	1
Has hiring-dominant pair	0.533	0.502	0	1
Number of projects	75			
Independent firm wins†	44			
Hiring firm wins†	17			
Subbing firm wins†	16			

†Does not sum to 75 because two winning firms are both hiring primes and subcontracting primes. Where indicated, bids are normalized by dividing by the engineer's estimate. Bid range measures the difference between the highest losing bid and the winning bid. Cash on table measures the difference between the lowest losing bid and the winning bid.

involve more than one horizontally subcontracting pair. The average number of pairs per project in this sample is just over two. The most common pair type is the subbing-firm-dominant pair in which the subbing firm undercuts its hiring firm. 76% of the sampled auctions contain at least one subbing-firm-dominant pair, while 53% contain at least one hiring-firm-dominant pair.

Table 4.2 shows summary statistics at the pair level. Subbing-firm-dominant pairs make up a small majority (57%) of the sampled pairs. For the average pair, the subbing firm bids lower (96% of the engineer's estimate versus 99% for the hiring firm) and is about half a firm lower in rank. On average, the estimated markup on horizontally subcontracted work is about 1.8% of the engineer's estimate. Since the estimated markup is occasionally negative, Table 4.2 also reports the summary statistics for the absolute value of the markup. On average, the difference between a hiring firm's

Table 4.2: Pair-level summary statistics

Variable	Mean	Std. Dev.	Min	Max
Subbing-firm-dominant pair	0.574	0.496	0	1
Total bid of hiring firm, p_H	0.990	0.198	0.474	1.598
Total bid of subbing firm, p_S	0.959	0.183	0.482	1.511
Bid difference, $p_H - p_S$	0.031	0.166	-0.450	0.686
Abs. value of bid diff., $\lvert p_H - p_S \rvert$	0.126	0.113	0.001	0.686
Bid rank of hiring firm	4.54	2.523	1	12
Bid rank of subbing firm	4.08	2.925	1	13
Markup $\hat{t} - \hat{c}_S^B$	0.018	0.048	-0.10	0.37
Abs. value of markup, $\left\lvert \hat{t} - \hat{c}_S^B \right\rvert$	0.026	0.044	0	0.37
Percent of bid hor. subcontracted, $\hat{t}/p_H$	0.228	0.200	0.001	0.95
Observations	155			

All bids are normalized by dividing by the engineer's estimate. The markup is calculated as the difference between the sum of hiring firm's item bids on horizontally subcontracted items and the sum of the subbing firm's item bids on the corresponding items. The percent of bid horizontally subcontracted is the sum of the horizontally subcontracted item bids of the hiring firm divided by the hiring firm's total bid. The bid rank represents the position of a firm's bid relative to all other bids for the same project, where bid rank = 1 denotes the winning prime.

estimated cost on horizontally subcontracted work and its subcontracting rival's bid on the same items is 2.6% of the engineer's estimate. The final summary statistic presented in Table 4.2 is the percentage of the hiring firm's bid which is horizontally subcontracted. On average, between one-fifth and one-fourth of the hiring firm's bid is horizontally subcontracted to a rival prime contractor.

To better understand the differences between subbing-firm-dominant pairs and hiring-firm-dominant pairs, Table 4.3 presents the pair-level summary statistics broken into these two groups. In many ways, the two pair types look similar; for example, the higher priced firm bids just above the engineer's estimate on average, and the lower priced firm typically bids about 10% below the engineer's estimate. Although both firms typically rank about half a firm better in subbing-firm-dominant pairs, the higher priced firm is usually ranked nearly three spots worse than the lower priced firm in both pair types. In addition, the percent of the hiring firm's bid that is horizontally subcontracted is essentially indistinguishable between the two groups. The type of projects on which the two types of pairs bid are also generally similar. The average number of prime bidders is about eight and the average number of individual project items is around fifty. However, one difference is very striking between the two groups: the estimated markup on horizontally subcontracted work is much higher on average for subbing-firm-dominant pairs. In addition, the average engineer's estimate is about \$800,000 higher for subbing-firm-dominant pairs, suggesting subbing-firm-dominant pairs might be more likely to form in higher-value projects.

Table 4.3: Pair-level summary statistics by pair type

Variable	Hiring-firm-dominant pair Mean	(Std. Dev.)	Subbing-firm-dominant pair Mean	(Std. Dev.)
<u>Pair Characteristics</u>				
Total bid of hiring firm, p_H	0.901	(0.155)	1.05	(0.201)
Total bid of subbing firm, p_S	1.013	(0.192)	0.919	(0.166)
Bid difference, $p_H - p_S$	-0.112	(0.103)	0.136	(0.119)
Bid rank of hiring firm	3.12	(2.20)	5.58	(2.22)
Bid rank of subbing firm	5.97	(3.13)	2.69	(1.76)
Markup, $\hat{t} - \hat{c}_S^B$	0.002	(0.028)	0.030	(0.056)
Abs. value of markup, $\left\|\hat{t} - \hat{c}_S^B\right\|$	0.018	(0.021)	0.032	(0.054)
Percent of bid hor. subcontracted, $\hat{t}/p_H$	0.228	(0.181)	0.228	(0.214)
<u>Project Characteristics</u>				
Engineer's estimate	2,298,727	(3,057,545)	3,101,517	(4,428,293)
ln(engineer's estimate)	13.96	(1.15)	14.13	(1.30)
Number of items	47.56	(25.53)	51.93	(39.02)
Number of prime bidders	8.38	(3.12)	7.51	(2.00)
Observations	66		89	

All bids are normalized by dividing by the engineer's estimate. The markup is calculated as the difference between the sum of hiring firm's item bids on horizontally subcontracted items and the sum of the subbing firm's item bids on the corresponding items. The percent of bid horizontally subcontracted is the sum of the horizontally subcontracted item bids of the hiring firm divided by the hiring firm's total bid. The bid rank represents the position of a firm's bid relative to all other bids for the same project, where bid rank = 1 denotes the winning prime.

Chapter 5

Empirical Methods and Results

5.1 Testing Proposition 3.2.1

Proposition 3.2.1 predicts that conditional on a subcontract, the negotiating firms' relative costs on non-subcontracted work (part A) determines which firm is the lower bidder. To test whether this result holds in the data, I compare the relative costs of non-subcontracted work and the relative prices by pair type. Table 5.1 breaks out the subcontracting pairs by relative price and relative cost. The grayed cells correspond to the pairs that behave in a manner consistent with Proposition 3.2.1. For 85 pairs, the subcontracting prime has both the lower price and a lower estimated cost on the non-subcontracted work. For 62 pairs, the hiring prime has both the lower price and the lower estimated cost on the non-subcontracted work. So for 147 out of 155 pairs, or 94.2% of pairs, the prime with the lower non-subcontractable cost also submits the lower price.

This result, while consistent with the theory, is unremarkable if the non-subcontractable part constitutes nearly all of the bid, so Table 5.1 also lists the mean percentages of the the hiring firms' bids which are not horizontally subcontracted. On average, non-horizontally-subcontracted work makes up 77% of the hiring firm's bid. While not conclusive evidence that costs on non-subcontractable work determine relative bids, it is suggestive that the firm with the lower costs on only 77% of the project submits the lower bid for 94% of pairs.

If the non-subcontracted work is the primary source of variation in costs across firms, then this variation will cause the cost on non-subcontracted work to be the primary driver of variation in prices as well. To address this concern, Table 3.2.1 presents the ratio of the coefficients of variation

Table 5.1: Examining Proposition 3.2.1: the low-cost firm on non-subcontracted work is the pair's low bidder

	S is low price	H is low price	Percent matching model
S is low cost on part A	85	4	95.5%
Mean $\hat{c}_H^A/p_H$	0.787	0.697	0.783
Relative CV	0.307	0.428	
H is low cost on part A	4	62	93.9%
Mean $\hat{c}_H^A/p_H$	0.439	0.777	0.757
Relative CV	0.980	0.330	
Percent matching model	95.5%	93.9%	94.2%
Mean $\hat{c}_H^A/p_H$	0.772	0.772	0.772

The observation level is a horizontally subcontracting pair (N = 155). Firm H is the hiring prime contractor; firm S is the subcontracting prime. Part A is defined as the part of the contract which is not horizontally subcontracted. Mean $\hat{c}_H^A/p_H$ denotes the mean percentage of the hiring firms' bids which are not horizontally subcontracted. Relative CV is the ratio of the coefficient of variation of the firms' bids on non-subcontracted work to the coefficient of variation of the firms' bids on horizontally subcontracted work, where the bids for each firm have been normalized by the engineer's estimate.

of the costs of the negotiating firms on both project parts, denoted the "relative CV." Formally, the relative CV is calculated as

$$Relative\ CV = \frac{\sigma_{c^A}/\mu_{c^A}}{\sigma_{c^B}/\mu_{c^B}}, \tag{5.1}$$

where σ_{c^j}/μ_{c^j} is the coefficient of variation of the costs of both hiring and subbing primes on part $j \in \{A, B\}$. The relative CV is less than one in all four categories in Table 3.2.1, indicating that costs on subcontracted work vary more than costs on non-subcontracted work. Consequently, large variations in cost on non-subcontracted work are unlikely to explain why prices among horizontally subcontracting firms are primarily driven by the cost differences in non-subcontractable work. As Table 5.1 shows, the eight pairs that are not consistent with Proposition 3.2.1 have a much lower mean non-horizontally subcontracted percentage. This discrepancy could be due to any of the measurement error discussed previously or to behavior that is not captured by a complete-information model. Since item-level cost is measured with error while price is not, I use the relative prices of the subcontracting pairs to identify the pair types in the remaining analysis.

5.2 Effect of pair type on winning price

The model predicts that the only motivation for a horizontal subcontract by a subbing-firm-dominant pair is to soften competition and raise the price. Intuitively, the reason for this is that since the subcontract is in a losing bid, no efficiency gains can be realized. Subbing-firm-dominant pairs should therefore charge higher markups on subcontracted work to soften competition, generating higher prices. Conversely, horizontal subcontracts by hiring-firm-dominant pairs could be intended either to improve the competitive position of the hiring firm or to soften competition by raising the opportunity cost of the subcontractor. On average, subbing-firm-dominant pairs should produce higher prices and markups than hiring-firm-dominant pairs. To test the effect of pair type on the price bid by the winning firm, I begin by estimating

$$WinningPrice_h = \beta_1 I(p_S < p_H)_h + \beta_2 I(p_H < p_S)_h + \boldsymbol{\beta X}_h + \epsilon_h, \tag{5.2}$$

where h indexes a horizontally subcontracting pair, and the winning price is normalized by the engineer's estimate. $I(p_S < p_H)_h$ is an indicator variable taking a value of one for subbing-firm-dominant pairs. Likewise, $I(p_H < p_S)$ is an indicator variable taking a value of one for hiring-firm-dominant pairs. The vector X includes the number of items in the project as a proxy for the complexity of the project. Since some projects have multiple pairs, the standard errors are clustered by project. The constant term is suppressed in equation (5.2), so the estimates of β_1 and β_2 represent the expected normalized price of subbing-firm-dominant pairs and hiring-firm-dominant pairs, respectively, when $\boldsymbol{X} = \mathbf{0}$. The model predicts that $\beta_1 > \beta_2$. The expected coefficient on the number of items is positive, since additional complexity should increase the cost of producing the project.

Table 5.2 presents the results of estimating Equation (5.2). Column (1) presents the simple form of the regression comparing the two main pair types. The average winning price is 85.9% of the engineer's estimate for subbing-firm-dominant pairs and 81.1% of the engineer's estimate for hiring-firm-dominant pairs.[1] The implication that subbing-firm-dominant horizontal subcontracts cause 5.9% higher winning prices than hiring-firm-dominant pairs is non-trivial: Bajari et al. (2006) report that profit margins for the highway construction industry is generally below 4%. The estimated coefficient on the number of items is positive as expected, but small and not statistically significant,

[1] The total estimated contribution of the mean number of items to the winning price is only 0.2%.

suggesting that normalizing the winning price by the engineer's estimate accounts for most of the additional costs caused by increased complexity.

Column (2) separates hiring-firm-dominant pairs into two categories: pairs for which the hiring firm wins the auction, and pairs which lose the auction to an independent firm. As described in section 3.4, subbing-firm-dominant pairs are predicted to produce the highest prices, and hiring-firm-dominant pairs which lose to an independent firm are predicted to produce the lowest prices. The regression results provide some evidence for this prediction; subbing-firm-dominant pairs produce the highest expected winning price of the three groups at 85.9% of the engineer's estimate. The winning price of auctions with subbing-firm-dominant pairs is about 3% higher than the winning price of auctions won by hiring firms, and 6.8% higher than the winning price of auctions with hiring-firm-dominant pairs that lose to an independent firm. The difference between the coefficients for hiring-firm-dominant pairs that lose to an independent firm and subbing-firm-dominant pairs is statistically significant. The coefficient on hiring-firm-dominant pairs that win the auction is not statiscally different from the coefficients on either of the other pair types. The lack of statistical significance could be due to small cell size (only 17 pairs are in this category) or to the indeterminant nature of these pairs; the theory cannot identify whether they should be more like the competition-softening pairs or more like the cost-saving pairs.

Column (3) adds the number of competing primes as an explanatory variable to control for the overall level of competition faced by the pair. The sign on the number of bidders is negative as expected (though not statistically significant), suggesting that additional competition lowers the winning price. The price difference between the most and least competitive pair types falls slightly from 5.5% of the engineer's estimate to 4.7% of the engineer's estimate, suggesting that the competition softening effects of horizontal subcontracting are more common in auctions with fewer competitors.

A potential problem with estimating equation (5.2) at the pair level is that it does not account for the potential interaction of pairs within projects. Since there are 155 horizontally subcontracting pairs distributed across a total of 75 projects, many projects involve more than one pair. Pairs within the same auction have the same dependent variable. To address this issue, I estimate

$$WinningPrice_a = \beta_0 + \beta_1 I(S \text{ wins})_a + \beta_2 I(H \text{ wins})_a + \boldsymbol{\beta X}_a + \epsilon_a, \tag{5.3}$$

where a indexes the auctions, and $I(i \text{ wins})$ is an indicator variable taking a value of one when firm i wins auction a. The vector $\boldsymbol{X}$ again includes project characteristics such as the number of items and the number of prime contractors. The advantage of estimation at the auction level is the independence of the observations. The disadvantages of this approach include the reduction of the sample to only 75 observations and a cruder measure of the effect of pair type on the winning price.

Table 5.3 presents the results of estimating equation (5.3). Column (1) presents the baseline regression with the number of items as the only included project characteristic. Compared to auctions won by an independent (non-horizontally subcontracting) firm, auctions won by subbing primes have a price that is 4.1 percentage points higher. Since the standard error is large, this coefficient estimate is weak evidence for the competition softening effect of subbing-firm-dominant pairs. The coefficient on auctions won by hiring firms is very small and negative, suggesting there is probably very little difference in the price the buyer pays when an independent firms wins the auction verses when a hiring firm wins. This lack of difference is not inconsistent with the model, since the price effect of hiring-firm-dominant pairs is ambiguous. Column (2) adds a control for the number of bidders. The estimated coefficient on the number of primes has the expected negative sign, but is not statistically significant. The coefficients on the other regressors do not change much in response to the addition of this variable.

Column (3) in Table 5.3 presents the results of estimating

$$WinningPrice_a = \beta_0 + \beta_1 N(p_S < p_H)_a + \beta_2 N(p_H < p_S)_a + \boldsymbol{\beta X}_a + \epsilon_a, \tag{5.4}$$

where $N(p_S < p_H)_a$ is the number of subbing-firm-dominant pairs and $N(p_H < p_S)_a$ is the number of hiring-firm-dominant pairs in auction a. The estimated coefficients suggest that each additional subbing-firm-dominant pair raises the winning price by about 2 percentage points, and each additional hiring-firm-dominant pair lowers the auction price by slightly more than 1 percentage point. Again, the signs on the estimated coefficients are consistent with the model's predictions, but the results are not statistically significant.

5.3 Effect of pair type on the markup on horizontally subcontracted work

In this section, I consider how pair type affects the markup on horizontally subcontracted work. According to the model, the horizontally subcontracting firms raise prices by raising each other's costs through the subcontract payment, t. Therefore, the markup on horizontally subcontracted work, $t - c_S^B$, should be higher for pairs that are subcontracting to soften competition relative to pairs that are subcontracting to lower costs. To test this implication, I estimate

$$\left(\hat{t}_j - \hat{c}_{Sj}^B\right)_h = \beta_0 + \beta_1 I\left(p_S < p_H\right)_{hj} + \epsilon_{hj}, \tag{5.5}$$

where j indexes a project-item and h indexes the horizontally subcontracting pair. The dependent variable, $\left(\hat{t}_j - \hat{c}_{Sj}^B\right)_h$ is the estimated item-level markup, calculated as the difference between a hiring firm's reported bid on a horizontally subcontracted item and the reported bid from the subbing firm that it hires to perform that task. Since the regression is estimated at the item level, the item bids are normalized by dividing by the average bid for the corresponding task across all of the projects in the sample. The average bid on a task is likely to be a better reflection of the true cost of supplying the item than the engineer's estimate, which reflects Caltran's estimated cost across *all* items in a particular project. $I(p_S < p_H)$ is an indicator variable for subbing-firm-dominant pairs. The expected sign on β_1 is positive since subbing-firm-dominant pairs are expected to soften competition more than hiring-firm-dominant pairs.

Table 5.4 presents the results from estimating equation (5.5). Column (1) shows that subbing-firm-dominant pairs mark up horizontally subcontracted items about 11.2 percentage points more than hiring-firm-dominant pairs. This result is statistically significant and consistent with the model's prediction that subbing-firm-dominant pairs use the horizontal subcontract to raise their rivals' costs. Column (2) adds a variable for the price difference (in absolute value) between the hiring and subbing firms. This variable is intended to capture the extent to which the markup could be due to underlying cost differences rather than to strategic cost increases. The coefficient on the pair type is substantially the same in the second column, suggesting that the strategic hypothesis is a better explanation for the higher markup by subbing-firm-dominant pairs. However, the coefficient on the price difference is positive and statistically significant suggesting that higher price differences are associated with higher markups.

Since the markup on horizontally subcontracted work is likely to be correlated across item bids for each pair, a better metric of the markup is the difference between the summed bids on *all* of the pair's horizontally subcontracted work. The estimated markup for each pair h then becomes $\left(\hat{t} - \hat{c}_S^B\right)_h$, where $\hat{t}$ and $\hat{c_S^B}$ are calculated according to equation (4.3) and normalized by dividing by the engineer's estimate. Using this markup, I estimate

$$\left(\hat{t} - \hat{c}_S^B\right)_h = \beta_0 + \beta_1 I\left(p_S < p_H\right)_h + \boldsymbol{\beta} \boldsymbol{X}_h + \epsilon_h. \tag{5.6}$$

The disadvantages of this approach are the reduction of the number of observations from 499 to 155 and a cruder normalization of costs using the engineer's estimate. The variable of interest is still $I(p_S < p_H)$ as described above. The vector $\boldsymbol{X}$ includes the percentage of the hiring firm's bid that is horizontally subcontracted. This variable is a necessary control since horizontal subcontracts over a larger fraction of the project should have a larger markup relative to the engineer's estimate on average, regardless of the strategic interaction.

Column (1) in Table 5.5 shows the results of estimating equation (5.6). As in the item-level regressions, subbing-firm-dominant pairs have a higher markup on average than hiring-firm-dominant pairs. The additional markup is about 2.8% of the engineer's estimate, translating to an additional $78,500 at the mean engineer's estimate. The estimated coefficient on the percentage of the hiring firm's bid horizontally subcontracted is positive as expected. Columns (2) and (3) each add a control for the cost differences between the firms in each pair; column (2) controls for the absolute value of the difference in the estimated costs of the non-subcontracted work, and column (3) controls for the absolute value of the difference of the total bids of the firms in a pair. The estimated coefficient on subbing-firm-dominant pairs does not change much across the three columns, suggesting that underlying cost differences cannot fully explain the additional markup by subbing-firm-dominant pairs. The combined results of Tables 5.4 and 5.5 provide robust evidence that the subcontracting firm uses the markup on horizontally subcontracted work to raise its rival's cost when it expects to undercut its hiring firm.

5.4 Effect of markup on price

Tables 5.4 and 5.5 suggest that larger price differences are associated with larger markups on subcontracted work. In this section, I evaluate the link between the markup on subcontracted work and the bid submitted by the lower priced firm in the pair. If the firms negotiate a high markup to raise the cost of the pair's non-dominant firm, then the dominant firm should respond to the resulting decline in competition by increasing its price. If instead, the firms are trying to take advantage of cost efficiencies to improve the competitive position of the dominant firm, then the markup on horizontally subcontracted work should be small to enable the dominant firm to lower its price. To test this hypothesis, I estimate

$$DominantBid_h = \beta_0 + \beta_1 \left(\hat{t} - \hat{c}_S^B\right)_h + \boldsymbol{\beta X}_h + \epsilon_h, \tag{5.7}$$

where $DominantBid_h$ is defined as the total bid of the lower priced firm of pair h, normalized by the engineer's estimate. The explanatory variable of interest is the markup, $\left(\hat{t} - \hat{c}_S^B\right)_h$, normalized by the engineer's estimate. The vector $\boldsymbol{X}$ includes the number of items and, in some specifications, an indicator for subbing-firm-dominant pairs.

Since higher markups are associated with higher prices, the expected sign of β_1 is positive. The markup is a better measure of the competitive motivation of the subcontracting pairs than pair type, which combines cost-reducing hiring-firm-dominant pairs with cost-raising hiring-firm-dominant pairs into a single type. If the effect of the markup on the dominant firm's bid is independent of the pair's type as the model predicts, then the coefficient on the subbing-firm-dominant-pair indicator variable should be be zero.

Table 5.6 presents the results from estimating equation (5.7). Column (1) displays the estimates with the number of items as the only covariate. The estimates show that increasing the markup on subcontracted work by \$1 increases the price of the dominant pair member by 82 cents. This result is consistent with the story that firms use the markup on subcontracted work to raise the their rivals' costs. Column (2) of Table 5.6 adds the indicator variable for subbing-firm-dominant pairs. The coefficient on the markup is substantively unchanged between columns (1) and (2). In addition, the estimated coefficient of subbing-firm-dominant pairs is essentially zero, indicating that once the markup is controlled for, subbing-firm-dominant pairs and hiring-firm-dominant pairs are indistinguishable.

Table 5.2: The effect of pair type on the winning price (pair level)

	(1)	(2)	(3)
Subbing-firm-dominant pair, $I(p_S < p_H)$	0.859***	0.859***	0.901***
$n = 89$	(0.0356)	(0.0357)	(0.0656)
Hiring-firm-dominant pair, $I(p_H < p_S)$	0.811***		
$n = 66$	(0.0397)		
Hiring-firm dominant, hiring firm wins		0.834***	0.872***
$n = 17$		(0.0538)	(0.0658)
Hiring-firm dominant, independent firm wins		0.804***	0.854***
$n = 49$		(0.0394)	(0.0644)
Number of prime bidders			−0.00526
			(0.00690)
Number of Items	0.00457	0.00458	−0.00103
	(0.0508)	(0.0510)	(0.0491)
R^2	0.971	0.971	0.971
F-statistic	689.6	525.8	416.1
Observations	155	155	155

F-test of coefficient equality

Null Hypothesis		F-Statistic	
Subbing dominant=Hiring dominant	2.80$^+$		
Subbing dominant=Hiring dominant, H wins		0.38	0.50
Hiring dominant, H wins=Hiring dominant, I wins		0.56	0.18
Subbing dominant=Hiring dominant, I wins		3.16$^+$	2.61

The observation level is a horizontally subcontracting pair. The dependent variable is the winning price of the pair's auction, divided by the engineer's estimate. The constant term is suppressed in all columns. Number of items is divided by 100 to display its estimated coefficient. Standard errors (in parentheses) are clustered by project. $^+$, *, **, *** represent significance at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

Table 5.3: The effect of pair type on the winning price (project level)

	(1)	(2)	(3)
Subbing firm wins auction	0.0412	0.0395	
	(0.0467)	(0.0467)	
Hiring firm wins auction	−0.00381	−0.00675	
	(0.0442)	(0.0457)	
Number of subbing-firm-dominant pairs			0.0196
			(0.0197)
Number of hiring-firm-dominant pairs			−0.0120
			(0.0108)
Number of prime bidders		−0.00358	−0.00295
		(0.00662)	(0.00741)
Number of items	0.00713	0.00499	0.00734
	(0.0343)	(0.0341)	(0.0327)
Constant	0.832***	0.860***	0.848***
	(0.0291)	(0.0576)	(0.0507)
R^2	0.0147	0.0182	0.0378
F-statistic	0.303	0.255	0.667
Observations	75	75	75

The observation level is an auction. The dependent variable is the winning price of the auction, normalized by the engineer's estimate. In columns (1) and (2), the omitted category is "independent firm wins auction." The number of items is divided by 100 to display its estimated coefficient. Robust standard errors are reported in parentheses. $^{+}$, *, **, *** represent significance at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

Table 5.4: The effect of pair type on the markup (pair-item level)

	(1)	(2)
Subbing-firm-dominant pair, $I\left(p_S < p_H\right)$	0.112**	0.115**
	(0.0415)	(0.0395)
Price difference, $\lvert p_H - p_S \rvert$		0.423*
		(0.188)
Constant	0.0622*	0.0118
	(0.0285)	(0.0367)
R^2	0.0163	0.0266
F-statistic	7.279	5.099
Observations	499	499

The dependent variable is the difference between a hiring firm's bid on a horizontally subcontracted item and its subcontractor's corresponding bid on the same item, $\left(\hat{t}_j - \hat{c}^B_{Sj}\right)$. Bids on each item j have been normalized by dividing by the average bid on that task across all projects. The price difference is the absolute value of the difference between the hiring firm's total bid and the subbing firm's total bid, normalized by the engineer's estimate. The observation level is a pair-item. Only items which are horizontally subcontracted are included in this regression. The omitted category is "hiring-firm-dominant pair, $I(p_H < p_S)$." Standard errors are clustered by project. $^{+}$, *, **, *** represent significance at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

Table 5.5: The effect of pair type on the markup (pair level)

	(1)	(2)	(3)
Subbing-firm-dominant pair, $I(p_S < p_H)$	0.0276^{***}	0.0278^{***}	0.0257^{***}
	(0.0072)	(0.0072)	(0.0069)
Percent of bid hor. subcontracted, $\hat{t}/p_H$	0.0680	0.0733^{+}	0.0716^{+}
	(0.0432)	(0.0435)	(0.0427)
Cost diff. on non-hor. subcontracted work, $\left\|\hat{c}_H^A - \hat{c}_S^A\right\|$		0.0688^{+}	
		(0.0380)	
Price difference, $\|p_H - p_S\|$			0.0768^{*}
			(0.0292)
Constant	-0.0135	-0.0229^{+}	-0.0228^{*}
	(0.0095)	(0.0123)	(0.0100)
R^2	0.164	0.190	0.196
F-statistic	7.487	5.197	5.519
Observations	155	155	155

The dependent variable is the difference between the sum of the bids of the hiring firm on horizontally subcontracted work and the sum of its subcontractor's bids on the same items, $\hat{t} - \hat{c}_S^B$, divided by the engineer's estimate. "Percent of bid horizontally subcontracted" measures the proportion of the hiring firm's bid that is horizontally subcontracted. "Cost difference on non-horizontally subcontracted work" is the difference between the sum of a hiring firm's bids on non-horizontally subcontracted work and the sum of its subcontractor's bids on the same items, all divided by the engineer's estimate. The price difference is the absolute value of the difference between the hiring firm's total bid and the subbing firm's total bid, normalized by the engineer's estimate. The observation level is a pair. The omitted category is "hiring-firm-dominant pair, $I(p_H < p_S)$." Standard errors (in parentheses) are clustered by project. $^{+}$, *, **, *** represent significance at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

Table 5.6: The effect of markup on the pair's dominant bid by pair type

	(1)	(2)
Markup on hor. subcontracted work, $\hat{t} - \hat{c}_s^B$	0.822^{*}	0.837^{*}
	(0.327)	(0.363)
Subbing-firm-dominant pair, $I\left(p_S < p_H\right)$		-0.00478
		(0.0346)
Number of Items	-0.0225	-0.0218
	(0.0527)	(0.0522)
Constant	0.908^{***}	0.910^{***}
	(0.0386)	(0.0424)
R^2	0.0649	0.0651
F-statistic	3.875	2.690
Observations	155	155

The dependent variable is the normalized price of pair h's low bidder, $DominantBid_h = \min\{p_H, p_S\}_h / Eng.Estimate_h$. The markup is calculated as the sum of the hiring firm's bid on all horizontally subcontracted work minus the sum of the subbing firm's bid on the same tasks, all normalized by the engineer's estimate: $(\hat{t} - \hat{c}_S^B)/Eng.Estimate$. The number of items is divided by 100 to display its estimated coefficient. Standard errors (in parentheses) are clustered by project. $^{+}$, *, **, *** represent significance at the 0.10, 0.05, 0.01, and 0.001 levels, respectively.

Chapter 6

Discussion and Conclusion

This paper develops and tests a model of horizontal subcontracting in a procurement setting. The model establishes two main motivations for horizontal subcontracting: reducing costs by hiring a lower cost rival and reducing competition by raising rivals' costs. The model identifies two main types of horizontal subcontracts: one in which the subbing firm underbids the hiring firm (subbing-firm-dominant) and one in which the hiring firm underbids its subcontractor (hiring-firm-dominant). The model predicts that subbing-firm-dominant subcontracts are primarily motivated by competition reduction, because any cost savings from the subcontract will not be realized. In contrast, hiring-firm-dominant subcontracts may have either motivation.

Analysis of bids on projects with horizontal subcontracting from the California Department of Transportation supports this theory; strategically-motivated subbing-firm-dominant pairs raise auction prices by 5.9% relative to hiring-firm-dominant pairs. Moveover, regardless of pair type, I find that higher markups on horizontally subcontracted work are associated with higher bids from the subcontracting pair's more competitive firm. These empirical results are suggestive that some (but not all) horizontal subcontracts soften competition by artifically raising the costs of competiting contractors. However these results should be treated with caution. Since the data for this paper do not include projects for which there is no horizontal subcontracting, there is insufficient evidence to conclude that strategic horizontal subcontracts raise prices relative to counterfactual auctions without any horizontal subcontracts (or that efficiency-driven horizontal subcontracts lower prices relative to the same counterfactual auctions).

Understanding how contractors use horizontal subcontracts to manipulate prices is important for formulating an appropriate policy response to these unique subcontracts. Even though procurers who are suspicious of anti-competitive motives may wish to prohibit horizontal subcontracting, a ban is unlikely to be the appropriate response for a couple of reasons. First, in addition to discouraging the formation of strategic price-increasing subcontracts, a ban on horizontal subcontracting would also discourage the formation of efficient cost-reducing horizontal subcontracts. Second, a ban on horizontal subcontracting would reduce competition in either the subcontract market or the procurement auction, because firms that would have been able to participate in both the upstream (subcontracting) and the downstream (prime) market must now choose only one of these markets. If the resulting reduction in competition has a significant effect on prices, then a ban on horizontal subcontracts might inadvertently raise prices.

A better response to horizontal subcontracting may be to restrict firms' ability to mark up subcontracted work. This approach has the advantage of preventing strategic price increases without restricting the formation of efficiency-driven horizontal subcontracts. However, in order for this policy to have the intended effect on prices, procurers must be able to verify the actual production costs of the subcontracting firm. If costs are not verifiable, then firms have incentive to hide subcontract markups. Moreover, if procurers identify costs—and thus subcontract markups—solely by comparing the bids of involved firms, then the negotiating firms could coordinate their bids to prevent accusations of anti-competitive behavior. This coordination may facilitate further bid-rigging or other collusive behavior. Finally, if costs are verifiable, a policy that limits subcontract markups is only appropriate if the bureaucratic costs of ensuring compliance do not exceed the gains from limiting strategic price increases.

Several interesting questions about horizontal subcontracting are left for future research. First, adding uncertainty by endogenizing the number of bidders is important for considering the subcontracting firm's decision about whether it wants to compete in the auction as a prime bidder or stay out of the auction and operate only as a subcontractor. Moreover, the potential for entry by independent firms limits the incentives to soften competition with a horizontal subcontract.

Second, endogenizing the roles of negotiating and independent primes could shed further light on the motivations behind observed horizontal subcontracts. Depending on the motive behind the horizontal subcontract, firms may prefer to work with either a weak competitor who has particularly low costs on some tasks, or a strong competitor who would otherwise limit their ability to charge a higher price.

Appendix A

Proofs

A.1 Proof of Proposition 3.2.1

In the case in which firm 2 hires firm 1 (formally, "1 is S"), firm H's cost is $\tilde{c}_2 = c_2^A + t$, and firm S cost is $c_1 = c_1^A + c_1^B$ if $p_I < p_2$ and $\tilde{c}_1 = c_1^A + t$ if $p_I > p_2$. Given $c_1^A < c_2^A$ and $t > c_1^B$ when firm 2 hires firm 1, it follows that $\tilde{c}_2 > \tilde{c}_1 > c_1$. Consequently, regardless of the strength of firm I, firm 1 bids below firm 2 in the auction subgame.

In the case in which firm 1 hires firm 2 (formally, "2 is S"), firm H's cost is $\tilde{c}_1 = c_1^A + t$. If firm I's cost is high (i.e., $c_I > \tilde{c}_1$), then firm S's cost is $\tilde{c}_2 = c_2^A + t$. Since, by definition, $c_1^A < c_2^A$, it follows that $\tilde{c}_1 < \tilde{c}_2$, consequently firm 1 bids below firm 2 in the auction subgame. If instead, firm I's cost is low (i.e., $c_I < \tilde{c}_1$), then firm S's cost is $c_2 = c_2^A + c_2^B$. The best responses of the higher cost firms are to submit their most competitive bid.[1] As a result, the firms should choose $t = c_2^B$ so that $\tilde{c}_1 < c_2$ and firm 1 bids a lower price than firm 2 in the auction subgame.

[1]Suppose instead that firms 1 and 2 negotiate $t = c_2^B + \gamma$ where γ is a nontrivial positive number. firm 1 submits the bid $p_1 = \tilde{c}_1 > c_1^A + c_2^B$. Firm I's best response it to undercut firm 1 by bidding $p_I = p_1 - \epsilon > c_1^A + c_2^B$. Firm 1 and firm 2 would have preferred to reduce t so that they could undercut p_I and win the auction. Consequently, in Stage 2, given that firms 1 and 2 have chosen "2 is S", they should jointly choose $t = c_2^B$.

A.2 Proof of Proposition 3.3.1

A.2.1 Solving Case 1

Let $c_1^B < c_2^B$ and $c_I < c_1 < c_2$. If firms 1 and 2 choose no subcontracting, then firm I wins the auction with $p_I = c_1 - \epsilon$; firm 1 bids c_1; and firm 2 bids c_2. Firm I earns positive profit equal to $c_1 - c_I - \epsilon$; firms 1 and 2 earn zero profit.

If firms 1 and 2 instead choose "1 is S" so that firm 2 hires firm 1, then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. Since $t > c_1^B$, firm 2 cannot undercut firm I, so firm 1's low cost competitor is firm I. By equation (3.2), firm 1's cost is $\tilde{c}_1 = c_1$. Firm I wins with price $p_I = c_1 - \epsilon$, firm 1 bids c_1, and firm 2 bids $\tilde{c}_2$. Again, firm I earns positive profit equal to $c_1 - c_I - \epsilon$, and firms 1 and 2 earn zero profit.

Finally, if firms 1 and 2 choose "2 is S" so that firm 1 hires firm 2, then firm 1's cost rises to $\tilde{c}_1 = c_1^A + t$. Since $t > c_2^B$, firm 1 still cannot undercut firm I, so firm 2's low cost competitor is firm I. By equation (3.2), firm 2's cost is $\tilde{c}_2 = c_2$. Firm I wins with price $p_I = \tilde{c}_1 - \epsilon$ and earns positive profit equal to $\tilde{c}_1 - c_I - \epsilon$. Firms 1 and 2 bid $\tilde{c}_1$ and c_2, respectively, and earn zero profit.

Since firms 1 and 2 earn zero profit in all possible auction subgames, the solution methods used in the two-firm model do not help to identify a unique equilibrium. Consequently, a slight adjustment needs to be made to the model in order to identify the subcontracting arrangement chosen by firms 1 and 2. One potential adjustment is the introduction of a small cost of writing a horizontal subcontract. If there is a small positive cost of subcontracting, then knowing that subcontracting does not lead to higher profits in the auction subgame, firms 1 and 2 optimally choose "No Subcontracting" in Stage 2.[2]

Alternatively, the model can be adjusted by allowing firms 1 and 2 to be uncertain about firm I's cost in Stage 2. For example, perhaps firms 1 and 2 believe that firm I's cost is distributed according to a density function which has a large mass point on c_I and a small positive value in the range $[c_2, V]$. In this case, firm 1 earns positive expected profit with $E\pi_1^{1 \text{ is } S} > E\pi_1^{NoSub} > E\pi_1^{1 \text{ is } S}$. Firm 2 earns positive profit only if it is the subcontracting prime ("2 is S"). Consequently, as in case A of the two-firm model, $\{1 \text{ is } S,\ 1 \text{ is } S\}$ is a Pareto dominant Nash equilibrium resulting in firm 2 hiring firm 1. The equilibrium subcontracting payment, t, is some value greater than c_2^B,

[2]This cost of writing a subcontract could be introduced into the two-firm model without changing its results as long as the cost is smaller than the potential gains to firms 1 and 2 from subcontracting.

since firm 2 earns zero profit regardless of t, and firm 1 can increase firm 2's cost, and thus raise the price that undercuts firm 2.

Firm 2 earns zero profit regardless of the realization of c_I. If firm I is, in fact, the low cost producer, then it wins at the price $p_I = \tilde{c}_1 - \epsilon > c_1 - \epsilon$ and firm 1 earns zero profit. If, instead, firm I's cost is between c_2 and V, then firm 1 wins the auction at a higher price than it would have absent the horizontal subcontract. In either case the outcome is efficient, because the low cost producer wins the auction; however, the winning price is higher with horizontal subcontracting than without.

A.2.2 Solving Case 4

Let $c_1^B < c_2^B$ and $c_1 < c_2 < c_I$. From the perspective of firms 1 and 2, this case is essentially the same as case A in the two-firm model, except that c_I rather than V is the binding constraint on how high firm 1 can raise firm 2's cost and thus the price. Ergo, in equilibrium, firm 2 hires firm 1 as its subcontractor ("1 is S"). Since firm 2's profit is invariant to t, firm 1 raises t until $\tilde{c}_2 = c_I$, so that $t = c_I - c_2^A$. Firm 1 wins with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1 = c_I - c_1 - \epsilon$. Firms 2 and I each bid c_I and earn zero profit. Absent subcontracting firm 1 would have won with price $p_1 = c_2 - \epsilon$, therefore, horizontal subcontracting results in a higher price.

A.2.3 Solving Case 8

Let $c_1^B < c_2^B$, $c_1 < c_I < c_2$, and $c_I < c_1^A + c_2^B$. If firms 1 and 2 choose no subcontracting, then firm 1 wins with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{\text{No Sub}} = c_I - c_1 - \epsilon$. Firms 2 and I each bid their costs and earn zero profit.

If instead, firms 1 and 2 choose "1 is S," then firm 2's cost is $\tilde{c}_2 = c_2^A + t$. Firm 1's cost, by equation (3.2), is $\tilde{c}_1 = c_1$ if firm I has lower cost than firm 2 and $\tilde{c}_1 = c_1^A + t$ if firm I has higher cost than firm 2. In either case, firm 1 wins the auction, and firms 2 and I both earn zero profit. In the former case, firm I is firm 1's lower cost rival, so firm 1 bids $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{1\text{ is }S} = c_I - c_1 - \epsilon$. Since the profits of both firm 1 and firm 2 are invariant to t, the equilibrium value of t is undetermined. In the latter case where firm 2 can undercut firm I, firm 1 bids $p_1 = c_2^A + t - \epsilon$ and earns profit $\pi_1^{1\text{ is }S} = c_2^A + t - c_1 - \epsilon$. Here, firm 1's profit is increasing in t so long as $\tilde{c}_2 < c_I$ or $t < c_I - c_2^A$. For $t \geq c_I - c_2^A$, $p_2 \geq p_I$, so firm 1 bids $p_1 = c_I - \epsilon$ and earns it maximum possible profit $\pi_1^{1\text{ is }S} = c_I - c_1 - \epsilon$. Consequently, firm 1 maximizes its profit by setting

$t \geq c_I - c_2^A$, and firm 2 accepts since it earns zero profit regardless of t. Notice that regardless of whether the horizontal subcontract with "1 is S" allows firm 2 to undercut firm I, the profits of all firms are the same as if no horizontal subcontract were written.

Finally, suppose firms 1 and 2 chose "2 is S." Since case 8 assumes that $c_I < c_1^A + c_2^B$, any horizontal subcontract with "2 is S" raises firm 1's cost above c_I, resulting in the independent firm winning the auction, and firms 1 and 2 earning zero profit. Firm 1 therefore strictly prefers "1 is S" or "No Sub" to "2 is S." Since firm 1 earns the same profit from either the "1 is S" arrangement or no subcontracting, and firm 2 always earns zero profit, the equilibrium of this case is either for firm 1 to be the subcontracting firm, or for firms 1 and 2 to forgo a horizontal subcontract. Here, the horizontal subcontract does not affect the price or the distribution of the gains from trade among the buyer and the firms.

A.2.4 Solving Case 9

Let $c_1^B < c_2^B$, $c_1 < c_I < c_2$, and $c_I > c_1^A + c_2^B$. The outcome of the auction subgame if the negotiating firms choose "No Subcontracting" or "1 is S" is exactly the same as case 8 above. Firm 1 wins with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{1 \text{ is } S} = \pi_1^{\text{No Sub}} = c_I - c_1 - \epsilon$. Firms I and 2 bid their cost and earn zero profit.

Consider now the auction subgame if the negotiating firms choose "2 is S." Since case 9 assumes $c_I > c_1^A + c_2^B$, firm 1 can still win the auction as a hiring prime if t is sufficiently low. However, since firm I is firm 1's lower cost rival, firm 1 cannot use the horizontal subcontract to raise its winning price. Consequently, firm 1 still wins the auction with the price $p_1 = c_I - \epsilon$. However, since firm 1 has hired firm 2 as a subcontractor, firm 1's profits are lower for two reasons. First the costs of production have risen from c_1 to $c_1^A + c_2^B$, and second, firm 1 must share some of the surplus with firm 2. Consequently, firm 1 strictly prefers "1 is S" or "No Subcontracting" to "2 is S". However, firm 2 earns positive profit only if "2 is S." The negotiating firms are not able to agree to a horizontal subcontract, so the outcome of case 9 is for there to be no horizontal subcontract.

A.3 Proof of Proposition 3.3.2

A.3.1 Solving Case 2

Let $c_2^B < c_1^B$ and $c_I < c_1^A + c_2^B$ so that firms 1 and 2 cannot undercut firm I, even with a cost-reducing subcontract. If firms 1 and 2 choose "No Subcontracting," then firm I wins with price $p_I = c_L - \epsilon$ and earns profit $\pi_I = c_L - c_I - \epsilon$ where $c_L = \min\{c_1, c_2\}$. Firms 1 and 2 each bid their cost and earn zero profit.

If firms 1 and 2 instead choose "1 is S" so that firm 2 hires firm 1, then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. Since $c_2^A > c_1^A$ and $t > c_1^B$, firm 2 cannot undercut firm I, so firm 1's low cost competitor is firm I. By equation (3.2), firm 1's cost is $\tilde{c}_1 = c_1$. Firm I wins with price $p_I = c_1 - \epsilon$, firm 1 bids c_1, and firm 2 bids $\tilde{c}_2$. Again, firm I earns positive profit equal to $c_1 - c_I - \epsilon$, and firms 1 and 2 earn zero profit.

Finally, if firms 1 and 2 choose "2 is S" so that firm 1 hires firm 2, then firm 1's cost becomes $\tilde{c}_1 = c_1^A + t$. Since $t > c_2^B$, firm 1 still cannot undercut firm I, so firm 2's low cost competitor is firm I. By equation (3.2), firm 2's cost is $\tilde{c}_2 = c_2$. Firm I wins with price $p_I = \tilde{c}_1 - \epsilon$ and earns positive profit equal to $\tilde{c}_1 - c_I - \epsilon$. Firms 1 and 2 bid $\tilde{c}_1$ and c_2, respectively, and earn zero profit.

As in case 1, the negotiating firms earn zero profits in all possible auction subgames. Modifying the model to include a small positive cost of subcontracting would induce firms 1 and 2 to choose "No Subcontracting."

Suppose instead that the model is adjusted so that firms 1 and 2 believe that firm I's cost is distributed according to a density function which has a large mass point on c_I and a small positive value in the range $[c_I, V]$. Firms 1 and 2 then optimally choose "2 is S" which allows the negotiating firms to combine to lower costs and increase their competitive position. They choose a small subcontracting payment $t \in [c_2^B, c_1^B)$ that lowers firm 1's total cost from c_1 to $c_1^A + t$, allowing firm 1 to submit a bid below c_1. If firm 1 wins, then both firms earn positive profit and efficiency is increased. Horizontal subcontracting thus yields a lower price, regardless of whether firm 1 or firm I wins the auction.

A.3.2 Solving Case 3

Let $c_2^B < c_1^B$ and $c_I > c_1^A + c_2^B$. If firms 1 and 2 choose "No Subcontracting," then firm I wins with price $p_I = c_L - \epsilon$ and earns profit $\pi_I = c_L - c_I - \epsilon$ where $c_L = \min\{c_1, c_2\}$. Firms 1 and

2 each bid their cost and earn zero profit.

If firms 1 and 2 instead choose "1 is S" so that firm 2 hires firm 1, then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. Since $c_2^A > c_1^A$ and $t > c_1^B$, firm 2 cannot undercut firm I, so firm 1's low cost competitor is firm I. By equation (3.2), firm 1's cost is $\tilde{c}_1 = c_1$. Firm I wins with price $p_I = c_1 - \epsilon$, firm 1 bids c_1, and firm 2 bids $\tilde{c}_2$. Firm I earns positive profit equal to $c_1 - c_I - \epsilon$, and firms 1 and 2 earn zero profit.

Finally, if firms 1 and 2 choose "2 is S" so that firm 1 hires firm 2, then firm 1's cost becomes $\tilde{c}_1 = c_1^A + t$. If t is sufficiently small, then firm 1 undercuts firm I with price $p_1 = c_I - \epsilon$ and earns profit equal to $\pi_1 = c_I - c_1^A - t$. Firm I bids its cost and earns zero profit. Firm 2 bids its cost $(c_2^A + t)$ and earns profit $\pi_2 = t - c_2^B$ from the subcontract work for firm 1. Since π_1 is decreasing in t and π_2 is increasing in t, the specific value of t that the negotiating firms decide is undetermined and depends on the nature of the bargaining between them. However, in order to earn any positive profit, t must be in the range $(c_2^B, c_I - c_1^A)$ so that firm 1 can undercut firm I.

Since "2 is S" is the only arrangement that yields positive profits for firms 1 and 2, both firms optimally choose this strategy. In this case, horizontal subcontracting strictly increases efficiency and competition, yielding positive profits for both negotiating firms and increased consumer surplus for the buyer.

A.3.3 Solving Case 6

Let $c_2^B < c_1^B$ and $c_2 < c_I < c_1$. If firms 1 and 2 choose no subcontracting, then firm 2 wins with price $p_2 = c_I - \epsilon$ and earns profit $\pi_2^{\text{No Sub}} = c_I - c_2 - \epsilon$. Firms 1 and I each bid their costs and earn zero profit.

If the negotiating firms instead choose "1 is S," then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. Since $c_2^A > c_1^A$ and $t > c_1^B$, it follows that $\tilde{c}_2 > c_1 > c_I$, so firm 2 loses the auction and earns zero profit. Since "No Subcontracting" guarantees positive profit for firm 2, "1 is S" is a weakly dominated strategy for firm 2. Since firm 2 cannot undercut firm I, firm 1's relevant opportunity cost is $\tilde{c}_1 = c_1 > c_I$. Consequently, firm I wins the auction with price $c_1 - \epsilon$, and firm 1 earns zero profit.

Finally, if firms 1 and 2 choose "2 is S" so that firm 1 hires firm 2, then firm 1's cost becomes $\tilde{c}_1 = c_1^A + t$. If t is sufficiently small, then firm 1 undercuts firm I with price $p_1 = c_I - \epsilon$ and earns profit equal to $\pi_1 = c_I - c_1^A - t$. Firm I bids its cost and earns zero profit. Firm 2 bids its cost

$(c_2^A + t)$ and earns profit $\pi_2 = t - c_2^B$ from the subcontract work for firm 1. Since π_1 is decreasing in t and π_2 is increasing in t, the specific value of t that the negotiating firms decide is undetermined and depends on the nature of the bargaining between them. However, in order to earn any positive profit, the negotiating firms must choose t in the range $(c_2^B, c_I - c_1^A)$ so that firm 1 can undercut firm I.

"2 is S" is the weakly dominant strategy for firm 1 since this is the only arrangement that generates positive profits for firm 1 as long as $t < c_I - c_1^A - \epsilon$. Firm 2 prefers "2 is S" as long as $t - c_2^B > c_I - c_2$ or $t > c_I - c_2^A - \epsilon$. Consequently, the equilibrium is for both firms to choose "2 is S" and announce some t in the range $(c_I - c_2^A - \epsilon, c_I - c_1^A - \epsilon)$. In this case, horizontal subcontracting strictly increases efficiency, but the price is unaffected since firm I is the binding competitor with or without horizontal subcontracting.

A.3.4 Solving Case 7

Let $c_2^B < c_1^B$ and $c_1 < c_I < c_2$. If firms 1 and 2 choose no subcontracting, then firm 1 wins with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{\text{No Sub}} = c_I - c_1 - \epsilon$. Firms 2 and I each bid their costs and earn zero profit.

If the negotiating firms instead choose "1 is S", then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. Since $c_2^A > c_1^A$ and $t > c_1^B$, it follows that $\tilde{c}_2 > c_1 > c_I$, so firm 2 loses the auction and earns zero profit. Because firm 2 cannot undercut firm I, firm 1's relevant opportunity cost is $\tilde{c}_1 = c_1 < c_I$. Consequently, firm 1 wins the auction with price $c_I - \epsilon$, and earns profit $\pi_1^{1 \text{ is S}} = c_I - c_1 - \epsilon$. Firm I bids its cost and earns zero profit.

Finally, if firms 1 and 2 choose "2 is S" so that firm 1 hires firm 2, then firm 1's cost becomes $\tilde{c}_1 = c_1^A + t$. If t is sufficiently small, then firm 1 undercuts firm I with price $p_1 = c_I - \epsilon$ and earns profit equal to $\pi_1^{2 \text{ is } S} = c_I - c_1^A - t$. Firm I bids its cost and earns zero profit. Firm 2 bids its cost $(c_2^A + t)$ and earns profit $\pi_2^{2 \text{ is } S} = t - c_2^B$ from the subcontract work for firm 1. Since $\pi_1^{2 \text{ is } S}$ is decreasing in t and $\pi_2^{2 \text{ is } S}$ is increasing in t, the specific value of t that the negotiating firms decide is undetermined and depends on the nature of the bargaining between them. However, in order to earn any positive profit, the negotiating firms must choose a t in the range $(c_2^B, c_I - c_1^A)$ so that firm 1 can undercut firm I.

"2 is S" is the weakly-dominant strategy for firm 2 since this is the only arrangement that generates positive profits for firm 2. Firm 1 prefers "2 is S" as long as $t < c_1^B$, i.e., as long as it is less expensive to hire firm 2 than to perform the work itself. Consequently, the equilibrium is for both firms to choose "2 is S" and announce some t in the range (c_2^B, c_1^B). In this case, horizontal subcontracting strictly increases efficiency, but the price is unaffected since firm I is the binding competitor with or without horizontal subcontracting.

A.4 Proof of Proposition 3.3.3

Case 5 can be broken up into two subcases, the first where $c_1 < c_2$ and the second where $c_2 < c_1$. The following subsections solve each of these cases in turn.

A.4.1 Solving Case 5A

Let $c_2^B < c_1^B$ and $c_1 < c_2 < c_I$. If firms 1 and 2 choose "No subcontracting," then firm 1 wins with price $p_1 = c_2 - \epsilon$ and earns profit $\pi_1^{\text{No Sub}} = c_2 - c_1 - \epsilon$. Firms 2 and I each bid their cost and earn zero profit.

If the negotiating firms instead choose "1 is S," then firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. If $t > c_I - c_2^A$, then firm I is firm 1's low-cost competitor, and firm 1's cost is then $\tilde{c}_1 = c_1$. Firm 1 wins the auction with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{1 \text{ is } S} = c_I - c_1 - \epsilon$. Firms 2 and I each bid their cost and earn zero profit.

If $t < c_I - c_2^A$, then firm 2 is firm 1's lost cost competitor, and firm 1's opportunity cost is then $\tilde{c}_1 = c_1^A + t$. Firm 1 wins the auction with price $p_1 = c_2^A + t - \epsilon$ and earns profit $\pi_1^{1 \text{ is } S} = c_2^A + t - c_1 - \epsilon$. Firms 2 and I each bid their cost and earn zero profit. Since higher t leads to higher profit for firm 1 and no change in profit for firm 2, it is Pareto efficient for firms 1 and 2 to choose any $t \geq c_I - c_2^A$ so that firm 1 wins with price $p_1 = c_I - \epsilon$ and earns profit $\pi_1^{1 \text{ is } S} = c_I - c_1 - \epsilon$.

Finally, if the negotiation firms choose "2 is S," then firm 1's cost become $\tilde{c}_1 = c_1^A + t$. Neither negotiating firm would choose $t > c_I - c_1^A$ since that would cause $c_I < \tilde{c}_1 < \tilde{c}_2$ so that firm I wins the auction and firms 1 and 2 earn zero profit. Given the firms choose $t < c_I - c_1^A$, firm 1 is firm 2's low cost competitor, so firm 2's opportunity cost is $\tilde{c}_2 = c_2^A + t$. Firm 1 wins the auction with price $p_1 = c_2^A + t - \epsilon$ and earns profit $\pi_1^{2 \text{ is } S} = c_2^A - c_1^A - \epsilon$. Firms 2 and I each bid their cost; firm I earns zero profit, but firm 2 earns profit $\pi_2^{2 \text{ is } S} = t - c_2^B$ from subcontracting. Since firm 1's profit is invariant to t and firm 2's profit is increasing in t, it is Pareto efficient for the negotiating firms to set $t = c_I - c_2^A$ so that $\tilde{c}_2 = c_I$ and firm 1 wins with price $p_1 = c_I - \epsilon$.

Firm 2's weakly dominant strategy is "2 is S," since that is the only strategy that yields positive profit. Given that firm 2 is choosing "2 is S," firm 1's best response is to also choose "2 is S," since $\pi_1^{2 \text{ is } S} > \pi_1^{NoSub}$. This horizontal subcontracting arrangement increases efficiency, but lowers competition since firm 1 uses the horizontal subcontract to raise firm 2's cost.

A.4.2 Solving Case 5B

Let $c_2^B < c_1^B$ and $c_2 < c_1 < c_I$. If firms 1 and 2 choose "No subcontracting," then firm 2 wins with price $p_2 = c_1 - \epsilon$ and earns profit $\pi_2^{\text{No Sub}} = c_1 - c_2 - \epsilon$. Firms 1 and I each bid their cost and earn zero profit.

If instead, firms 1 and 2 choose "1 is S," firm 2's cost becomes $\tilde{c}_2 = c_2^A + t$. If $\tilde{c}_2 < c_I$, then firm 1's cost is $\tilde{c}_1 = c_1^A + t < \tilde{c}_2$ and firm 1 wins the auction with price $p_1 = \tilde{c}_2 - \epsilon$. If $\tilde{c}_2 > c_I$, then firm 1's cost is $\tilde{c}_1 = c_1$, and firm 1 wins the auction with price $p_1 = c_I - \epsilon$. In either case, firm 2 loses the auction and earns zero profit. Since firm 2 can guarantee positive profit by choose "No subcontracting," firm 2 will never agree to a subcontract in which "1 is S."

Finally, if firms 1 and 2 choose "2 is S," firm 1's cost becomes $\tilde{c}_1 = c_1^A + t$. Neither negotiating firm would choose $t > c_I - c_1^A$ since that would cause $c_I < \tilde{c}_1 < \tilde{c}_2$ so that firm I wins the auction and firms 1 and 2 earn zero profit. Given the firms choose $t < c_I - c_1^A$, firm 1 is firm 2's low cost competitor, so firm 2's opportunity cost is $\tilde{c}_2 = c_2^A + t$. Firm 1 wins the auction with price $p_1 = c_2^A + t - \epsilon$ and earns profit $\pi_1^{2 \text{ is } S} = c_2^A - c_1^A - \epsilon$. Firms 2 and I each bid their cost; firm I earns zero profit, but firm 2 earns profit $\pi_2^{2 \text{ is } S} = t - c_2^B$ from subcontracting. Since firm 1's profit is invariant to t and firm 2's profit is increasing in t, it is Pareto efficient for the negotiating firms to set $t = c_I - c_2^A$ so that $\tilde{c}_2 = c_I$ and firm 1 wins with price $p_1 = c_I - \epsilon$. Consequently, the profits for firms 1 and 2 are $\pi_1^{2 \text{ is } S} = c_2^A - c_1^A - \epsilon$ and $\pi_2^{2 \text{ is } S} = c_I - c_2$.

Since $c_I - c_2 > c_1 - c_2 - \epsilon$, firm 2 prefers "2 is S" to "No Subcontracting." Firm 1 likewise prefers "2 is S" to no subcontracting since "2 is S" yields positive profit for firm 1 and "No subcontracting" does not. Consequently, the equilibrium is for firm 1 to hire firm 2 and for both firms to set $t = c_I - c_2^A$. This horizontal subcontracting arrangement increases efficiency, but lowers competition since firm 1 uses the horizontal subcontract to raise firm 2's cost.

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