Subcontracting and Competitive Bidding on Incomplete Procurement Contracts

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Abstract

This paper investigates the cost implications of contractual incompleteness and its effect on subcontracting decisions in the bridge construction industry. Construction contracts are incomplete because the original blueprints and specifications may require modifications during construction. According to the transactions cost theory of the firm—Coase (1937), Williamson (1985)—such contract revisions can lead to significant bargaining and renegotiation costs. Furthermore, theory predicts these costs are larger if a subcontractor performs the work. Forward looking contractors anticipate these costs and incorporate them in their bids. I develop an empirical framework to quantify the impact of incompleteness on cost for both integrated and non-integrated transactions and apply it to 32 bridge contracts procured by the California Department of Transportation. Contracts contain many work items (e.g. casting concrete, drilling, traffic striping). For each item, contractors decide whether to perform work themselves or hire a subcontractor and submit a bid. The difference between the work item quantity in the original contract and the quantity actually installed after revisions proxies for incompleteness. In estimation, I account for the strategic aspects of bidding to recover cost from bids and exploit the panel data structure to account for the endogeneity of subcontracting decisions. On average, incompleteness explains a small portion of cost, 2%, for integrated transactions and a large portion, 13%, for non-integrated transactions. The results provide quantitative evidence in support of incomplete contracting theories of the firm and have practical significance for evaluating procurement practices.

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1 Introduction

Subcontractors play a vital role in the construction industry. They perform 50% of the work on civil projects and 75% to 100% on a typical private construction project.[1] But, the contractual hazards of subcontracting plague the industry. Sweet (2004), an expert on the legal aspects of construction contracting, expresses this sentiment by titling his chapter on subcontracting "The Achilles Heel of Construction Management." The hazards he refers to usually involve contract changes, and the costs manifest in many ways. On a small scale, changes disrupt day-to-day construction operations, but they can also lead to very costly outcomes such as arbitration and litigation. Semple et al. (1994) finds the average claim in their sample delays construction by 60% of the contract duration and comes with a cost equal to the value of the original contract. Stories of subcontract misgovernance frequently reach headlines. An example is Boston's notorious "Big Dig" which required drastic changes in construction plans.[2]

Construction projects begin with the preparation of plans, specifications, and blueprints. For reasons largely unpredictable and out of the control of both buyers and contractors, modifications and revisions will be made.[3] Such changes require contractors and their subcontractors to adapt the construction process without direction from a prior written contract. This is the sense in which construction contracts are incomplete. According to incomplete contracting theories of the firm—(Coase, 1937; Williamson, 1985)—frictions in the bargaining and renegotiation process that accompanies a contract change generate ex-post adaptation costs. Theory predicts these costs are higher when the process involves subcontractors. These cost considerations influence contractors' decisions to hire subcontractors, or—using the term coined in the literature, their "make or buy" decisions.

In the public sector, construction projects are typically procured using competitive bidding. The most common contracting format is called *design-bid-build*. First, the buyer's engineers prepare specifications and blueprints. Then contractors bid in a competitive auction and the low bidder is

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[1] Source: Bartholomew (1998)

[2] The "Big Dig" was a multi-billion dollar project that encountered unknown underground conditions. Modifications called for tunnel rerouting and strengthening. Much of the affected work was performed by subcontractors and several claims were filed. In the largest, the primary contractor paid $417 million in restitution for mismanagement of subcontractors. Source: Washington Post Dec 26. 2007, "On Dec. 31, It's Official: Boston's Big Dig Will Be Done."

[3] For a detailed example, consider the most drastic modification from the rebuilding of the collapsed 35W bridge in Minneapolis. The engineering team failed to notice a drainage system located at the base of the bridge piers. It was unmarked on sewage diagrams and hidden from sight by the wreckage of the collapsed bridge. Upon discovery, the drilling sites and piers had to be moved 20 feet. The drilling subcontractor had already arrived on-site. This change altered the design of substructures, and the superstructure was redesigned to bear the load of a longer span. Throughout the paper, I consider many examples from this project. My knowledge comes from daily, personal observations as well as weekly tours and discussions with contractors and structural engineers.

hired to build the project. These contracts abide by the principle of *forward pricing*; bids submitted ex-ante, not costs incurred ex-post, establish the terms of compensation. Primary contractors, who submit bids, and the subcontractors they hire are liable for all costs. Consequently, forward looking, rational contractors will assess the likelihood that design changes will occur and incorporate anticipated adaptation costs into their bids.

I develop a model representation of the *design-bid-build* process and propose a measure of contractual incompleteness to address four quantitative questions. What is the effect of incompleteness on cost if a subcontractor performs work? What is the effect if a primary contractor performs work? Do these effects differ? Finally, what are the dollar-valued magnitudes? The baseline prediction is that cost increases in the degree of incompleteness under both arrangements, but with a larger marginal effect for work performed by a subcontractor. I apply the framework to bridge projects procured by the California Department of Transportation (Caltrans).

A vast body of empirical work qualitatively analyzes how firms are organized. These traditional studies, lacking cost measures, only address the third question listed above: does incompleteness (or some other parameter) affect the probability of subcontracting? There is very little quantitative evidence about the impact of firm boundaries on economic outcomes such as cost. This has been a major critique in this literature (Hubbard, 2008; Lafontaine and Slade, 2007; Klein, 2005). This paper offers one of the first attempts to bring the missing data, examine the cost primitives of the theory, and, stated bluntly, to show that firm boundaries matter. Such a research design is made possible because bids reflect cost. The main finding is that incompleteness has a negligible effect on cost for work performed by a prime contractor. The effect is large for subcontracting; incompleteness accounts for 13% of cost.

The unit of analysis is at a detailed level. The engineer's specifications list construction work items and corresponding quantities. On bridge contracts, tasks range from heavy engineering jobs such as installing structural concrete, steel, asphalt, and drilling to ancillary tasks such as traffic striping, fencing, and landscaping. For each task, bidders decide whether to perform work themselves or hire a subcontractor. They also submit a unit price bid expressed as dollars per unit of quantity. Unit price bids are aggregated according to a scoring rule to determine the low bidder.

Incompleteness is inherently a difficult concept to measure. A measurement should capture contractors' beliefs about the non-contracted contingencies that might occur during the ex-post build phase. Many contingencies alter blueprints, which, in turn, requires an adjustment in quantities actually installed. I propose a measure based on quantity changes. Specifically, the difference between the work item quantity in the original blueprints and the quantity actually installed after blueprint revisions proxies for incompleteness. Those tasks that experience little or no change were likely perceived by contractors to have a low degree of incompleteness while those with large changes a high degree of incompleteness. This is an exogenous measure because contractors have little ability, ex-ante and ex-post, to influence installed quantities. Quantities change because of external circumstances.

Bidding and subcontracting decisions depend on incompleteness. I do not explicitly model the mechanics of the ex-post bargaining process; nor do I model any other ex-ante actions taken in anticipation of bargaining. Instead, I treat the predictions of theory in a reduced form manner and use the model to show why the incompleteness proxy affects forecasted unit costs and the subsequent subcontracting decision.[4] In a subgame, I model subcontract formation.

I model the strategic aspects of bidding which also depend on quantity changes. These are scoring auctions. The total bid is calculated by multiplying unit price bids with original quantities, then summing those values across tasks. For each task, the winner is paid its unit price bid times the quantity actually installed. Differences in original and final quantities induce strategic bidding behavior. The basic intuition described by Athey and Levin (2001) shows that bidders skew unit price bids above cost on tasks expected to overrun on quantity and below cost on tasks expected to underrun. By skewing, a bidder earns a higher profit without affecting its total bid and hence probability of winning the contract. Bid skewing is risky. If the overrun (or, for that matter underrun) does not occur, the winning bidder suffers a lose. The principles for allocating unit price bids are analogous to concepts from modern portfolio theory (Markowitz, 1952). The specific modeling choices match industry practitioners' intuition about unit price bidding. They credit these ideas to Gates (1959). I apply results from the scoring auction literature to formally characterize equilibrium bidding behavior (Asker and Cantillon, 2008).

The model collapses to a linear econometric specification. A unit price bid is the dependent variable and the proxy for incompleteness is the key explanatory variable. There are two potentially confounding factors: bid skewing and the endogeneity of subcontracting decisions. Bid-skewing terms derived from the auction model enter linearly. To account for the endogeneity of subcontracting decisions, I use a fixed effect method which exploits the unique panel data structure. I see multiple observations of very similar transactions. For example, within a project there are multiple bidders, and across projects, the same set of construction tasks.

Finally, I add flexibility by making a distinction between heavy construction tasks and ancillary tasks. The predominant view in the industry is that prime contractors lack core competencies and a minimum efficient scale on ancillary tasks. I will argue that it is ambiguous whether the effect of incompleteness on subcontracting costs should be hypothesized to be greater than that for primecontracting. (*I invent the word "primecontracting" for a dichotomy with the term subcontracting. Primecontracting means the prime contractor elects to perform work*).

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[4] The original theoretical ideas of Coase (1937) and Williamson (1985) are qualitative, recent work by Gibbons (2005), Bajari and Tadelis (2001), Tadelis (2002) formalize those ideas and provide micro-foundations.

1.1 Contribution to Existing Literature

This study joins an emerging literature that quantities the impact of firm boundaries on economic outcomes. Recent examples include Gil (2008) (*industry*: cinemas and *performance outcome*: movie run length), Ciliberto (2006) (hospitals and capital investments), Forbes and Lederman (2007) (airlines and flight delays), and Novak and Stern (2008) (automobiles and consumer quality ratings). Others—Baker and Hubbard (2004) (trucking and fuel economy) and Levin and Tadelis (2008) (municipal services and city expenditures)—consider but do not focus on performance outcomes.

I adopt a more structural approach than most work in this literature by analyzing an auction setting. The timing of bid submissions provides a crisp division between ex-ante contract formation (design and bid) and ex-post contract execution (build). This means bids capture all costs of both ex-anted incentive distortions and ex-post bargaining. Whereas many of the previous studies consider intermediate outcomes that partially related to the profitability objectives of firms, bids fully encapsulate contractors' objectives. They choose organizational arrangements that minimize cost.[5] The challenge in conducting an performance based "make or buy" study is to account for endogeneity in subcontracting decisions. The panel data structures provides controls.

This study of contractual incompleteness falls into the class of empirical work that considers uncertainty and complexity of a transaction. Seminal contributions include Monteverde and Teece (1982), Masten (1984) and Masten et al. (1991). They find a higher degree of complexity is associated with a lower probability of subcontracting. Recent work by Gil (2007) (movies), Acemoglu, Aghion, Griffith, and Zilibotti (2007) (R&D intesity), Forbes and Lederman (2006) (airlines) Levin and Tadelis (2008) (municipal services) obtain the same result. The literature on forward integration into retailing finds mixed evidence.[6] Williamson (1985) and, in particular, his earlier work Williamson (1975), identified uncertainty as one of the key determinants of firm boundaries for empirical researchers to take to the data.[7] This factor is losing favor, in part, because of the difficulty of measuring uncertainty. Typically, studies rely on survey data of industry practitioners or measures of market volatility. Uncertainty is notoriously measured with error. This creates severe attenuation bias that leads to statistically insignificant estimates.[8] A strength of this study is that the proxy captures a precise notion of incompleteness: changes in the construction contract measured at the detailed level of a work item transaction.

Besides providing evidence about theory, this study has practical significance. Public procure-

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[5] In general, cost-quality tradeoffs are important in the construction industry. Informational asymmetries between inexperienced buyers and contractors can result in poor quality or cost overruns born by the buyer. Quality considerations are of secondary importance for competitively tendered contracts procured by an experienced buyer like Caltrans. Shirking on quality becomes a cost to the contractor.

[6] See Lafontaine and Slade (2007) for a survey of these results.

[7] Holmstrom and Roberts (1998) provide this textual interpretation. The other two are specificity and frequency of a transaction.

[8] Klein (2005) notes the problem of measurement error.

ment agencies emphasize the competitive aspects of contracting. They try to promote competition with the goal of reducing bidder markups. Markup estimates are small, around 4%.[9] This suggests there are negligible gains available from promoting further competition. Instead, efforts to write more complete construction plans could generate significant cost savings—up to 17% for the transactions most sensitive to incompleteness. Moreover, the civil engineering industry is important to study given the urgency to replace and repair "structurally deficient" public infrastructure. The Federal Highway Administration projects the need for an annual spending increase on bridges from \$5 billion to \$40 billion. In the conclusion, I offer a more in-depth analysis and motivate ideas for policy research.

This work is related to the empirical auctions literature. There is an especially large body of work on highway procurement auctions including the contributions of Porter and Zona (1993), Hong and Shum (2002), Krasnokutskaya (2004), Jofre-Bonet and Pesendorfer (2003), Bajari, Houghton, and Tadelis (2007), Marion (2008), De Silva et al. (2008), and Bajari and Lewis (2008). This is the first study to use work items as the unit of observation within the context of a structural auction model. [10]

Previous empirical work on bid skewing (Athey and Levin, 2001; Bajari et al., 2007) restricted attention to just one dimension of skewing. I model the bid skewing decision as a portfolio choice problem. That is, the correlation structure in quantity change risk across all tasks determines the optimal skew on any given task. The proposed empirical technique recovers the correlation structure of risk. Risk aversion in auctions has attracted attention in both the empirical auctions and experimental economics literature.[11] Adapting the method could provide field evidence on Arrow-Pratt risk aversion coefficients with large amounts of money at a stake.

In summary, this study offers four contributions. First, I quantity, rather than qualitatively assess, the effects of incompleteness and integration decisions on cost. The second contribution regards the quality of the data. I perform analysis at the detailed level of a work item. The sample includes over 12,000 individual transactions. I propose a well defined notion of incompleteness, and the unique panel data structures provides controls for unobserved heterogeneity. Third, the cost implications have significance for procurement practices. Fourth, I contribute to the empirical auctions literature by expanding the empirical framework to handle bid skewing.

The paper is organized as follows; section 2 presents a model of the procurement process. Section 3 describes the data; section 4, the estimation procedure. Section 5 presents results. Section 6 discusses robustness; section 7 concludes.

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[9] Estimate taken from Bajari et al. (2007). Their survey of the literature finds similar markups.

[10] Marion (2008) is closely related to this paper on two dimensions. He studies a California affirmative action law regarding highway subcontracting. He uses work items observations but does not account for bid skewing.

[11] See Campo, Guerre, Perrigne, and Vuong (2003), and Harrison and Rutström (2008) for discussions.

2 Model of Subcontracting and Competitive Bidding

This section develops a model representation of the *design-bid-build* procurement process. I first outline the timing then describe the rules of the auction. I show how incompleteness affects cost in a reduced form manner and follow with a discussion. The section concludes with a model of unit price bidding.

Design Caltrans' resident engineers write blueprints and specifications. They include T tasks indexed $t = 1, \ldots, T$ and quantities for each task q_t^e (in vector notation $\mathbf{q}^e = [q_1^e, q_2^e, \ldots, q_T^e]$).[12] Examples include concrete, steel, excavation, and traffic striping. Contractors (and subcontractors) inspect blueprints and the job-site to forecast costs. They do not participate in the design process.

Bid *and Sign Subcontracts* Prime contractors submit unit price bids and choose which tasks to subcontract. These are the two endogenous decisions. In a subgame, prime contractors receive bids from subcontractors.

Build During the construction phase contingencies arise which require modifications in design. Modifications require adjustments to quantities. Denote the quantity actually installed for task t as q_t^a (in vector notation $\mathbf{q}^a$). Renegotiation occurs during this phase.

2.1 Auction Rules

Each participating bidder (i.e. prime contractor), indexed $i = 1, \ldots, N$, submits sealed unit price bids for every task. Let b_{it} denote bidder i's unit price bid on task t (in vector notation $\mathbf{b}_i$). The total bid is calculated by multiplying a unit price bid with the corresponding quantity from the engineer's original plans then summing those values across all tasks; it is the dot product of the unit price bid vector and the vector of engineer's quantities. Call the total bid the score, $s_i = \mathbf{b}_i \cdot \mathbf{q}^e$, because this auction belongs to the class of scoring auctions. The bidder with the lowest score wins the contract.

Payment to the winning bidder is based on quantities actually installed: it is the dot product of the vector of unit price bids and the vector of installed quantities (revenue, $R_i = \mathbf{b}_i \cdot \mathbf{q}^a$). Bidders do not choose actual quantities. Losing bidders do not receive payment.

2.2 Subcontracting Subgame and Ex-Post Adaptation

In a pre-bidding phase, subcontractors submit unit price bids to prime contractors. Denote the subcontract unit price bid received by prime contractor i for task t as b_{it}^{sub}. Payment to subcontractors,

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[12] For convenience many variables are expressed as vectors with length T. These variables will unambiguously be denoted in boldface.

based on final quantities, $b_{it}^{sub} q_t^a$, is disbursed by the hiring prime contractor, not Caltrans.

When forecasting unit costs, contractors consider not only physical costs of construction (labor wages, equipment rental rates, and materials costs), but also anticipated costs of ex-post adaptation. This follows because payment is based solely on the bids submitted ex-ante. For exposition of the model, inc_t is just some notion of incompleteness. I elaborate in discussion that follows. A subcontractor's forecasted unit cost, $c_{it}^{sub}(inc_t)$ depends on incompleteness. Primecontracting unit costs also depend on incompleteness. Under the assumption of perfect competition, subcontract unit price bids equal unit cost: $c_{it}^{sub}(inc_t) = b_{it}^{sub}$. Industry sources state subcontract markets are very competitive; markups are only a few percentage points above cost. Analysis does not change if a markup, independent of incompleteness, is assumed into subcontract unit cost.

A prime contractor's subcontracting cost is not necessarily equal to the subcontract unit price bid. Prime contractors incur managerial costs to oversee work and a share of hold-up costs. Subcontracting costs, c_{it}^s, and primecontracting costs, c_{it}^p are given by,

$$\begin{aligned} c_{it}^s &= b_{it}^{sub} + H_{it}(inc_t) \\ c_{it}^p &= c_{it}^p(inc_t) \end{aligned}$$

where $H_{it}(inc_t)$ captures the incidence of subcontracting cost born by the prime contractor.[13]

Once a prime contractor forecasts both costs, c_{it}^s and c_{it}^p (in vector notation $\mathbf{c}_i^s$ and $\mathbf{c}_i^p$) it makes a subcontracting decision. The cost to perform a task (denoted c_{it} without superscript) takes on the value of either c_{it}^s or c_{it}^p, corresponding to whichever subcontracting arrangement is chosen.

The winning bidder's profit is its revenue less its total cost evaluated at the actual installed quantities: $\pi(\mathbf{b}_i, \mathbf{c}_i; \mathbf{q}^a) = (\mathbf{b}_i - \mathbf{c}_i) \cdot \mathbf{q}^a$. Losing bidders earn zero profits and their subcontracts are dissolved with no payments made.

2.3 Incompleteness Discussion

Throughout the construction phase contingencies arise that require adaptation to the construction process. Many, though perhaps not all, will have an effect on installed quantities. I measure incompleteness as the deviation between actually installed quantities and the engineer's original quantity: $\left|\frac{q_t^a - q_t^e}{q_t^e}\right|$. When contractors inspect the original plans and job-site they assess the likelihood of changes being made and forecast how these changes will affect unit costs. This measure captures what they likely perceived during inspection. Changes are primarily caused by differing site conditions. This is common for work involving subsurface conditions such as excavation and drilling. Changes also occur because of deficiencies in design that compromise structural in-

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[13] Arditi and Chotibhongs (2005) document prime contractors incorporating managerial and hold-up costs for subcontracted work into their bids.

tegrity, unknown local regulatory codes, preferences changes of the buyer with regard to function or aesthetics, or because of errors, ambiguities or omissions in the design.[14]

It is important to emphasize that changes occur for external reasons uncontrollable by contractors and Caltrans' engineers. Both parties have limited ability to influence installed quantities during the ex-post construction phase.[15] Caltrans is an experienced buyer; therefore, contractors cannot exploit informational advantages to manipulate actual quantities with the intention of extracting extra profits. This assertion would not hold in private construction because of information asymmetries between inexperienced buyers and contractors. Furthermore, contractors cannot take actions ex-ante to influence quantities because they do not participate in the design phase. Actual quantities are random variables from the perspective of contractors.

Contracts do not fully specify the ex-post actions to be taken if plans are modified. Non-contracted adaptations are made through a bargaining process. Disputes commonly arise over payment, scheduling, acceleration (working overtime and mobilizing additional workers and equipment), overcrowded work-sites, design ambiguities, and quality standards (Bartholomew, 1998; Levin, 1998; Arditi and Chotibhongs, 2005). That a contract specifies payment for all possible realizations of actual quantities does not imply it is complete.

There are three interpretations from the transactions cost literature for why incompleteness affects cost. First, ex-post haggling generates costs. These costs could manifest as work stoppages or disruptions to the flow of work, or in severe cases as lost time and fees incurred during arbitration or litigation. Second, an inefficient outcome could arise if asymmetric information is present. For example, accelerating the pace of work might be the lowest cost, ex-post, means of adapting. With asymmetric information an agreement to work overtime might not be reached. Third, bargaining distorts ex-ante incentives. The parties may not choose construction or management methods that would flexibly accommodate a change out of fear of appropriation by the other party. Theory predicts primecontracting mitigates these costs and incentive distortions.

The degree of incompleteness matters for two reasons. One interpretation is that a large change has a higher probability of triggering a hold-up situation. A second is that a large change creates a more severe hold-up problem. For example, a minor change might only cause a brief haggle whereas a large change could cause a dispute about a major issue such as acceleration.

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[14] Consider a few examples from the 35W bridge. The unmarked drainage system, discussed in the introduction, is an example of a differing site condition. With regards to a preference change, the piers were originally designed to be block legged. A community board voted to have aesthetically appealing arched piers. This change decreased the amount of concrete and increased the amount of steel reinforcement in the piers. Another severe source of uncertainty, not involving quantities, occurred when a chemical plant spill, 14 mile away, drained onto the construction site. Contractors had scheduled to move precast concrete blocks into position that week. Instead, they had to work on another part of the project.

[15] Caltrans employs a team of *quantity surveyors* who are specialist in reading blueprints to determine quantities. On the job-site they monitor contractors and measure quantities. Contractors are only paid for the quantities that quantity surveyors authorize.

Bargaining occurs along contractual links besides the subcontract. They can involve Caltrans. Subcontractors frequently circumvent prime contractors by negotiating directly with Caltrans where contractual links are absent. This practice is known to exacerbate contract disputes (Hinze, 1993). There can be bilateral bargaining between prime contractors and Caltrans, within a firm, amongst tiers of management.

Ex-post adaptation costs would not appear if a prime contractor or subcontractor could easily switch to another partner at the renegotiation phase. There are two sources of lock-in. Temporal specificity is the first. It would be costly for prime contractors to either find another subcontractor on short notice or mobilize its own resources. Similarly, subcontractors might not be able to find work on another project. Second, there is a legal commitment device—unique to California public works projects—that creates lock-in. A key stipulation in California's *Subletting and Subcontracting Fair Practice Act*,[16] prohibits a prime contractor from hiring any additional subcontractors or making subcontractor substitutions after it has been awarded a project. Even if there is mutual agreement about a severance, a prime contractor cannot hire a replacement subcontractor. The law severely limits a prime contractor's outside options.

2.4 Heavy Construction Tasks vs. Ancillary Tasks

Subcontracting and primecontracting should not be thought of as "black or white" concepts. The heavy civil engineering industry is composed of many arms-length transactions. There are transactions involving material suppliers, laborers, truckers, and equipment rental yards (hereafter referred to as input markets).[17] An incomplete contract affects these transactions.

The view of industry practitioners is that prime contractors lack core competencies and do not achieve a minimum efficient scale of operation on ancillary tasks, such as landscaping, traffic striping, and painting (Hinze, 1993; Sweet, 2004; Arditi and Chotibhongs, 2005). Individually these tasks are a small part of a heavy civil engineering project. I interpret this to mean that transactions between a prime contractor and input markets resemble one-shot transactions. There

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[16] California was the first state to adopt this law, 10 other states have followed. It is intended to prevent the practice of post award bid shopping; it prevents winning prime contractors from exercising monopsony power to garner price concessions from subcontractors. The law binds with the exception of cases involving the solvency of a contractor, breaches of subcontracting agreements, or if it is later deemed a contractor does not have the capabilities to perform a particular task. For transparency, the law requires bidding contractors to furnish to the public procuring agency the names, addresses, and lists of work to be performed for all subcontractors with its bid submittal. The public information disclosure is one reason why Caltrans contracts were chosen for this study.

[17] The lead contractor on the 35W project came from Denver Colorado, 800 miles away. They owned none of the equipment used on the project. To my knowledge, the only physical items they owned were some steel falsework that they could cost effectively barge up the Mississippi from a previous job rebuilding a bridge after Hurricane Katrina. Seventy employees serving managerial roles came to Minneapolis. Otherwise, all input market transactions were their first.

could be significant bargaining costs to hire or fire inputs on short notice.

In contrast, specialty subcontractors performing ancillary tasks are tightly integrated with input markets. They operate in local markets where they have long term relationships and frequent transactions with input markets. They achieve the minimum efficient scale of operation to warrant their specialty by logging a steady flow of work across many projects, even those outside of heavy civil engineering. They can swiftly reallocate inputs to and from projects to accommodate changes. My interpretation is that ordering subcontracting and primecontracting transactions in terms of their degree of integration is ambiguous.

Prime contractors' core competencies are in heavy construction tasks, such as those involving concrete, steel, and asphalt. Therefore, the distinction about integration with input markets is not important. The data section provides evidence that while prime contractors lack core competencies on ancillary tasks, they are not lacking when it comes to heavy construction tasks.

In summary, the cost of subcontracting is predicted to increase in the degree of incompleteness for both types of tasks due to hold-up costs in subcontracts. The cost of primecontracting is predicted to increase as well. For heavy construction tasks, the relative marginal effect is predicted to be larger for subcontracting. For ancillary tasks, the relative marginal effect is ambiguous because frictions in primecontracting input market transactions could exceed subcontract frictions.

2.5 Bidding Strategies Example

If unit cost were directly observed, I could proceed without further discussion of the auction. But there is an important strategic reason for why unit price bids might differ from unit cost. Like the incompleteness proxy, it depends on quantity changes.

I present the intuition behind bidding strategies with an example that construction professionals credit to Gates (1959). His insight motivates the remaining modeling choices.

	task	bid	q^e	q^a	Score	Revenue	Cost	Profit
Bid at Cost	Mobilization	**600**	1	1	1400	1800	1800	0
	Concrete(m^3)	**2**	400	600				
Correct Skew	Mobilization	200	1	1	1400	2000	1800	200
	Concrete(m^3)	3	400	600				
Incorrect Skew	Mobilization	200	1	1	1400	500	800	-300
	Concrete(m^3)	3	400	100				

Consider a project with 2 tasks: 1 unit of Mobilization (setting up shop at the work-site) and the installation of 400 cubic meters of concrete. The above table depicts two possible bidding strategies and two realizations of final quantities. In one situation, concrete quantities overrun by 200 cubic meters, in the other they underrun by 300; the quantity on Mobilization is fixed at 1 in both cases. In the baseline example labeled “Bid at Cost” the bidder submits unit price bids equal to unit costs. When concrete quantities overrun, revenue increases above the score, but profits are zero. In case of an underrun (not depicted in table), revenue decreases, but profits remain zero. Suppose the bidder forecasts concrete quantities to overrun. In the column labeled “Correct Skew” the bidder skews the unit price bid on concrete above unit cost, and below cost on Mobilization. Revenue and profit increase as compared to a strategy of bidding at cost, yet, the bidder maintains the same score, thereby not diminishing its chances of winning the auction. Such a strategy comes with risk as the entry labeled “Incorrect Skew” illustrates. If the concrete quantity underruns, the bidder suffers a loss of profits. Gates (1959) intuition is about the risk-reward tradeoff of skewing bids away from cost.

2.6 Continued Auction Description

I model the auction in the private values paradigm. Actual quantities are drawn from the joint density $g(\mathbf{q}^a)$. Realization of the draw occurs after bidding. Ex-ante bidders have symmetric information about this density.[18]

Bidder i's costs are drawn from the joint density, $f_i(\mathbf{c}_i^s, \mathbf{c}_i^p)$. Densities may differ across bidders. A bidder knows it own realization from the cost draw, but only knows the distributions its rivals are drawing from. Note that this realistically captures an implicit assumption that bidders do not know the subcontracting choices of their opponents.

Following the intuition of Gate's example, bidders are modeled to exhibit risk aversion over profits. Let bidders have identical utility over profits, represented by a twice continuously differentiable, increasing, weakly concave utility function $U(\cdot)$.

The expected utility of a bidder if it wins the contract is $E_{\mathbf{q}^a}\left[u\left(\pi(\mathbf{b}_i, \mathbf{c}_i; \mathbf{q}^a)\right)\right]$ where the expectation is integrated across possible realizations of actual quantities. This value is normalized to zero for losing bidders. Bidder i's auction payoff is its expected utility if it wins the auction times the probability it wins the auction.

$$E_{\mathbf{q}^a}\left[u\left(\pi(\mathbf{b}_i, \mathbf{c}_i, \mathbf{q}^a)\right)\right] \times Pr(s_i < s_j \quad \forall j \neq i)$$

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[18] Athey and Levin (2001) analyze timber auctions where a similar phenomenon occurs. The amount of timber species bid on and harvested differs. A model with affiliated signals about actual quantities is appropriate in their setting because bidders sample only small portions of a forest. In this application all bidders inspect exactly the same plans and job site so it is not clear why they would receive different signals about installed quantities. Furthermore modeling a general affiliated values auction makes formal analysis intractable with more than two tasks.

2.7 Characterization of Bidding

The equilibrium concept for this auction is a Bayesian Nash equilibrium. Bidders select unit price bids and subcontracting arrangements that are best responses to the equilibrium distribution of opponents bids. A best response solves the following maximization problem

$$\begin{aligned} \max_{\mathbf{b}_i,\mathbf{c}_i} \quad & E_{\mathbf{q}^a}\left[u\left(\pi(\mathbf{b}_i,\mathbf{c}_i,\mathbf{q}^a)\right)\right] \times Pr(s_i < \hat{s}_j \quad \forall j \neq i) \\ s.t. & \mathbf{b}_i \in \mathbf{R}_+^T \\ & c_{it} \in \{c_{it}^s, c_{it}^p\} \end{aligned}$$

where $\hat{s}_j$ is the equilibrium score for some type of opponent j. It is a strictly dominating strategy for contractors to choose the lowest cost subcontracting arrangement. Following the general result on scoring auctions in Asker and Cantillon (2008), bidding behavior is characterized by separating the problem into two parts. In the first part, bidders choose an optimal score, $\hat{s}_i$, that is a best response to their rivals' scores. In the second part, bidders allocate unit price bids subject to the constraint that they sum to the chosen score, $\mathbf{b}_i \cdot \mathbf{q}^e = \hat{s}_i$.

Consider the second stage problem of allocating unit price bids. There is a special type of task: lump sum tasks. Actual quantity do not differ from the engineer's quantity for lump sum tasks. Stated precisely, this implies that $Pr(q_t^a = q_t^e) = 1$. Mobilization is an example. Designate the first $t = 1, \ldots, L$ tasks as lump sum, and normalize their unit of measurement to one, so that $q_t^a = q_t^e = 1$. The remaining $t = L+1, \ldots, T$ tasks are called variable quantity tasks. The unit price bid allocation problem is,

$$\max_{\mathbf{b}_i} \quad E_{\mathbf{q}^a}\left[u\left(\sum_{t=1}^{L}(b_{it}-c_{it}) + \sum_{t=L+1}^{T}(b_{it}-c_{it})\,q_t^a\right)\right] \tag{1}$$

$$s.t. \qquad \sum_{t=1}^{L} b_{it} + \sum_{t=L+1}^{T} b_{it} q_t^e = \hat{s}_i \tag{2}$$

For emphasis, lump sum and variable quantity tasks are separated.

This problem mimics the standard portfolio choice problem in finance where a risk averse investor chooses how to allocate wealth amongst risk-free and risky assets. The engineer's quantity, q_t^e, corresponds to the price of an asset today; the actual quantity, q_t^a, tomorrow's price; the unit price bid, b_{it}, the number of shares that an investor purchases; the score, $\hat{s}_i$, wealth. Because actual quantities do not vary from the engineer's quantity for lump sum tasks and do vary for variable quantity task, the two classes of tasks correspond to risk-free and risky assets.

Two immediate observations are available by inspecting the maximization problem. First, a bidder earns risk free profits by submitting a bid at cost on the variable quantity tasks, and allocating the remainder of the bid to the lump sum tasks. The markup appears on the bids for lump sum tasks. Second, the allocation of bids across lump sum tasks is indeterminant. This is analogous to the notion in finance that owning a variety of issues of risk free assets is redundant. The importance of this remark is that observation of a submitted bid on any individual lump sum task is uninformative of cost unless other bidding motivations are taken into consideration.[19]

To further characterize bidding behavior take the first order conditions for an interior solution:

$$\begin{aligned} E\left[u'\left(\pi(\mathbf{b}_i)\right)\right] &= \lambda \qquad \forall t = 1, \ldots, L && (3) \\ E\left[u'\left(\pi(\mathbf{b}_i)\right)\right] q_t^e &= E\left[u'\left(\pi(\mathbf{b}_i)\right) q_t^a\right] \qquad \forall t = L+1, \ldots, T && (4) \end{aligned}$$

where $\pi(\mathbf{b}_i) = (\mathbf{b}_i - \mathbf{c}_i) \cdot \mathbf{q}^a$ is profit as a function of the bid vector and λ is the Lagrange multiplier on the constraint. To obtain an analytical closed form solution, I parameterize the utility function with a constant absolute risk aversion (CARA) representation: $u(x) = \frac{-1}{\gamma} e^{-\gamma x} + k$ where k is a constant that normalizes a losing bidder's payoff to zero. I perform a first order Taylor series expansion around bids at cost, ($\mathbf{b}_i = \mathbf{c}_i$ for the variable quantity task) to obtain a linearized unit price bidding equation that maps unit costs into unit price bids. See appendix for derivation.

If there is only one variable quantity task, the unit price bidding equation is,

$$b_{it} = c_{it} + \frac{1}{\gamma} \frac{E[q_t^a] - q_t^e}{E[(q_t^a - q_t^e)^2]} \tag{5}$$

A unit price bid is a linear function of unit cost and a skewing term that depends on the difference in a bidder's expectation of the actual quantity and the engineer's original quantity. The comparative statics match the intuition presented in Gate's (1959) example. If a bidder expects quantity to overrun, it skews its bid above cost, and skews below cost if an underrun is expected. Skewing aggression increases for larger quantity differences. Risk considerations temper skewing aggression. The term in the denominator, γ, is the Arrow-Pratt measure of absolute risk aversion; a more risk averse bidder skews less aggressively. The variance-like expression $E[(q_t^a - q_t^e)^2]$ is the riskiness of a quantity change; bidders skew less aggressively if quantity changes are more volatile. If a bidder forecasts no change and expects volatility, it would submit a bid equal to cost.

With more than one variable quantity task, the unit price bidding equation, stacked by task, is

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[19] Caltrans may reject a bid if it is deemed irregular. A bid of zero is grounds for rejection. In the data, rejection only occurs in cases when a large lump sum task has a bid of zero. Bids on variable quantity tasks are highly skewed. Some lump sum tasks have maximum bid limits. For example, the bid for Mobilization is often capped at 10% of the total bid to prevent "front end loading": over bidding on work paid near the beginning of the project.

$$\mathbf{b}_i = \mathbf{c}_i + \frac{1}{\gamma} E\left[(\mathbf{q}^a - \mathbf{q}^e)(\mathbf{q}^a - \mathbf{q}^e)'\right]^{-1} \left(E[\mathbf{q}^a] - \mathbf{q}^e\right) \tag{6}$$

Boldface vectors have length equal to the number of variable quantity tasks. Unit price bids are a linear function of unit cost and a skewing term that involves an expression resembling the inverse of a covariance matrix of quantity overruns. Not only does the expected overrun on a quantity affect the direction and aggression of a skew, skewing also depends on the covariances and expected overruns of other tasks. This is analogous to the idea in finance that an optimal portfolio depends on the correlation of returns across all assets. Like modern investors, contractors use sophisticated computer algorithms that take into account the correlation structure of risk.[20] The econometric procedure places restrictions on the covariance-like matrix $E\left[(\mathbf{q}^a - \mathbf{q}^e)(\mathbf{q}^a - \mathbf{q}^e)'\right]$ to recover unit costs from unit unit price bids.

An especially convenient feature of this derivation is that unit price bids do not depend on the bidding behavior of rivals. Intuition of first price auctions suggests a unit price bid should include a profit markup that depends on the competitiveness of the auction. Strategic interaction only matters for the choice of the score and consequently, the lump sum component of the bid. Interest centers on variable quantity tasks because I cannot measure incompleteness for lump sum task. Therefore it is sufficient to only consider this bidding equation.[21] Characterization (unreported) of the first stage problem, choosing a score, follows the standard derivation for a first price auction with bidder types defined by a pseudo-type, $\mathbf{c}_i \cdot \mathbf{q}^e$.

3 Data and Descriptive Evidence

The data were collected from public records of construction projects procured by the California Department of Transportation. The sample includes 32 bridge projects bid on and built between 2002 and 2005 using the *design-bid-build* procurement method. Most of the variables from the modeling section are found directly in the bidding documents. They list construction tasks, engineer's quantities, unit price bids, and a complete record of subcontracted tasks for all bidders. [22] In addition, they contain identifying information for bidders (names, addresses, phone numbers), and the names of, and tasks to be performed by, each subcontractor hired by a prime contractor.

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[20] Cattell et al. (2007) reviews these methods.

[21] This lack of dependence on strategy interaction is an artifact of the CARA utility. A bidder with decreasing absolute risk aversion skews more aggressively as wealth increases. In the model, wealth is higher for larger values of $\hat{s}_i - \mathbf{c}_i \cdot \mathbf{q}^e$. This can be demonstrated by following the same derivation with constant relative risk aversion—a representation with decreasing absolute risk aversion. In unreported work I perform the tests proposed in Athey and Levin (2001) and reject the hypothesis that bidders behave in accordance with decreasing absolute risk aversion. I conclude a CARA representation is appropriate.

[22] To comply with the *Subletting and Subcontracting Fair Practice Act*, contractors name all subcontractors that perform more than 1/2% of the work.

Subcontracting information is available for all bidders, even those that lose the auction. In grand total there are 17,018 observations of prime contractors' "make or buy" decisions for individual work items.

The sample includes 331 contractors. Of these, 74 participate as a prime contractor. In total they submit 178 bids on the 32 projects. On average, a project receives 5.6 bids with a minimum of 2 and maximum of 13. 274 contractors participate as subcontractors. 17 contractors participate at least once as a prime contractor and at least once as a subcontractor. The average project-bidder subcontracts 37% of project work by value.

These are not monumental bridges. Engineers estimate a "fair and reasonable" cost. By this measure, project range in size from \$700,000 to \$22,700,000 with an average of \$7,000,000. For comparison, the replacement 35W bridge is valued at \$234 million and the new east span of the San Francisco Oakland Bay Bridge into the billions of dollars. From visual inspection of Google Earth satellite images[23] I see the sample includes interstate overpasses, ramps and exchanges, and state highway bridges spanning rivers, creeks, washes, and hillside ravines.[24] For the average project there are 94 tasks; by comparison, Caltrans highway paving projects average 33 tasks.[25] Bridges require more tasks because a free standing structure is built in addition to some paving work that all bridge contracts require.

3.1 Construction Tasks

Across the 32 projects, there are 2,511 variable quantity and 482 lump sum project-tasks (indexed ct). The index, c, references contracts or projects. Caltrans classifies tasks using a coding system similar to NAIC industrial classifications. The sample includes 982 distinct tasks (indexed t). On average a task, t, is used on 3 of the 32 projects. Table 1 lists 26, Caltrans defined, categories of construction tasks at an aggregated level of grouping (hereafter referred to as industries and indexed τ). Industry literature and primary sources list the types of tasks that are considered ancillary and heavy construction tasks.[26] Taking this knowledge, I separate the industries into the two groups. Caltrans' documents do not separate heavy and ancillary tasks. The table also lists the dollar-

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[23] A bridge's precise location was found by cross referencing location data in the bidding documents with information from the Federal Highway Administration's National Bridge Inventory.

[24] Sample inclusion requires a project to use the task labeled "Structural Concrete, Bridge." All bridges, even steel bridges, require concrete. Many projects let during this time period were sound walls where a bridge member is built for a section of masonry wall. I only included bridges designed for vehicular traffic. Also excluded are very large interstate construction projects with project values on the magnitude of hundreds of millions of dollars into the billions.

[25] Statistic from Bajari et al. (2007).

[26] Sources include scholarly articles and books from the construction management literature (Arditi and Chotibhongs, 2005; Hinze, 1993; Sweet, 2004). Primary sources include discussions with contractors on the 35W bridge project and the annual investor report of Granite Construction, the only publicly traded company in the sample.

valued amount of work performed in each industry and the fraction of work subcontracted. As previously discussed, ancillary tasks are separated from heavy industries because prime contractors lack core competencies on ancillary tasks. This assertion is evident in the data. If a contractor sells its services on the subcontract market, it likely has a core competency in that task. Prime contractors have a 6% share of subcontracts for heavy construction tasks, and there are only a few exceptions where a prime contractor serves as a subcontractor on ancillary tasks.[27] That an industry, such as "Reinforcement" (installing rebar), is always subcontracted does not indicate prime contractors lack core competencies. Historic iron worker union rules prohibit employment by a firm that hires any non-union workers on a particular project. Thus a prime contractor must subcontract reinforcement. There are cases where a prime contractor subcontracts reinforcement, yet serves as a subcontractor for a rival bidder.

Caltrans provides blue book prices for all standardized tasks in its *California Cost Data Book*. This booklet is published annually. Blue book prices are based on unit price bids for all contracts awarded by Caltrans.

3.2 Incompleteness

Actual installed quantities, q^a_{ct}, were collected from final payment forms, administered by Caltrans' finance department. Incompleteness is measured as deviations in installed quantities from those specified in the original plans, $inc_{ct} = \left| \frac{q^a_{ct} - q^e_{ct}}{q^e_{ct}} \right|$. For lump sum tasks it is not possible to quantify a task specific measure of incompleteness because, by definition, quantities cannot vary. Variable quantity tasks exhibit a large amount of variation; they change 30% for the average task. Caltrans and contractors consider 20% to 25% changes as large. Table 2 presents a tabular histogram with quantity changes grouped into bins of small, medium, and large quantity overruns and underruns, as well as perfectly designed tasks where the original and final quantities are the same. Many of the project-tasks, 25%, have very large quantity changes of more than 35% (both underruns and overruns). Over a third are perfectly designed. There is no systematic tendency for tasks to be perfectly designed.[28] For bid skewing it is the direction, not just magnitude of quantity changes that matters. On average, quantities overrun by 3%; weighted by dollar-value, they underrun by 1%. There is large variation in the overall degree to which a project is completely specified. Weighted by dollar value, the most completely designed project averages quantity deviations of just 1%; the

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[27] Modern Alloys, a large firm that installs metal beam guard rails and concrete barriers once participated as a prime contractor. Granite Construction, the largest firm in the sample did a $300,000 subcontract for concrete sidewalks. Twice a prime contractor performed clearing and grubbing, once removed a tree, and once installed a small concrete barrier.

[28] The concern is that tasks measured in discrete units, such as a stoplight where the original quantity is a number like 4, would be perfectly designed whereas tasks measured in continuous units, such as cubic meters of concrete, would have at least a minor change. This is not the case.

most incomplete, 45%.

3.3 Prime Contractors and Subcontractors

The industry is localized for both subcontractors and prime contractors. The average prime contractor enters bids on 2.4 of the 32 projects; the average subcontractor enters subcontracting agreements on 2.5 projects. The average distance between a firm's nearest construction office and project is 98 miles for subcontractors and 94 miles for subcontractors.[29] Some of the contractors operate in the California wide market. This generates skew in the size distribution of firms. I classify any bidder that enters bids on fewer than 4 projects as a "fringe" firm. Ten of the 74 prime contractors are classified as non-fringe. Studies of highway procurement commonly make this distinction.[30]

What distinguishes subcontractors from prime contractors is their degree of specialization. The average prime contractor performs work in 2 of the 26 industries; the average prime contractor, in 16. Finally, as anecdotal evidence, 149 of the 274 (54%) subcontractors' business names references a construction specialty whereas only 5 of 74 for prime contractors. [31]

3.4 Unit Price Bids

The median bottom line bid, s_i is 5% above the engineer's cost estimate and the standard deviation of total bids divided by engineer estimates is 0.22. The moderate bid dispersion represents heterogeneity in bidders' total costs (in the model, heterogeneity in pseudo-types $\mathbf{c}_i \cdot \mathbf{q}^e$). The median unit price bid , b_{cit}, is 22% above the blue book value and the standard deviation is very large, 3.25. The large bid dispersion cannot be fully attributed to cost heterogeneity. Bids are skewed.

3.5 Excluded Data

For estimation, lump sum tasks are excluded because incompleteness cannot be measured and the bid need not reflect cost by the indeterminacy result. Non-standard tasks are excluded because they do not fall into industries classifications and blue book costs are unavailable. These exclusions do not pose problems. Many lump sum tasks are administrative duties or do not involve a construction service (pollution permits, warranties, mobilization). Nonstandard tasks are customized items like

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[29] Construction office locations found by cross referencing address data from the bidding documents with address information provided by companies own websites, and Google maps "find business" directory. I visually verified that the address is a construction office and not equipment yard or private residence. For contractors with multiple offices, the nearest office is paired to a project.

[30] See Bajari et al. (2007), Krasnokutskaya (2004).

[31] Examples of subcontractor specialty titles: Mike Brown Electric, West Coast Demolition, Pisor Fence. Prime contractor specialty titles: Lees Paving, Security Paving, Parnum Paving, Modern Alloys, Benco Bridges. Example non-specialty names: Shasta Constructors, Sterndahl Enterprises, Kiewit Pacific.

those labeled “drinking fountain”, “bat habitat”, “San Francisco manhole”. Exclusions shrink the sample size from 17,018 observations to 7,114 for ancillary tasks, and 5,240 for heavy construction tasks.

Table 3 lists additional summary statistics. Tables 4 and 5 list summary statistics for all variables used in estimation. Some of these variables will be defined in the following section.

4 Estimation

The goal of estimation is to determine the effect of incompleteness on unit cost for both primecontracting and subcontracting. In this section I describe the parametrization of cost functions and state hypotheses. Next, I discuss partial identification using a probit specification. Then, I discuss the fixed effect identification strategy to account for self-selection bias. I also introduce a source of endogeneity for incompleteness and discuss why the fixed effects control for this source of endogeneity. Finally, I present the technique to correct bid skewing.

4.1 Parametrization of Cost Functions

Rather than working directly with unit costs, that, across types of construction tasks, do not share a common unit of measurement, I instead use a normalized measure of unit costs. To normalize divide unit costs by a task’s blue book value. Normalization admits a natural interpretation of bids and costs as deviations from blue book value. It also controls for unobserved cost heterogeneity across types of tasks.

Observations are indexed by contract c, bidder i, and task t. Let c^*_{cits} and c^*_{citp} be the (normalized) unit cost of subcontracting and primecontracting and c^*_{cit} be the cost of the chosen arrangement. According to the subcontracting decision rule, prime contractors choose the lowest cost alternative. Thus,

$$sub_{cit} = \begin{cases} 1 & \text{if} \quad c^*_{cits} < c^*_{citp} \\ 0 & \text{if} \quad c^*_{cits} \geq c^*_{citp} \end{cases}$$

where the variable sub_{cit} indicates whether or not subcontracting is observed. The asterisks on cost variables emphasize that neither cost is directly observed by the econometrician (they are both known to the bidder). The asterisk on c^*_{cit} emphasizes that unit cost is not observed. Bids are observed.

I specify cost functions linearly:

$$\begin{aligned} c^*_{citp} &= \mathbf{x}'_{citp}\beta_{0p} + \beta^{inc}_{0p} inc_{ct} + e_{citp} \\ c^*_{cits} &= \mathbf{x}'_{cits}\beta_{0s} + \beta^{inc}_{0s} inc_{ct} + e_{cits} \end{aligned}$$

The main variable of interest is incompleteness, $inc_{ct} = \left|\frac{q^a_{ct} - q^e_{ct}}{q^e_{ct}}\right|$. The other covariates are $\mathbf{x}_{cit}$; e_{cits} and e_{citp} are error terms. The parameters, β_{0s} and β_{0p} capture marginal effects on subcontracting and primecontracting costs, respectively. The predictions discussed in section 2 are,

Predictions			
Heavy Construction tasks	$\beta^{inc}_{0s} \geq 0$	$\beta^{inc}_{0p} \geq 0$	$\beta^{inc}_{0s} - \beta^{inc}_{0p} > 0$
Ancillary tasks	$\beta^{inc}_{0s} \geq 0$	$\beta^{inc}_{0p} \geq 0$	$\beta^{inc}_{0s} - \beta^{inc}_{0p} =?$

Other covariates include the log of the distance between the job-site and the prime contractors nearest construction office and an indicator variable for whether the prime contractor is a fringe firm. Distant prime contractors—who are infrequent participants in input markets, unfamiliar with local ordinances, and facing higher costs to transport their own equipment — are predicted to have higher primecontracting costs. For reputation reasons distant contractors are predicted to have higher subcontracting costs. Overall, its ambiguous how distance affects the relative costs of subcontracting and primecontracting. For scale economies reasons, non-fringe contractors may have large enough logs of work to warrant maintaining divisions in a broad scope of construction activities. Thus fringe firms are predicted to have higher costs for primecontracting. I predict this is more relevant for ancillary tasks. Fringe status also captures reputation factors for both subcontracting and primecontracting.

Industry sources indicate project-task scale economies are an important determinant of unit cost. They arise by spreading out project-task fixed costs across more work and because of learning-by-doing. I include a normalized measure of the quantity: $\frac{q^e_{ct}}{\bar{q}^e_t}$. The denominator is the sample average engineer quantity for task, t.

4.2 Partial Identification: Probit Estimation

Partial identification is possible without any observation of bids, consideration of selection bias, or correction for bid skewing. The specification resembles a single index, binary discrete choice model. According to the subcontracting decision rule, a prime contractor hires a subcontractor if $\mathbf{x}'_{cit}\beta_{0s} - \mathbf{x}'_{cit}\beta_{0p} < e_{citp} - e_{cits}$. Define the random variable $\mu_{cit} = e_{citp} - e_{cits}$, which, under a probit specification, is assumed to be normally distributed with mean zero and variance $\sigma^2_{0\mu}$.[32] Conditional on the observed covariates, the probability of observing observation cit subcontracted is,

$$\begin{aligned} Pr(sub_{cit} = 1|\mathbf{x}_{cit}) &= Pr(\mathbf{x}'_{cit}(\beta_{0s} - \beta_{0p}) < \mu_{cit}) \\ &= \mathbf{N}\left(\frac{\mathbf{x}'_{cit}(\beta_{0s} - \beta_{0p})}{\sigma_{0\mu}}, 1\right) \end{aligned}$$

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[32] Single index discrete choice models are identified under weaker parametric assumptions than normality.

This has been the traditional method of inference in the "make or buy" literature. There are disadvantages. The parameters, β_{0s} and β_{0p}, are not separately identified; only the differential marginal effect $\beta_{0p} - \beta_{0s}$ is identified. Because the variance is normalized, scale is not identified. Even if interest were only in the differential effect, there is a potential loss in efficiency by not using the bidding data. All of these drawbacks can be overcome because bid data is available. Nonetheless, I consider probit estimates as part of the body of evidence.

4.3 Self-Selection Bias

For the moment suppose unit price bids equal unit cost. There is a potential self-selection bias in OLS estimation of the separate cost equations. Inconsistency arises if an omitted variable has a different effect on subcontracting costs and primecontracting costs. There is also the potential for inconsistency due to the endogeneity of incompleteness. The identification strategy exploits the panel data structure to control for both self-selection bias and incompleteness endogeneity.

The specifications include individual effects to capture industry, contract, and bidder specific characteristics. Expand the composite error term:[33]

$$\begin{aligned} e_{citp} &= \alpha_{\tau p} + \alpha_{cp} + \alpha_{ip} + \epsilon_{citp} \\ e_{cits} &= \alpha_{\tau s} + \alpha_{cs} + \alpha_{is} + \epsilon_{cits} \end{aligned}$$

The individual effects $\alpha_{\tau s}$ and $\alpha_{\tau p}$ capture factors specific to industries [34] for both primecontracting and subcontracting; the terms α_{cs} and α_{cp}, factors specific to the project or contract; and α_{is} and α_{ip} bidder specific factors. Individual effects are allowed to be fixed: correlated with regressors. They can be represented by dummy variables. Define $\mathbf{z}_{cits} = [\mathbf{x}_{cit}, \alpha_{\tau s}, \alpha_{cs}, \alpha_{is}]$ and $\mathbf{z}_{citp} = [\mathbf{x}_{cit}, \alpha_{\tau p}, \alpha_{cp}, \alpha_{ip}]$. With dozens to hundreds of observations in each cluster, dummy variable estimation will not be inconsistent due to an incidental parameters problem.

The residual error terms are assumed to reflect exogenous cost shocks common across primecontracting and subcontracting. That is, conditional on the fixed effect dummies, observed covariates, and subcontracting choices,

$$\begin{aligned} E[\epsilon_{cits} - \epsilon_{citp} | \mathbf{z}_{citp}, \mathbf{z}_{cits}, sub_{cit} = 1] &= 0 \\ E[\epsilon_{citp} - \epsilon_{cits} | \mathbf{z}_{citp}, \mathbf{z}_{cits}, sub_{cit} = 0] &= 0. \end{aligned}$$

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[33] Negative costs are in the support of the distribution because the specifications is in levels. The alternative, taking the logarithm of unit costs, is an unattractive specification. Doing so, without the blue book normalization, requires an individual effect for each type of task. This creates an incidental parameters problem. Moreover, when I introduce bids, the bid skewing equation 6 is characterized in levels, not logs.

[34] τ subscripts refer to industry clusters, distinct from the t subscripts referencing tasks. See table 1 for the list of industries.

The use of fixed effects for identification requires justification. In general, fixed effect specifications are attractive because they control for a lot of the unobserved heterogeneity. I will not attempt to exhaustively list all omitted variables that could generate self-selection bias. Instead I will discuss a few that are important to other theories of the firm.

I consider the property rights (Grossman and Hart, 1986; Hart and Moore, 1990; Hart, 1995), agency (Holmstrom and Milgrom, 1991), and relational contracting (Baker et al., 2002) theories of the firm. Property rights theory predicts asset characteristics determine ownership: that is, whether performance of a task is complementary to the management activities of a prime contractor. Industry fixed effects control for these characteristics. Agency theory regards the importance of monitoring employees. For some tasks, such as drilling, the care and maintenance of equipment requires attentive monitoring. Contract fixed effects also capture the importance monitoring. Monitoring is important for projects with limited construction zone accessibility.[35] Bidder fixed effects capture the reputation status of prime contractors. Industry fixed effects capture institutional features such as the labor union provisions for iron workers (discussed in the data section).

The residual error terms, ϵ_{cits} and ϵ_{citp}, capture cost shocks that are common across subcontracting and primecontracting. It represents idiosyncratic input cost shocks incurred by any subcontractor or prime contractor on a contract-task (i.e. labor wages, equipment rental rates, material costs).[36] It also represents a bidder's private information about managerial and oversight costs.

Endogeneity of incompleteness is a concern for two reasons. The first regards the job-site environment; the second, quality and workmanship standards. A project's location could present significant engineering challenges. This would be the case for a project in a mountainous ravine. Such an environment would increase the cost of construction and make it more costly to write a complete design. Project's with high unobserved quality standards have a high cost and require the engineer to write a more complete design. The typical example of a high quality, highly complete design, is an airport paving project. Contract fixed effects control for these omitted variables.

In the robustness section, I consider the Heckman (1979) control function approach as an alternative identification strategy.[37]

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[35] On the 35W bridge separate contractors performed work on the north and south end of the bridge because the alternative river crossings were clogged with traffic. Contractors could not monitor both ends of the bridge. A bridge in my sample was along a mountain pass where materials and contractors came from distant towns on opposite ends of the pass.

[36] This generates correlation in cost shocks across observations within a contract-task cluster. I use contract-task cluster robust standard errors.

[37] Technically, the error term in the probit specification lacks full support under these assumptions. Fixed effects control for the key omitted variables theory predicts are important. Factors, such as the working condition of a contractor's machinery used for a particular task, are minor in comparison and not the basis for a theory of firm boundaries. This technicality will be discussed in the context of the Heckman (1979) approach.

4.4 Bid Skewing Correction

In this section I describe the technique to correct bid skewing.

The general bidding equation with all contract-task engineer quantities normalized to one,

$$\mathbf{b}_{ci} = \mathbf{c}_{ci} + \frac{1}{\gamma} E\left[(\mathbf{q}_c^a - \mathbf{1})(\mathbf{q}_c^a - \mathbf{1})'\right]^{-1} (E[\mathbf{q}_c^a] - \mathbf{1})$$

is an additive function of unit cost and a skew term. For estimation I place three restrictions on the covariance-like expression to exploit its symmetry. Rename the matrix $\mathbf{V}_c := \gamma E\left[(\mathbf{q}_c^a - \mathbf{1})(\mathbf{q}_c^a - \mathbf{1})'\right]$ with the i, j cell denoted as v_{ij}^c. With some abuse of notation, the superscript c references the contract.

Diagonal elements capture the variance of task overruns. The first restriction assumes tasks within an industry, τ (i.e. roadwork, bridgework, ancillary tasks) share a common variance.

Restriction 1 $v_{ii}^c := v_\tau^c$ *for all* $i \in \tau$

Off diagonal terms capture covariances in task overruns. The second restriction assumes pairwise task covariances within industries and across industries are the same no matter which task pair is considered.

Restriction 2 $v_{ij}^c := v_{\tau\tau'}^c$ *for any* $i \in \tau$ *and* $j \in \tau'$ *and* $(i \neq j)$

Quantity overrun riskiness varies across projects. The third restriction preserves the relative variances and covariances of industries and scales these values by project riskiness. Let the scalar η_c represent the riskiness of contract c.

Restriction 3 $\eta_c \mathbf{V} = \mathbf{V}_c$

The following example $\mathbf{V}$ matrix illustrates the symmetric structure. There are 6 tasks and 2 industries: 3 (r)oad tasks and 3 (b)ridge tasks ($\tau \in \{r, b\}$).

$$\begin{pmatrix} v_r & v_{rr} & v_{rr} & v_{rb} & v_{rb} & v_{rb} \\ v_{rr} & v_r & v_{rr} & v_{rb} & v_{rb} & v_{rb} \\ v_{rr} & v_{rr} & v_r & v_{rb} & v_{rb} & v_{rb} \\ v_{rb} & v_{rb} & v_{rb} & v_b & v_{bb} & v_{bb} \\ v_{rb} & v_{rb} & v_{rb} & v_{bb} & v_b & v_{bb} \\ v_{rb} & v_{rb} & v_{rb} & v_{bb} & v_{bb} & v_b \end{pmatrix}$$

Placing restrictions by industry structure follows the finance analogy. It is like assuming stock returns within a sector share the same variance, and covariances are common amongst stocks within and across sectors. That contract riskiness varies is analogous to the notion that market riskiness varies across countries.

In the context of construction, these restrictions are reasonable. Events can have an effect that ripple across tasks. For example, an event could increase the length of road by 10% which would require a 10% increase in roadwork quantities. For another example, consider the modification to the 35W bridge discussed in the footnote of the introduction. When the piers were moved 20 feet, extra concrete, drilling and steel reinforcements were needed to bear the additional load of a longer span.

Inversion preserves symmetry. With $\mathbf{A} := \mathbf{V}^{-1}$, the unit price bidding equation becomes, $\mathbf{b}_{ci} = \mathbf{c}^*_{ci} + \frac{1}{\eta_c} A E[(\mathbf{q}^a_c - \mathbf{1})]$. Expanding around some contract-task ct in industry τ provides a map between a unit price bid and unit cost with a linear skewing correction:

$$b_{cit} = c^*_{cit} + \frac{1}{\eta_c}\left[a_\tau (E[q^a_{ct} - 1]) + \sum_{\tau'} \left(a_{\tau\tau'} \left(\sum_{ct' \in \tau' \cup c \; ct' \neq ct} (E[q^a_{ct'} - 1]) \right) \right) \right] + \psi_{cit} \tag{7}$$

The diagonal coefficients, a_τ, and off diagonal coefficients, $a_{\tau\tau'}$ (as a collection $\mathbf{a}$) are called bid-skew parameters. They can be estimated from bid data. Actual quantities, q^a_{ct} serve as a measure for expected actual quantities, $E[q^a_{ct}]$. Rather than estimating contract riskiness terms from bid data, I use the average squared overruns on a project, $\frac{1}{T_c}(\mathbf{q}^a_c - \mathbf{1})'(\mathbf{q}^a_c - \mathbf{1})$, as an estimate of contract riskiness, η_c. The error term, ψ_{cit}, represents expectational error and idiosyncratic variations in bid skewing. Tasks are grouped by 3 industries: roadwork, bridgework and ancillary tasks. There are a total of 9 bid-skew parameters. [38]

The specification is a system of four cost equations: on the subsamples of primecontracted and subcontracted tasks for both heavy industries and ancillary tasks. Cross equation restrictions are placed on the 9 covariates related to bid skewing.

Measurement error presents a limitation. The incompleteness proxy is measured with error and there is expectational error in the bid-skewing variables.[39] I consider the implications of measurement error while interpreting results and further discuss in the robustness section.

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[38] Alternatively the covariance structure could have been estimated from quantity data. This creates additional non-linear measurement error because it is multiplied with the measurement already present in the overrun term. As a robustness check I consider nested variants of the restrictions.

[39] Variables in a bidder's current information set could serve as valid instruments for expectational error. Hansen and Singleton (1982) used lagged assets returns as instruments. Using the analog of their instruments, lagged quantity overruns, does not work because overruns are not correlated across projects located in geographically distinct locations.

5 Results

I first present the cost estimates for the incompleteness parameter. Table 7 reports results for the preferred, baseline specification. It excludes bidder fixed effects because the fringe and distance variables already capture reputation factors. Table 6 presents probit estimates. Next, I expand the testing procedure to distinguish between changes that increase the amount of work and decrease the amount of work: Table 8. Finally, I comment on bid skewing (Tables 9 and 10) and other cost control variables.

5.1 Heavy Industry Incompleteness

For heavy construction tasks incompleteness has a positive and significant marginal effect on subcontracting costs ($\beta = 0.35$ standard error: $se = 0.18$). Interpreted as a dollar-valued elasticity, a 10 percentage point increase in quantity deviation leads to a 3.5 percentage point increase in unit cost relative to the blue book value. There are many tasks, around 1/3, with perfect design where the variable for incompleteness takes on a value of 0 and about 20% with quantity deviations exceeding 35%. In this range of incompleteness, subcontracting costs increase 10 percentage points. This result confirms the first prediction about subcontracting costs.

Incompleteness has zero effect on primecontracting costs ($\beta = -0.046$, $se = 0.039$). This results indicates adaptation costs are mitigated if work is performed within the firm. Given the large magnitude for subcontracting, this result is not likely an artifact of attenuation bias.

To be a determinant of the "make or buy" decision it is the differential marginal effect that matters; it is statistically significant and large. First stage probit estimates corroborate this finding; there is a statistically significant decrease in the probability of subcontracting as the degree of incompleteness increases. To reiterate the advantages of basing inference on cost outcomes, the probit analysis cannot deliver the result that incompleteness has zero effect on primecontracting, nor does it provide any indication about the magnitude of the effect on subcontracting costs. This result validates the theory and shows there are large dollar-valued magnitudes.

5.2 Ancillary Task Incompleteness

The evidence for ancillary tasks is different. Incompleteness has a modest positive marginal effect on subcontracting costs ($\beta = 0.15$, $se = 0.09$) that is substantially lower than the point estimate of 0.35 for heavy tasks. Incompleteness has a large positive marginal effect on primecontracting costs ($\beta = 0.54$, $se = 0.18$). To interpret the magnitude of this effect consider a change from perfect design to a quantity deviation of 35 percent; unit cost increases 15 percentage points. The differential marginal effect between subcontracting and primecontracting is positive and statistically significant. Probit estimates corroborate this finding; the probability of subcontracting increases in the degree of incompleteness. This finding indicates incompleteness generates bargaining costs between prime contractors and input markets—predicted by the core competency argument—that are more costly than bargaining costs with subcontractors.

In summary, incompleteness explains a large portion of costs. Consider the counterfactual that incompleteness is zero for all transactions. Incompleteness explains 7% of subcontracting costs and 0% of primecontracting costs for the average heavy construction transaction and 7% of subcontracting costs and 17% of primecontracting costs for the average ancillary task transaction. If primecontracting of heavy construction tasks and subcontracting of ancillary tasks are considered integrated transaction whiles subcontracting of heavy construction tasks and primecontracting of ancillary tasks are considered non-integrated, then incompleteness explains 2% and 13% for the average integrated and non-integrated transaction, respectively.

5.3 Overrun Underrun Distinction

Contract changes that increase the amount of work versus decrease the amount of work may cause different types of adaptation costs. A leading source of dispute regards scheduling and acceleration (working overtime and mobilizing additional workers and equipment). Quantity overruns are likely to trigger these disputes. Heavy construction tasks are included in schedule planning; ancillary tasks, which typically occur towards the end of a project, are excluded.[40] The prediction is that scheduling pressures from overruns are relevant for heavy construction tasks, not ancillary tasks.

Industry sources state that quantity underruns cause disputes about lost revenue (Sweet, 2004). Subcontractors lose business and cannot recoup project specific fixed costs. Prime contractors have less incentive to haggle with Caltrans over lost revenue on any given task because quantity overruns and underruns tend to even out.

To test if the effect of incompleteness differs for overruns and underruns, recast the cost equations as:

$$\begin{aligned} c^*_{citp} &= \mathbf{z}'_{cit}\beta_{0p} + \beta_{0p}^{incover}\left|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right|\mathbf{1}(q^a_{ct}\geq q^e_{ct}) + \beta_{0p}^{incunder}\left|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right|\mathbf{1}(q^a_{ct}< q^e_{ct}) + e_{citp} \\ c^*_{ns} &= \mathbf{z}'_{cit}\beta_{0s} + \beta_{0s}^{incover}\left|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right|\mathbf{1}(q^a_{ct}\geq q^e_{n}) + \beta_{0s}^{incunder}\left|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right|\mathbf{1}(q^a_{ct}< q^e_{ct}) + e_{cits} \end{aligned}$$

Under this specification an indicator for whether the task overruns or underruns on quantity interacts with the deviation in quantity (the measure of incompleteness in the original specification). Correcting for bid skewing is critical in this specification. Without a correction, a positive estimate on overruns partially reflects upward bid skewing. Estimates on underruns would be biased lower.

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[40] Contractors use a computerized system called the *critical path method* to schedule construction. As noted by Levin (1998) ancillary tasks are omitted.

For heavy construction tasks, overruns have a large effect on subcontracting costs ($\beta = 0.46$, $se = 0.19$). Underruns have zero effect on subcontracting cost ($\beta = 0.02$, $se = 0.29$). Overruns and underruns do not have a statistically significant effect on primecontracting costs (overrun: $\beta = -0.02$, $se = 0.04$ underrun: $\beta = -0.18$, $se = 0.20$). I postpone the interpretation of the negative coefficient to the discussion of bid skewing. Results indicate incompleteness generates scheduling adaptation costs with subcontractors. These costs are not present when a prime contractor performs work. Payment disputes about underruns are not significant.

For ancillary tasks, overruns have a negligible effect on subcontracting costs ($\beta = 0.09$, $se = 0.09$). Underruns have a large effect ($\beta = 0.74$, $se = 0.25$). This is the largest magnitude found so far. A change from perfect design to a quantity underrun of 35 percent increases unit cost 21 percentage points. This result indicates scheduling pressures do not matter, yet payment disputes about lost revenue are severe. Unlike the baseline specification that only found modest subcontract frictions, this specification detects a particularly severe hold-up problem.

For ancillary tasks, overruns and underruns have a large effect on primecontracting costs (overrun: $\beta = 0.62$, $se = 0.22$ underrun: $\beta = 0.28$, $se = 0.27$). The difference between overruns and underruns is not statistically significant. It is costly for prime contractors to adapt to any kind of quantity change.

There is a tentative explanation for why underruns cause payment disputes for ancillary tasks but not heavy construction tasks. It regards a government program about subcontracting to Disadvantaged Business Enterprises (DBEs). DBEs are firms owned by racial minorities and women. A two-part subcontract, with a fixed and marginal component would alleviate payment frictions. A subcontractor could recoup its fixed costs. For heavy construction tasks there is leniency on the part of Caltrans to allow flexible subcontracts. Ancillary tasks are more closely overseen by Caltrans because they involve DBEs. The DBE compliance form explicitly restricts subcontracts to be one-part. In the data, 30% of all subcontracts for ancillary tasks are with DBEs, just 4% for heavy construction tasks.

5.4 Bid Skewing

The top of table 9 presents estimates of the 9 bid-skewing parameters for the baseline specification. The diagonal terms are positive for all three industries. As expected, bidders skew up on overruns and down on underruns. The bottom of the table reports point estimates of the variance matrix **V**—the inverse of the estimates for **A**.

For ancillary tasks the diagonal term is small (variance high) relative to bridge and road tasks. Quantity changes are risky and bidders do not skew aggressively on these tasks. The covariances amongst ancillary tasks, and with road and bridge tasks are small in comparison. For road and bridge tasks the diagonal terms are large (variance low). The covariances amongst and across these tasks are significant. Bidders skew aggressively on bridge and road tasks. The correction for bid skewing is important for road and bridge tasks and less critical for ancillary tasks.

Table 10 reports estimates of the the bid-skewing parameters and variance matrix (**A** and **V**) for the specification with an overrun/underrun distinction. Compared to the baseline specification the estimates for **A** are attenuated lower for road and bridge task. Because of expectational error in the skew variables the estimates are already attenuated in both specifications. Further attenuation is a product of contamination bias. Contamination occurs because the skew variables are highly correlated with the two incompleteness proxies, which themselves are measured with error. The degree of bid skewing is being underestimated. It is possible to predict the direction of bias for the incompleteness measures. For heavy tasks, overrun incompleteness is biased upward and underrun incompleteness is biased downwards. This explains the negative estimate on primecontracting for underruns. The relative differential between overruns and underruns for subcontracting is exaggerated because of the bias. This means underruns have an effect of subcontracting costs and scheduling pressures are not as severe as the point estimates indicate.

In contrast to road and bridge tasks, the ancillary task bid-skew parameter for **A** is larger in the overrun/underrun specification than the baseline specification. The degree of bid skewing is being overestimated. Overrun incompleteness is biased downwards, and underrun incompleteness is biased upwards. The positive effect of underruns on subcontracting costs—reflecting payment disputes—is overestimated. For primecontracting the differential between overruns and underruns is underestimated. I reinterpret the result to mean the prospects of acquiring additional inputs is more costly that the prospects of laying off inputs.

5.5 Fringe Status and Distance

The coefficients on fringe status and distance generally have the expected signs. Fringe and distant firms have higher primecontracting costs for heavy construction tasks. For ancillary tasks there is no effect. This result rejects the hypothesis that larger, non-fringe firms attain a minimum efficient scale on ancillary tasks. Fringe firms have higher subcontracting costs for both types of tasks. This suggests reputation matters. Distance has a minimal effect on cost.

Cost based estimates cannot distinguish statistically significant differential effects between primecontracting and subcontracting. Probit estimates detect significant differentials. Distant and larger firms are more likely to subcontract heavy construction tasks. The results are exactly the opposite for ancillary tasks. Probit results for distance are not robust to the inclusion of bidder fixed effects.

5.6 Scale Economies

Task economies of scale are significant and explain the majority of the variation in unit price bids. Consider the baseline specification. For heavy construction tasks performed by the prime contractor, the estimated elasticity of scale ($\beta = -0.39$, $se = 0.04$) indicates a 10 percentage point increase in quantity relative to the average amount of work performed on the same type of task decreases unit costs by 3.9 percentage points. For subcontracting the elasticity is smaller in magnitude ($\beta = -0.31$, $se = 0.04$). Given that subcontractors typically perform work on many more projects in a construction season than prime contractors, there is less learning-by-doing for subcontractors on any given project. The difference in elasticities suggests prime contractors close the learning gap with more work. Probit estimates confirm this result; prime contractors are less likely to hire subcontractors at high quantities. For ancillary tasks the results are similar, except elasticities are slightly smaller in magnitude (primecontracting: $\beta = -0.37$, $se = 0.06$; subcontracting: $\beta = -0.25$, $se 0.04$). Probit estimates do not detect a significant differential between primecontracting and subcontracting.

6 Robustness

The identification strategy relies on fixed effects to control for selection. An alternative specification considers a switching regression technique that uses a control function approach (Heckman, 1979). In the Roy (1951) model framework, where selection is based solely on cost outcomes and not on non-monetary considerations, finding valid exclusion restrictions is challenging. This is especially challenging because the excluded variables should be at the detailed level of a project-task. [41] Fixed effects already control for most observed variables. On technical grounds the control function approach—even without exclusion restrictions—should be used.[42] The coefficients on the control functions are statistically insignificant. Therefore, it is not necessary to include them in the cost equation estimates. Results differ negligibly under this method.

I also consider a specification that relaxes the Roy (1951) model framework and uses an exclusion restriction. The exclusion restriction is based on the requirement to make a "good faith effort" to hire disadvantaged business enterprise (DBE) subcontractors. The DBE requirement (stated as a percentage of total contract value) could be a plausible exogenous shifter of subcontracting probabilities that has no effect on either subcontracting or primecontracting costs. There is a strong correlation in the data that higher DBE goals are associated with more subcontracting of

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[41] To identify subcontracting costs the excluded variables should affect primecontracting costs and not subcontracting costs. To identify primecontracting costs the excluded variables should affect subcontracting costs and not primecontracting costs.

[42] As mentioned in the estimation section, the assumptions on the residual error terms lack full support in the probit specification. The control function approach is a technical solution to this problem.

ancillary tasks, and less subcontracting of heavy construction tasks. This follows because there are subcontracting caps that bind for many bidders. A higher DBE goal increases the amount of ancillary tasks subcontracted and, when the cap bids, requires a reduction in the amount of heavy construction tasks subcontracted. In the data, DBE's almost exclusively perform ancillary tasks (30% of all ancillary task subcontracts and 4% of heavy construction subcontracts). Estimates preserve results, but magnitudes differ.[43]

Unit price bids display an extreme amount of dispersion which adversely impacts estimation efficiency. Beeston (1975) first documented this fact and I find it in this data. For example, within the same project-task the highest bid is on average 7.49 times greater than the lowest. In situations when the same subcontractor is hired for a project-task—presumably costs are nearly identical—this ratio is 3.49. Other measures of bid dispersion show the same pattern. This dispersion cannot be reconciled by heterogeneity in cost or risk aversion. There are 4 possible explanations. First, pairwise task correlation could be quite high in which case those tasks are skewed as a pair rather than individually. Allocation within the pair is arbitrary. Second, if bidders do not expect volatility in quantity the task resembles a lump sum task. Third, with an average of 94 tasks, where quantities average out to zero overrun, there is little aggregate risk to arbitrarily allocating unit price bids. Fourth, industry sources state that contractors have an incentive to conceal their true unit costs from Caltrans and rivals by randomizing bids. The correction accounts for systematic bid skewing but cannot control the full amount of bid dispersion.

There is an alternative interpretation of the ancillary/heavy task distinction. The property rights theory is also based on contractual incompleteness. It predicts incompleteness affects cost. Taken in isolation, incompleteness is not predicted to have a differential effect on subcontracting and primecontracting costs. Broadly speaking, how important an investment decision in an asset is with the investment decision of a prime contractor determines how a transaction should be arranged. It is plausible the construction methods for performing ancillary tasks are unimportant for the management activities of a prime contractor. The result about incompleteness magnifies this differential.

7 Conclusion

This paper provides empirically evidence that the bargaining frictions caused by contractual incompleteness have a substantial impact on cost in the construction industry. In particular, the effect differs for primecontracting (in-house) and subcontracting (market) transactions. Unlike traditional studies of the "make or buy" decision that provide qualitative evidence about firm

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[43] The primary disadvantage of this method is that the DBE goal is absorbed by the contract fixed effect. The incompleteness measure is potentially correlated with contract characteristics.

boundaries, this study quantifies the cost of those decisions. Such a research design is made possible because contractors' bids reflect all costs, including anticipated bargaining and renegotiation frictions.

I developed a model of the subcontracting and competitive bidding process for Caltrans bridge contracts. For each work item, prime contractors submit a unit price bid and decide whether to perform work themselves or hire a subcontractor. After describing the environment, I made predictions about the effect of incompleteness on cost for primecontracting and subcontracting. They differ for heavy construction and ancillary tasks. I proposed a measure of incompleteness—the difference in original and revised work item quantities. Finally, I characterized bidding behavior which shows how bidders forecast quantity changes to allocate unit price bids based on principles analogous to those in modern portfolio theory. I embed this characterization into the econometric procedure and use a fixed effects strategy to control for the endogeneity of subcontracting decisions.

For heavy construction tasks, incompleteness does not affect primecontracting costs. This indicates hold-up problems are mitigated within the firm. Subcontracting involves significant costs. Changes from perfect design, that occur about a third of the time, to quantity overruns of 35% or more, again not uncommon, cause a 10% increase in subcontracting costs. The asymmetric result, that costs increase in anticipation of extra work, indicates scheduling pressures and conflict over acceleration are the source of hold-up.

For ancillary tasks, incompleteness impacts cost under both forms of organization. The effect for subcontracting is modest, except one case. In anticipation of quantity underruns, there are severe frictions likely stemming from disputes about lost revenue. In the mentioned range, cost increases 21%. The effect for primecontracting is quite large. Cost increases 15%. I attribute this result to a consideration of frictions in input market transactions. They resemble one-shot transactions for prime contractors. In contrast, specialty subcontractors are tightly integrated with input markets.

This paper also provided a glimpse of evidence about relational determinants of firm boundaries by considering the fringe status of contractors and their proximity to the job-site. Reputation factors differ for heavy and ancillary tasks. There is interest in further studies of relational contracting in this industry.

In conclusion, I will interpret the results to offer directed thoughts about how to achieve cost savings. The most stark prescription would be for engineers to prepare more complete plans and for buyers to avoid making ex-post changes. For heavy construction tasks, avoiding changes that increase the amount of work or create scheduling pressures would be an especially effective means of reducing cost. As a qualification, I am unable to comment on the cost of writing more complete contracts. For ancillary tasks I offer two prescriptions. They both concern the *Subcontracting and Subletting Fair Practice Act.* The results indicate prime contractors are ill-suited to perform these tasks. One potential explantation for why they do not hire subcontractors more often is because of restrictive subcontracting limits. Relaxing limits for ancillary tasks could be a more effective means of reducing cost than an attempt to write more complete designs. The second consideration is about the requirement to name all subcontractors at the time bids are submitted. Because ancillary tasks occur near the end of a project, let contractors choose subcontractors at a later date when designs could be more certain. This would also free up contractors' time during the hectic pre-bidding phase.

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A Derivation of Unit Price Bidding Equations

Omit bidder subscripts and make a change of variables. Define $\tilde{\mathbf{b}} = \mathbf{b} - \mathbf{c}$, such that positive entries for $\tilde{\mathbf{b}}$ correspond to bidding above cost (like taking a long position in an asset); negative entries, bidding below cost (a short position). According to the indeterminacy of lump sum bids, group the lump sum bids and costs as: $b_l = \sum_{t=1}^{L} b_t$ and $c_l = \sum_{t=1}^{L} c_t$. With the change of variables and CARA utility function, rewrite the first order conditions for variable quantity task t as:

$$E\left[\frac{1}{\exp((s-c_l-\mathbf{c}\cdot\mathbf{q}^e+\tilde{\mathbf{b}}\cdot(\mathbf{q}^a-\mathbf{q}^e))\gamma)}\right]q_t^e = E\left[\frac{1}{\exp((s-c_l-\mathbf{c}\cdot\mathbf{q}^e+\tilde{\mathbf{b}}\cdot(\mathbf{q}^a-\mathbf{q}^e))\gamma)}q_t^a\right] \quad (8)$$

The denominator term uses the equality on the constraint that bids sum up to the score to substitute out the lump sum bid, b_l. Now boldface vectors have length $T-L$. To linearize the function $u'(\pi(\tilde{\mathbf{b}}))$ take a first order Taylor series expansion around bids at cost, $\tilde{\mathbf{b}}=\mathbf{0}$

$$\begin{aligned}\frac{1}{\exp(\pi(\tilde{b})\gamma)} &\approx \frac{1}{\exp(\pi(\mathbf{0})\gamma)} - \frac{\gamma}{\exp(\pi(\mathbf{0})\gamma)}(\mathbf{q}^a-\mathbf{q}^e)'\tilde{\mathbf{b}} \\ \pi(\mathbf{0}) &= s-c_l-\mathbf{c}\cdot\mathbf{q}^e\end{aligned}$$

Substituting this linearized expression back into the first order conditions and performing further algebraic manipulation yields,

$$\frac{1}{\gamma}E[q_t^a-q_t^e] = E\left[(q_t^a-q_t^e)(\mathbf{q}^a-\mathbf{q}^e)'\right]\tilde{\mathbf{b}} \quad (9)$$

Then stacking by tasks and substituting $\tilde{\mathbf{b}}=\mathbf{b}-\mathbf{c}$ gives the unit price bidding equation

$$\mathbf{b}_i = \mathbf{c}_i + \frac{1}{\gamma}E\left[(\mathbf{q}^a-\mathbf{q}^e)(\mathbf{q}^a-\mathbf{q}^e)'\right]^{-1}(E[\mathbf{q}^a]-\mathbf{q}^e) \quad (10)$$

B Tables

Table 1: Construction Industry List

Percent of Work Subcontracted	Industry	Value of Work Performed($)
Heavy Industries		
12.0%	Concrete Structures	38,000,000
12.0%	Bituminous Seals	5,718,948
15.8%	Miscellaneous Metal	878,599
16.0%	Pipes Sewers Drainage	2,205,067
17.0%	Steel Structures	4,198,709
22.8%	Slope Protection	1,741,642
23.0%	Earthwork	16,200,000
42.7%	Shotcrete	130,040
46.3%	Asphalt Concrete	13,200,000
47.8%	Portland Cement Pavement	2,899,470
85.5%	Piling	10,700,000
87.0%	Prestressing Concrete	1,933,822
99.3%	Reinforcement	14,900,000
	Total Heavy Industry Work	112,706,297
Ancillary Industries		
13.5%	Markers And Delineators	31,296
18.1%	Traffic Control Devices	8,763,694
43.5%	Concrete Curbs And Sidewalks	1,248,134
47.7%	Clearing And Grubbing	620,460
50.3%	Waterproofing	205,623
59.3%	Existing Highway Facilities	7,460,883
67.5%	Railings And Barriers	4,957,768
67.6%	Signs	1,384,097
71.6%	Erosion Control And Planting	3,118,165
83.4%	Traffic Stripes And Markings	642,315
86.7%	Fences	303,895
98.2%	Electrical	3,445,871
98.9%	Painting	3,975,775
	Total Ancillary Work	36,157,976
	Total All Work	148,864,273

Industry size based on winning bids. Subcontracting percentage based on submitted bids. Nonstandard tasks excluded. Lump sum tasks included. Noteworthy lump sum task: "Remove Existing Bridge" in industry "Existing Highway Facilities". Remaining tasks are the removal of signs, barriers and traffic striping.

Table 2: Quantity Overruns and Underruns

			Frequency		
		$\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}$	All Tasks	Heavy Tasks	Ancillary Tasks
	Perfect Design	0	35.4%	39.9%	32.1%
	Small	(0,.1]	11.0%	13.3%	9.3%
Overruns	Medium	(.1,.35]	7.2%	7.2%	7.2%
	Large	$>.35$	10.0%	5.6%	13.3%
	Small	[-.1,0)	13.6%	17.0%	11.1%
Underruns	Medium	[-35,-.1)	8.4%	7.1%	9.4%
	Large	[-1,-.35)	14.3%	9.9%	17.5%
Project task	Observations		2201	941	1260

Table 3: Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
Across Projects					
Engineer's Cost Estimate($)	32	6,985,134	6,414,246	701,000	22,200,000
Number of Bidders	32	5.56	2.38	2	13
Number of Line Item Tasks	32	93.53	42.45	37	221
Weighted Average Incompleteness	32	0.109	0.097	0.012	0.448
Across Industries					
Percent Contract Value Subcontracted	26	49.46%	31.61	1.77%	99.28%
Value of Industry Work($)	26	5,742,537	7,741,581	26,457	35,800,000
Number of Distinct Tasks	26	25.3	29.7	1	131
Occurrences on Projects(out of 32)	26	21.9	9.6	2	32
Across Project Bidders					
Total Bid/Engineer's Cost Estimate	178	1.06	0.22	0.62	2.10
Distance to Project(mi)	178	107.3	126.0	0.3	663.0
Percent Contract Value Subcontracted	178	37.22%	13.55	8.92%	77.38%
Across Project Tasks (Not Lump Sum)					
Absolute Quantity Change $\frac{\lvert q^a_{ct}-q^e_{ct}\rvert}{q^e_{ct}}$	2511	0.302	0.749	0	14.487
Quantity Change $\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}$	2511	0.035	0.807	-1	14.487
Across Prime Contractors					
Total Value Primecontracts Tendered($)	74	18,400,000	20,600,000	1,083,000	93,700,000
Contract Participation(out of 32)	74	2.405	2.013	1	11
Contracts Awarded(out of 32)	74	0.432	0.684	0	3
Industry Performance(out of 26)	74	16.351	4.001	7	26
Across Subcontractors					
Total Value Subcontracts Tendered($)	274	1,856,867	4,362,414	3,072	46,400,000
Contract Participation(out of 32)	274	2.460	2.767	1	19
Prime Contractor Partners(out of 74)	274	5.062	5.587	1	37
Industry Performance(out of 26)	274	1.985	1.526	0.0	11

Weighted average incompleteness: absolute quantity change weighted by bluebook values. Value of industry work based on winning bids.

Table 4: Summary Statistics: Variables Used in Estimation

	Obs	Mean	Std. Dev.	Min	Max
Heavy Subcontracted					
Incompleteness					
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert$	1577	0.169	0.460	0	7.681
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a \geq q_{ct}^e)$	1577	0.075	0.413	0	7.681
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a < q_{ct}^e)$	1577	0.094	0.236	0	1
Fringe (indicator)	1577	0.564	0.496	0	1
Log Distance to Project	1577	4.099	1.276	-1.346	6.497
Task Scale Economies $\frac{q_{ct}^e}{\bar{q}_t^e}$	1577	1.095	1.035	0.0002	10.113
Normalized Unit Price Bid $\frac{b_{cit}}{c_t^{bb}}$	1577	1.901	2.362	0.001	32.648
Heavy Primecontracted					
Incompleteness					
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert$	3663	0.251	0.838	0	12.444
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a \geq q_{ct}^e)$	3663	0.146	0.819	0	12.444
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a < q_{ct}^e)$	3663	0.105	0.251	0	1
Fringe (indicator)	3663	0.542	0.498	0	1
Log Distance to Project	3663	3.937	1.223	-1.346	6.497
Task Scale Economies $\frac{q_{ct}^e}{\bar{q}_t^e}$	3663	1.083	1.225	0.0009	10.113
Normalized Unit Price Bid $\frac{b_{cit}}{c_t^{bb}}$	3663	2.016	2.682	0.001	50.036
Ancillary Subcontracted					
Incompleteness					
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert$	3597	0.379	0.754	0	10.735
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a \geq q_{ct}^e)$	3597	0.219	0.739	0	10.735
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a < q_{ct}^e)$	3597	0.159	0.303	0	1
Fringe (indicator)	3597	0.535	0.499	0	1
Log Distance to Project	3597	3.854	1.192	-1.346	6.497
Task Scale Economies $\frac{q_{ct}^e}{\bar{q}_t^e}$	3597	1.037	1.069	0.0002	10.986
Normalized Unit Price Bid $\frac{b_{cit}}{c_t^{bb}}$	3597	1.689	2.286	0.007	53.227
Ancillary Primecontracted					
Incompleteness					
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert$	3517	0.317	0.539	0	6.667
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a \geq q_{ct}^e)$	3517	0.159	0.497	0	6.667
$\left\lvert\frac{q_{ct}^a-q_{ct}^e}{q_{ct}^e}\right\rvert \mathbf{1}(q_{ct}^a < q_{ct}^e)$	3517	0.158	0.305	0	1
Fringe (indicator)	3517	0.560	0.497	0	1
Log Distance to Project	3517	3.997	1.213	-1.346	6.497
Task Scale Economies $\frac{q_{ct}^e}{\bar{q}_t^e}$	3517	0.973	0.929	0.0002	7.423
Normalized Unit Price Bid $\frac{b_{cit}}{c_t^{bb}}$	3517	1.980	4.678	0.001	189.251

Table 5: Summary Statistics: Bid Skewing Correction Variables

	Obs	Mean	Std. Dev.	Min	Max
Diagonal Skew Variables					
a_b	3422	-0.024	1.423	-11.936	11.277
a_r	1818	-0.320	1.808	-10.980	10.353
a_a	7114	-0.144	2.528	-15.084	40.630
Off Diagonal Skew Variables					
a_{bb}	3422	6.890	60.654	-120.934	103.495
a_{rr}	1818	-32.501	84.012	-295.461	91.951
a_{aa}	7114	-16.459	120.918	-386.906	318.106
a_{br}	5240	-12.707	65.584	-295.461	103.495
a_{ba}	10536	-3.684	90.894	-386.906	318.106
a_{ra}	8932	-29.361	92.046	-386.906	318.106
Project Riskiness					
$\frac{1}{T_c}\left(\mathbf{q}_c^a - \mathbf{1}\right)'\left(\mathbf{q}_c^a - \mathbf{1}\right)$	32	0.524	0.669	0.019	2.708

"b": bridge tasks "r": road tasks "a": ancillary tasks

See estimation section for definition of variables.

Table 6: Probit: Subcontracting Probabilities

	Heavy Industries		Ancillary Tasks	
	I	II	III	IV
Incompleteness $\left\|\frac{q^a-q^e}{q^e}\right\|$	-0.077	-0.088	0.110	0.118
	(0.035)	(0.037)	(0.028)	(0.028)
Other Cost Controls				
Fringe(indicator)	0.127		-0.041	
	(0.047)		(0.036)	
Log Distance to Project	0.092	-0.092	-0.054	-0.031
	(0.020)	(0.042)	0.016)	(0.032)
Task Scale Economies $\frac{q^e}{\bar{q}^e}$	-0.036	-0.039	0.021	0.021
	(0.021)	(0.021)	(0.018)	(0.018)
Industry Effect(N=13)	Fixed	Fixed	Fixed	Fixed
Project Effect(N=32)	Fixed	Fixed	Fixed	Fixed
Bidder Effect(N=74)	None	Fixed	None	Fixed
Contract Task Observations	5240	5240	7114	7114
Subcontracted Tasks	1577	1577	3597	3597
Pseudo-R squared	0.272	0.324	0.14	0.219

Regressand: Subcontracting Indicator. Negative coefficients imply subcontracting costs relatively higher than primecontracting costs. Standard errors in parentheses. That there are 13 ancillary industries and 13 heavy industries is pure coincidence.

Table 7: Cost Estimates: Baseline Specification

	Heavy Industries		Ancillary Tasks	
	Sub	Prime	Sub	Prime
Incompleteness $\left\lvert\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right\rvert$	**0.353**	**-0.046**	**0.153**	**0.540**
	(0.148)	(0.039)	(0.090)	(0.183)
Other Cost Controls				
Fringe(indicator)	0.159	0.101	0.069	-0.005
	(0.117)	(0.097)	(0.086)	(0.140)
Log Distance to Project	0.034	0.087	-0.024	0.038
	(0.039)	(0.045)	(0.041)	(0.049)
Task Scale Economies $\frac{q^e_{ct}}{\bar{q}^e_t}$	-0.305	-0.391	-0.247	-0.373
	(0.041)	(0.032)	(0.037)	(0.058)
Industry Effect(N=13)	Fixed	Fixed	Fixed	Fixed
Project Effect(N=32)	Fixed	Fixed	Fixed	Fixed
Bidder Effect(N=74)	None	None	None	None
Contract Task Observations	5240	5240	7114	7114
Subcontracted Tasks	1577	1577	3597	3597

Regressand: Unit price bid/Blue book unit cost
contract-task robust standard errors in parentheses
R-squared 0.35
Skew-term estimates shown in table 8
That there are 13 ancillary industries and 13 heavy industries is pure coincidence.

Table 8: Cost Estimates: Overrun/Underrun Distinction

	Heavy Industries		Ancillary Tasks	
	Sub	Prime	Sub	Prime
Overrun				
Incompleteness $\left\|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right\| \mathbf{1}(q^a_{ct} \geq q^e_{ct})$	**0.461**	**-0.019**	**0.089**	**0.619**
	(0.190)	(0.039)	(0.090)	(0.216)
Underrun				
Incompleteness $\left\|\frac{q^a_{ct}-q^e_{ct}}{q^e_{ct}}\right\| \mathbf{1}(q^a_{ct} < q^e_{ct})$	**-0.020**	**-0.184**	**0.738**	**0.281**
	(0.292)	(0.195)	(0.248)	(0.267)
Other Cost Controls				
Fringe(indicator)	0.160	0.101	0.074	-0.005
	(0.117)	(0.097)	(0.086)	(0.140)
Log Distance to Project	0.034	0.087	-0.027	0.036
	(0.039)	(0.045)	(0.041)	(0.049)
Task Scale Economies $\frac{q^e_{ct}}{\bar{q}^e_t}$	-0.308	-0.392	-0.246	-0.367
	(0.040)	(0.032)	(0.038)	(0.058)
Industry Effect(N=13)	Fixed	Fixed	Fixed	Fixed
Project Effect(N=32)	Fixed	Fixed	Fixed	Fixed
Bidder Effect(N=74)	None	None	None	None
Contract Task Observations	5240	5240	7114	7114
Subcontracted Tasks	1577	1577	3597	3597

Regressand: Unit price bid/Blue book unit cost
contract-task robust standard errors in parentheses
R-squared 0.35
Skew-term estimates shown in table 9
That there are 13 ancillary industries and 13 heavy industries is pure coincidence.

Table 9: Skew Matrix Estimates: Absolute Value Incompleteness

($\mathbf{A} = \mathbf{V}^{-1}$) Inverse Covariance Matrix			
	Bridge	Road	Ancillary
Bridge (diagonal)	0.0947		
	(0.0236)		
Bridge (off diagonal)	0.0196		
	(0.0043)		
Road (diagonal)		0.0867	
		(0.0440)	
Road (off diagonal)	0.0100	0.0067	
	(0.0037)	(0.0037)	
Ancillary (diagonal)			0.0176
			(0.0307)
Ancillary (off diagonal)	-0.0025	0.0005	0.0004
	(0.0042)	(0.0041)	(0.0015)
($\mathbf{V}$) Covariance Matrix			
Bridge (diagonal)	11.26		
Bridge (off diagonal)	-2.05		
Road (diagonal)		11.82	
Road (off diagonal)	-1.00	-0.68	
Ancillary (diagonal)			57.25
Ancillary (off diagonal)	1.34	-0.59	-0.89

standard errors in parentheses.

Matrix (**A**) estimated from bid data. Matrix (**V**) inverse of matrix (**A**) point estimates.

See estimation section for description of matrices and estimation procedure.

Table 10: Skew Matrix Estimates: Over/Under Incompleteness

($\mathbf{A} = \mathbf{V}^{-1}$) Inverse Covariance Matrix			
	Bridge	Road	Ancillary
Bridge (diagonal)	0.0655		
	(0.0304)		
Bridge (off diagonal)	0.0196		
	(0.0043)		
Road (diagonal)		0.0600	
		(0.0427)	
Road (off diagonal)	0.0100	0.0068	
	(0.0037)	(0.0037)	
Ancillary (diagonal)			0.0248
			(0.0323)
Ancillary (off diagonal)	-0.0026	0.0004	0.0005
	(0.0041)	(0.0041)	(0.0015)
($\mathbf{V}$) Covariance Matrix			
Bridge (diagonal)	17.31		
Bridge (off diagonal)	-4.48		
Road (diagonal)		17.47	
Road (off diagonal)	-1.94	-1.33	
Ancillary (diagonal)			40.64
Ancillary (off diagonal)	1.38	-0.65	-0.51

standard errors in parentheses.

Matrix ($\mathbf{A}$) estimated from bid data. Matrix ($\mathbf{V}$) inverse of matrix ($\mathbf{A}$) point estimates.

See estimation section for description of matrices and estimation procedure.