

An Experimental Study of Bidding Behavior in Procurement Auctions with Subcontract Bids*

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Abstract

In order to lower the estimates of the total project costs, prime contractors often solicit bids from subcontractors which can complete their works with lower costs than they do by themselves, prior to submitting their own bids in procurement auctions. This paper presents a simple model of such two-stage auctions and shows some observations in a laboratory experiment conducted to examine theoretical predictions. Our main observations are as follows. (1) Subcontractors bid more aggressively (i.e., they lower their bids) in the first-price subcontract auctions, as compared to the case where there is no second-stage competition among prime contractors. (2) Second-price subcontract auctions render higher profits to prime contractors than first-price auctions. (3) First-price subcontract auctions more likely achieve *ex post* efficient allocations of a subcontract work than second-price auctions. The policy implications are also discussed.

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1 Introduction: Unobservable Subcontract Bids

It is commonly observed in practices that prime contractors solicit bids from the agents which can complete subcontract works with lower costs than they do by themselves, in order to lower the estimates of the total project costs. The auctioneers in those subcontract auctions will become bidders in subsequent procurement auctions. This paper casts light on such procurement auctions with subcontract bids in order not only to study bidding behavior of both prime contractors and subcontractors but also to draw policy implications towards practices.

We first present a simple theoretical model of this two-stage auction. The first stage is for subcontract auctions, and the second stage is for a procurement auction. It is, however, extremely difficult to collect a complete set of field data of subcontract bids in many countries: the results of procurement auctions are publicly opened to observe, whereas in subcontract auctions few agents can observe actual bids. By using the data obtained by the computerized laboratory experiment, we thus next statistically examine our theoretical predictions.

In our model, a procurement buyer asks for bids from two prime contractors, and each prime contractor solicits bids from two subcontractors, respectively. In each subcontract auction, first or second-price sealed-bid auction is conducted, and the lowest bidder makes a subcontract agreement with the prime contractor. For each subcontractor, the cost for completing the subcontract work is private information. There is no work that the prime contractors do by themselves after subcontracting. The cost of each prime contractor is then the payment to the winner of the subcontract auction, but the payment is due only when the prime contractor wins the procurement auction. In the subsequent procurement auction, first-price sealed-bid auction is conducted.

Collusion among bidders is often pointed out in both theory and practices. We thus carefully designed our experimental protocol. Any communications among subjects are prohibited during our experiment. At the beginning of each procurement auction with subcontract bids, we draw dice to assign a role to each subject, so that subjects cannot identify any other subjects. Each subject who is assigned to a subcontractor draws a cost from a uniform distribution over $[1000, 2000]$. The domain of the cost is announced to all subjects, but the value is shown on his or her computer screen only. Then, each subject posts a sealed bid on his or her computer screen. When the subcontract auction is over, the cost of a prime contractor is shown on the screen of the subject who is assigned to the prime contractor. After seeing the cost, the subject posts a sealed-bid on the screen. Finally, the payoff of each subject is shown on his or her screen.

Our main observations are as follows. (1) Subcontractors bid more aggressively (i.e., they lower their bids) in the first-price subcontract auctions, as compared to the case where there is no second-stage competition among prime contractors. (2) Second-price

subcontract auctions render higher profits to prime contractors than first-price auctions. (3) First-price subcontract auctions more likely achieve ex post efficient allocations of a subcontract work than second-price auctions. As far as a one-shot procurement auction with subcontract bids is concerned, Obs.(2) suggests that the prime contractors should adopt the second-price mechanism in terms of their profits, but Obs.(3) recommends that they should employ the first-price mechanism from the viewpoint of the social welfare. All the above observations are matched with our theoretical predictions.

We further observed that the subjects were risk averse in subcontract auctions. Risk aversion also induces bidders to lower their bids for enhancing their winning probability. The coefficient of constant relative risk aversion (CRRA) of the subjects are exactly computable from our data, if they are subcontractors. In the case of prime contractors, however, the subjects do not know the bidding function of subcontractors including the CRRA coefficient, and thus we cannot completely specify the determinants of profits in procurement auctions. To confirm the robustness of our conclusion, we had a computer program play as the pre-coded risk-neutral prime contractors in a part of each experimental session.

The remaining part of this paper is organized as follows. Sect.2 describes our model of procurement auctions with subcontract bids and provides some theoretical predictions. Sect.3 explains the experiment procedures. Sect.4 discusses the experiment results. Sect.5 gives the policy implications of our results.

2 The Theoretical Set-up: Symmetric Bidding Functions

Consider a situation where a procurement buyer, for a project, asks for bids from two prime contractors PC_1 and PC_2 . Let V be the value of the project. The procurement buyer, e.g., a local government, cannot solicit bids directly from subcontractors.¹ As is mentioned in Sect.1, the procurement auction is thus actually conducted in the second stage. Prior to submitting a bid in the procurement auction, each PC_i holds a subcontract auction by soliciting bids from two subcontractors $SC_{i,1}$ and $SC_{i,2}$, which can complete the subcontract work. Let V be the value of the project for the procurement buyer. This is the first stage. In practices, such projects consist of subcontractable works and non-subcontractable ones. In this paper, for simplicity, there is only one work for the project, which is subcontractable, and thus there is no work that a prime contractor actually does after subcontracting the work. We assume that neither $SC_{i,1}$ nor $SC_{i,2}$ is allowed to submit his or her bid to PC_j , where $j \neq i$.

¹In many cases, the procurement buyers do not exactly know what kinds of work are needed to complete their projects. This is a reason why they ask prime contractors to propose the specifications of works and estimate the project costs.

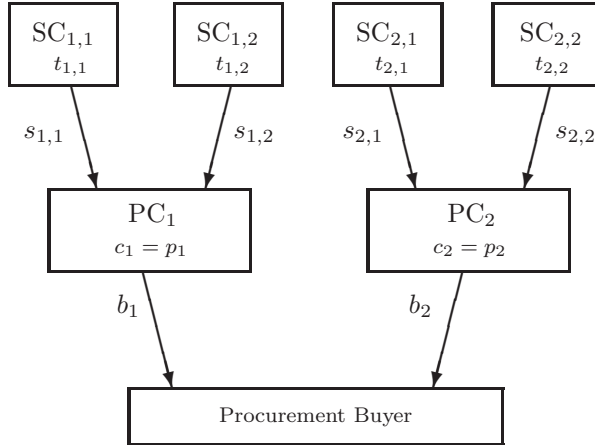


Figure 1: Theoretical set-up

In the first stage, first or second-price sealed-bid reverse auctions are conducted by prime contractors, and the lowest bidder in each of these subcontract auctions makes a subcontract agreement with the prime contractor. We deal with the case where the same auction mechanism is used by both prime contractors. Let $t_{i,k}$ stand for the cost that $SC_{i,k}$ spends for completing the subcontract work. For all i and all k , $t_{i,k}$ is independently and uniformly distributed over $[\underline{t}, \bar{t}]$. For both PCs, the lowest cost for completing the subcontract work is more than \bar{t} , and thus they make subcontract arrangement with a subcontractor. Upon solicitation of subcontract bids, $SC_{i,j}$ draws $t_{i,j}$ and submits his or her bid $s_{i,j}$ to PC_i . Each subcontractor knows his or her own cost, but no one else can observe it. Collusive bidding is prohibited. Every subcontractor is, for now, assumed to be risk-neutral. (We introduce risk-aversion in Subsect.4.2.)

In the second stage, a first-price sealed-bid reverse auction is conducted by the procurement buyer, and the lowest bidder in this procurement auction wins the project. The winner $SC_{i,k}$ of the subcontract auction conducted by PC_i is awarded the subcontract work with the payment p_i , if PC_i wins the project; otherwise, not. Note that $p_i = \min(s_{i,1}, s_{i,2})$ in the case of the first-price action, and $p_i = \max(s_{i,1}, s_{i,2})$ in the case of the second-price action. PC_i submits its bid b_i , given the cost c_i . As is assumed above, there is no work that a prime contractor actually does after subcontracting the work; thus, $c_i = p_i$. The cost c_i is known to PC_i (and possibly SC_{i1} or SC_{i2}) but not to PC_j , $SC_{j,1}$, and $SC_{j,2}$ ($j \neq i$). Collusive bidding is prohibited also in this stage. Every prime contractor is assumed to be risk-neutral. The sequence of decision-making in our theoretical set-up is illustrated with some notations in Fig.1.

We hereafter consider the symmetric bidding functions. When both prime contractors have the same increasing bidding function, subcontractor $SC_{i,k}$ is awarded the subcontract work if and only if $s_{i,k} < \min(s_{i,k'}, s_{j,1}, s_{j,2})$, where $k' \neq k$ and $j \neq i$. It is therefore easy to see that, in the second-price case, there is a dominant strategy for each $SC_{i,k}$, which is

$$s^{**}(t_{i,k}) = t_{i,k}. \quad (1)$$

In the first-price case, a symmetric equilibrium bidding function of $SC_{i,k}$ is characterized as follows. Let $s(\cdot)$ be the symmetric bidding function of subcontractors such that $s_{i,k} = s(t_{i,k})$. Because $t_{i,k}$ is independently and uniformly distributed over $[\underline{t}, \bar{t}]$, each $SC_{i,k}$ determines his or her bid $s_{i,k}$ so as to maximize his or her expected payoff

$$\begin{aligned} & (s_{i,k} - t_{i,k})\text{Prob}(s_{i,k} < \min(s_{i,k'}, s_{j,1}, s_{j,2})) \\ &= (s_{i,k} - t_{i,k})\text{Prob}(s^{-1}(s_{i,k}) < t_{i,k'})^3 \\ &= (s_{i,k} - t_{i,k})[1 - \text{Prob}(s^{-1}(s_{i,k}) \geq t_{i,k'})]^3 \\ &= (s_{i,k} - t_{i,k})\left[1 - \frac{s^{-1}(s_{i,k}) - \underline{t}}{\bar{t} - \underline{t}}\right]^3. \end{aligned}$$

The derivative of $s^{-1}(s_{i,k})$ w.r.t. $s_{i,k}$ is $1/s'(t_{i,k})$. The FOC is then $s'(t_{i,k})[\bar{t} - s^{-1}(s_{i,k})]^3 - 3(s_{i,k} - t_{i,k})[\bar{t} - s^{-1}(s_{i,k})]^2 = 0$. Because $s^{-1}(s_{i,k}) = t_{i,k}$, we have $s'(t_{i,k})[\bar{t} - t_{i,k}]^3 - 3s_{i,k}[\bar{t} - t_{i,k}]^2 = -3t_{i,k}[\bar{t} - t_{i,k}]^2$, i.e., $s(t_{i,k})[\bar{t} - t_{i,k}]^3 = -3 \int t_{i,k}[\bar{t} - t_{i,k}]^2 dt_{i,k}$. The constant of integration is determined at $t_{i,k} = \bar{t}$. The symmetric equilibrium bidding function of subcontractors is then

$$s^*(t_{i,k}) = t_{i,k} + \frac{\bar{t} - t_{i,k}}{4}. \quad (2)$$

[4] argued some properties on subcontractors' bidding functions derived in a more general case.

As a comparison, consider the case where there is no second-stage competition. Subcontractor $SC_{i,k}$ is then awarded the subcontract work and surely paid if and only if $s_{i,k} < s_{i,k'}$, where $k' \neq k$. The symmetric bidding function is computed as $s(t_{i,k}) = t_{i,k} + (\bar{t} - t_{i,k})/2$. From this and (2), we have a theoretical prediction.

Prediction 1: If the first-price mechanism is used in subcontract auctions, subcontractors lower their bids, taking into account the second-stage competition among prime contractors.

Next, we characterize the symmetric bidding function of prime contractors. Let $b(\cdot)$ be the symmetric bidding function of prime contractors such that $b_i = b(c_i)$. In the second-price case, given $s_{i,k} = t_{i,k}$ (as described in (1)), the cost c_i of PC_i is independently distributed over $[\underline{c}, \bar{c}]$, where $\underline{c} = \underline{t}$ and $\bar{c} = \bar{t}$. Each PC_i then determines

its bid b_i so as to maximize his or her expected payoff

$$\begin{aligned}
(b_i - c_i)\text{Prob}(b_i < b_j) &= (b_i - c_i)\text{Prob}(b_i < b(c_j)) \\
&= (b_i - c_i)\text{Prob}(b^{-1}(b_i) < c_j) \\
&= (b_i - c_i)\text{Prob}(b^{-1}(b_i) < \max(s_{j1}, s_{j2})) \\
&= (b_i - c_i)[1 - \text{Prob}(b^{-1}(b_i) \geq \max(s_{j1}, s_{j2}))] \\
&= (b_i - c_i)[1 - \text{Prob}(b^{-1}(b_i) \geq s_{j1})\text{Prob}(b^{-1}(b_i) \geq s_{j2})] \\
&= (b_i - c_i)[1 - (\frac{b^{-1}(b_i) - \underline{c}}{\bar{c} - \underline{c}})^2]
\end{aligned}$$

The derivative of $b^{-1}(b_i)$ w.r.t. b_i is $1/b'(c_i)$. By the FOC and $b^{-1}(b_i) = c_i$, we have $b'(c_i)[(\bar{c} - \underline{c})^2 - (c_i - \underline{c})^2] - 2b_i(c_i - \underline{c}) = -2c_i(c_i - \underline{c})$. Solving this differential equation yields the symmetric equilibrium bidding function of prime contractors in the second-price case

$$b^{**}(c_i) = \frac{(2/3)(\bar{c}^3 - c_i^3) - \underline{c}(\bar{c}^2 - c_i^2)}{(\bar{c} - \underline{c})^2 - (c_i - \underline{c})^2}. \quad (3)$$

In the first-price case, the cost c_i of PC_i is independently distributed over $[\underline{c}, \bar{c}]$. Given the above bidding function of subcontractors, $\underline{c} = (3/4)\underline{t} + (1/4)\bar{t}$ and $\bar{c} = \bar{t}$. Each PC_i then determines its bid b_i so that he or she maximizes the expected payoff

$$\begin{aligned}
(b_i - c_i)\text{Prob}(b_i < b_j) &= (b_i - c_i)\text{Prob}(b_i < b(c_j)) \\
&= (b_i - c_i)\text{Prob}(b^{-1}(b_i) < c_j) \\
&= (b_i - c_i)\text{Prob}(b^{-1}(b_i) < \min(s_{j1}, s_{j2})) \\
&= (b_i - c_i)\text{Prob}(b^{-1}(b_i) < s_{j1})\text{Prob}(b^{-1}(b_i) < s_{j2}) \\
&= (b_i - c_i)[1 - \frac{b^{-1}(b_i) - \underline{c}}{\bar{c} - \underline{c}}]^2
\end{aligned}$$

Similarly as above, by the FOC and $b^{-1}(b_i) = c_i$, we have $b'(c_i)(\bar{c} - c_i)^2 - 2b_i(\bar{c} - c_i) = -2c_i(\bar{c} - c_i)$. The symmetric equilibrium bidding function of prime contractors in the first-price case is thus

$$b^*(c_i) = \frac{\bar{c}^3 - c_i^2(3\bar{c} - 2c_i)}{3(\bar{c} - c_i)^2}. \quad (4)$$

Let t^* be the cost of the subcontractor who is awarded the subcontract work. We say that an allocation of a subcontract work is *ex post* efficient if $V - t^*$ is maximized. We now have other theoretical predictions. The proofs are available upon request ([6]).

Prediction 2: Second-price subcontract auctions render higher profits to prime contractors than first-price auctions.

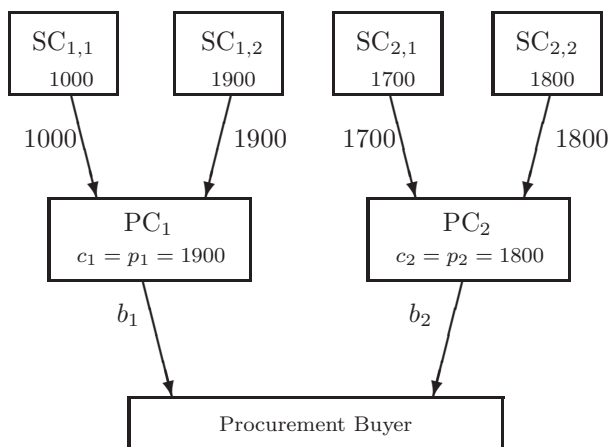


Figure 2: Inefficient allocation in second-price case

Prediction 3: First-price subcontract auctions more likely achieve *ex post* efficient allocations of a subcontract work than second-price auctions.

Fig.2 illustrates an example where second-price subcontract auctions incur an inefficient allocation; The *ex post* efficiency is attained when SC_{1,1} is awarded a subcontract work. Given subcontractors' dominant strategy (1) and the prime contractors' symmetric bidding function, however, SC_{2,1} is awarded the work. The dead weight loss is $t_{2,1} - t_{1,1} = 1700 - 1000 = 700$.

3 The Experimental Procedures

We had, in total, six experimental sessions to examine how subjects behave in the situation described in Sect.2. Our subjects are 36 undergraduate students at University of Tsukuba, Japan. They are all freshman students. Each session consists of three subsessions. In Subsession 1, there is no second-stage competition; the winner of each subcontract auction is surely awarded the subcontract work and paid by his or her prime contractor. For the subcontractors, the bidding situation is the same as in the standard reverse auction. In Subsession 2, a computer program (machine) bids as each prime contractor according to the symmetric equilibrium bidding function, which is (3) in the second-price case and (4) in the first-price case. In Subsession 3, the procurement auction with subcontract bids are played by only subjects.

There are 10 to 20 periods in subsessions. At the beginning of each period, subjects are randomly assigned to PC_{*i*} or SC_{*i,k*}, where $i = 1, 2$ and $k = 1, 2$. In Subsessions 1

	# of PC(s)	PC(s) played by machine?	# of subcontract. auctions	# of periods	# of subj. per period
Subsession 1	1	—	20	10	4
Subsession 2	2	Yes	20	10	4
Subsession 3	2	No	40	20	6

session no.	subc. auction mechanism	show-up fee (JPY)	point-to-JPY ratio	# of subj.	experiment date	mean earnings
1	1st-price	1,000	.2	6	Jan.28, 2010	1,318
2	2nd-price	1,000	.2	6	Jan.28, 2010	1,599
3	1st-price	3,500	1	6	Feb.6, 2010	5,485
4	2nd-price	3,500	1	6	Feb.6, 2010	5,899
5	1st-price	3,500	1	6	Feb.7, 2010	4,927
6	2nd-price	3,500	1	6	Feb.7, 2010	6,335

Table 1: Features of our experimental sessions

and 2, the subjects who are not assigned to subcontractors do not play and earn no point in that period. Next, for each i and k , the cost $t_{i,k}$ of $SC_{i,k}$ is shown only on the computer screen of the subject who plays as $SC_{i,k}$. The subject places a value of his or her subcontract bid on that screen. Given those subcontract bids, in Subsessions 1 and 2, the computer returns to that screen the bids and earned points in the subcontract auction which the subject attends. In Subsession 3, the computer shows the cost $c_i = p_i$ of PC_i only on the computer screen of the subject who plays as PC_i , where $i = 1, 2$. The subject places a value of his or her bid on that screen. Given those bids, the computer returns to that screen the bids and earned points in the procurement auction. The bids and earned points in the corresponding subcontract auctions are also shown to the subjects who play as its subcontractors. No one can see the computer screen of the other subjects. All of these are explained to our subjects and any communications among them are prohibited.

Before each subsession starts, we gave some review questions on the auctions conducted in that subsession and their answers to our subjects. Further, there is a trial run of 3 periods in each subsession. The results in this trial run account for nothing of subjects' total points. The payment to each subject was made in JPY, according to the point he or she earned in the session. The experiment date, show-up fees, point-to-JPY ratios, and other features are listed in Table 1. Throughout this experiment, we set $V = 2000$ and $t_{i,k} \sim U[1000, 2000]$, which is an iid for any i and k . The minimum unit of bids the subjects can place on the computer screen is 1 point.

4 The Experimental Results

We first mention that the difference in pay scale did not seriously affect subjects' bidding behavior in our experiment. The show-up fee and the point-to-JPY rate in Sessions 1 and 2 are lower than those in the other sessions (Table 1). Truly, the subjects were motivated to bid more or less by the different pay scales, but we nevertheless confirmed that, in the presence of the second-stage competition, subjects lowered their subcontract bids in the first-price case, while they bid almost the same values as their costs in the second-price case ([5]). Between the first-price and second-price cases, the inequality relation in average prime contractors' profit was preserved as well as the inequality relation in efficiency rate, even under different pay scales. We thus show our experimental results, aggregating data in all sessions.

4.1 Subcontractors' Aggressive Bidding

We implemented OLS and fixed effects (FE) regressions of subcontract bids on the costs and two dummy variables. The ID number of each subject was used in the FE regressions to fix his or her heterogeneity. The Subsession l dummy variable takes one if the data were taken from Subsession l and zero otherwise, where $l = 2, 3$. The estimation results are reported in Table 2.

It was statistically significant that, in the first-price subcontract auctions, the subjects lowered their bids in the presence of the second-stage competition among prime contractors. In each regression, the coefficients of each dummy variable were estimated to be negative and the null hypothesis that the coefficient is zero was rejected at the 1% significance level. Prediction 1 was therefore statistically confirmed.

In the second-price subcontract auctions, on the other hand, the null hypothesis that the coefficient of each dummy variable is zero was not rejected even at the 5% significance level. In each regression, instead, the coefficient of cost was estimated to be almost one and the null hypothesis that the coefficient is zero was rejected at the 1% significance level, while the constant was estimated to be negative and the null hypothesis that the constant is zero was rejected at 5% significance level. These estimation results jointly imply that, in the second-price subcontract auctions, the subjects bid the values which were lower than their costs by some small amount to enhance their winning probability, although that is not the best strategy. Namely, "over-bidding" was observed also in our experiment, which has been often reported in the literature, e.g., [2] and [3].²

We also implemented the Welch's t -test to examine whether subjects changed their bidding behavior substantially when the prime contractors were played by a computer

²[2] summarizes the main experimental results on auctions.

	First-price		Second-price	
	OLS	FE	OLS	FE
Cost	0.70** (60.28)	0.70** (63.95)	1.03** (80.79)	1.03** (98.91)
Subs. 2 dummy	-38.89** (4.21)	-41.23** (4.73)	-16.66 (1.67)	-11.24 (1.40)
Subs. 3 dummy	-50.82** (6.36)	-53.02** (7.04)	-5.76 (0.67)	-2.90 (0.42)
Constant	586.10** (32.31)	585.58** (32.53)	-52.154* (2.56)	-49.182* (2.44)
Observations	480	480	480	480
R-squared	0.89	—	0.93	—
# of subject IDs	—	18	—	18

Note: Absolute values of t -statistics are in parentheses; The coefficients with * are significant at .05 and those with ** are significant at .01. Subject ID is used to fix his or her heterogeneity (fixed effect).

Table 2: Regressions of SC's bids on costs and others

program. More concretely, we examined whether the average markups (bid minus cost) are different between Subsessions 2 and 3. Table 3 shows the test results. The null hypothesis that Subsessions 2 and 3 have the same average markup is not rejected at .05 significance level, in both first-price and second-price cases. We thus hereafter suppose that there is no difference in subjects' bidding behavior between Subsessions 2 and 3. This point is important when we examine Prediction 2 in Subsection 4.2. Note that the other test results are compatible with the regression results described in Table 2.

	1st-price	2nd-price
Subsession 1 vs. 2	3.360**	0.729
Subsession 2 vs. 3	-0.522	-1.003
Subsession 3 vs. 1	-3.027**	0.076

Note: ** indicates the difference in the average markup between the paired subsessions is significant at .01.

Table 3: Two sample Welch's t -test

4.2 Prime Contractors' Profits and Risk Attitude

Table 2 also shows that the goodness of fit measured by R-squared was remarkably high, around .90, in each OLS regression, although subcontractors (as well as prime contractors) are assumed to be risk-neutral in Sect.2. In the second-price case, there is a dominant strategy $s^{**}(t_{i,k}) = t_{i,k}$ for each $SC_{i,k}$, regardless of his or her risk attitude. In the first-price case, however, the equilibrium bidding functions should be modified with the estimate of some measure of risk aversion.

Suppose that the utility function of subcontractors is represented as a power func-

tion: $u(y) = y^r$, where y stands for the profit level and $(1 - r)$ is the Arrow-Pratt coefficient of constant relative risk aversion (CRRA). When prime contractors bid after subcontract auctions (Subsessions 2 and 3), the symmetric equilibrium bidding function (2) for subcontractors is then replaced with

$$s^*(t_{i,k}) = t_{i,k} + \frac{\bar{t} - t_{i,k}}{4}r. \quad (5)$$

When there is no second-stage competition among prime contractors (Subsession 1), the bidding function is similarly replaced with $s(t_{i,k}) = t_{i,k} + (\bar{t} - t_{i,k})r/2$. These bidding functions both imply that subcontractors bid more aggressively as they are more risk-averse (i.e., smaller r), when the first-price mechanism is used for subcontract auctions.

Let $s_{i,k}$ and $t_{i,k}$ be $SC_{i,k}$'s actual bid and cost, respectively. By taking the average of $r_{i,k} = 4(s_{i,k} - t_{i,k})/(\bar{t} - t_{i,k})$, we estimated the CRRA coefficient r of subjects, for instance, in Subsession 2, which was about .80 with the standard deviation almost .01. The domain of c_i in the prime contractors' bidding function (4) is then $[\underline{c}', \bar{c}']$, where $\underline{c}' = \underline{t} + (\bar{t} - \underline{t})(.80)/4 = 1200$ and $\bar{c}' = \bar{t} + (\bar{t} - \bar{t})(.80)/4 = 2000$. The domain of bidding function (3) is not changed, because subcontractors obey their dominant strategy in the equilibrium. We use those above considerations on risk aversion in what follows.

Subsession 2						
	PC's costs			PC's profits		
mechanism	mean	obs	std dev	mean	obs	std dev
1st-price	1,459.8	60	176.31	211.76	30	36.53
2nd-price	1,618.2	60	264.88	300.95	30	155.46

Subsession 3						
	PC's costs			PC's profits		
mechanism	mean	obs	std dev	mean	obs	std dev
1st-price	1,428.7	120	140.33	114.93	60	71.80
2nd-price	1,674.6	120	241.38	155.50	60	125.96

Table 4: PC's costs and profits

Table 4 shows that, in Subsession 3, second-price subcontract auctions rendered, on average, higher profits to prime contractors than first-price auctions. There is, however, no evidence that the prime contractors knew the subcontractors' bidding function (5). On the other hand, prime contractors might know subcontractors' tendency of over-bidding in the second-price case, because they had experienced bidding as subcontractors in Subsessions 1 and 2. Further, prime contractors themselves might be risk averse. We cannot estimate the CRRA coefficient of prime contractors, because the distribution function of c_i cannot be specified unless subcontractors bid according to their equilibrium bidding function. As far as Subsession 3 is concerned, we have no further device to estimate how these factors affected the prime contractors' profits.

We thus wished to assume a situation where the risk-neutral prime contractors bid according to their equilibrium bidding function (4) ((3) in the second-price case), expecting that the subcontractors obey their equilibrium bidding function (5) ((1) in the second-price case), in the first-price case. Again, Table 2 shows that R-squared was around .90 in each OLS regression. In the first-price case, moreover, the remaining difference between the theoretical and actual bids was explained by the risk-attitude of subcontractors, as above. It is now not impossible to assume that subcontractors bid according to their equilibrium bidding functions (5) with $r = .80$ and (1).

In Subsession 2, in fact, such prime contractors were played by a computer program. Note that, in both first-price and second-price cases, we can suppose that there is no difference in subjects' bidding behavior between Subsessions 2 and 3, according to the results of Welch's t-test. Table 4 shows that, also in Subsession 2, the second-price subcontract auctions gave, on average, higher profits to prime contractors than first-price auctions. Prediction 2 was therefore plausible.

4.3 Efficiency Rate

We defined in Sect.2 that an allocation of a subcontract work is *ex post* efficient if the social surplus $V - t^*$ is maximized, where t^* is the cost of the subcontractor who is awarded the subcontract work. Namely, the maximum social surplus is $V - \min(t_{11}, t_{12}, t_{21}, t_{22})$.

Table 5 shows the sample means of realized social surplus (SS realized) and maximum social surplus (SS maximum), and others observed in our experiment. The results of two-sample *t*-tests indicate that, in every pair of the same subsessions, there was statistically significant difference in efficiency rate between the first-price and second-price subcontract auctions. In Subsession 1, second-price auctions attained higher efficiency rate on average than first-price auctions, because there is no second-stage competition among prime contractors, i.e., the standard reverse auctions were actually conducted. In Subsessions 2 and 3, on the other hand, the first-price subcontract auctions attained higher efficiency rate on average than second-price auctions. Prediction 3 was therefore statistically confirmed.

5 Final Remarks

Some readers may be anxious about whether the subjects bid seriously throughout the experiment. In every session, however, we could not observe subjects who bid remarkably higher or lower values than they did in the first five periods in each subsession, as compared to their bids in the remaining periods. Thus, our experimental results are reliable.

		SS realized (A)	SS maximum (B)	(A)/(B)	<i>t</i> -statistics FPA vs. SPA
1st-price	Subs. 1	671.9	699.2	96.1%	2.4885**
	Subs. 2	778.9	798.6	97.5%	1.9914*
	Subs. 3	792.8	820.9	96.6%	3.7110**
2nd-price	Subs. 1	673.1	677.9	99.3%	
	Subs. 2	772.8	835.9	92.4%	
	Subs. 3	660.0	755.3	87.4%	

Note: ** (*) indicates the difference in efficiency rate between first-price and second-price cases is significant at .01 (.05).

Table 5: Efficiency rates

To control subjects' motivation, some experiments in the literature introduced a random payment scheme where each subject was paid by the sum of the points he or she earned in some rounds which were randomly chosen by examiners at the end of a session. Also in the literature, however, random payments affects the risk attitude of subjects. Our experiment did not employ such a payment scheme, because, as explained in Subsect.4.2, we wished to measure the CRRA coefficient of subcontractors as precisely as possible.

Prediction 3 suggests the first-price mechanism should be used in subcontract auctions in terms of social welfare, whereas Prediction 2 implies that prime contractors prefer second-price subcontract auctions in terms of their profits. Because, as noted in Sect.1, there are few agents who can observe actual subcontract bids, "bid-shopping" is never unusual in many countries. Bid-shopping is, in this context, the practice of divulging subcontract bid(s) to other prospective subcontractor(s) before the award of a subcontract work in order to secure a lower bid. Even if first-price mechanism is used in subcontract auctions, the final allocations of subcontract works and payments to the awarded subcontractors become thus similar to the ones in second-price case, when bid-shopping is conducted. Namely, bid-shopping in subcontract auctions incurs the social welfare loss. Therefore, the procurement buyers should pay more attention to subcontract auctions to improve the efficiency rate of their projects.

To confirm our predictions in a more realistic situation, needled to say, we should introduce multi-object and multi-unit reverse auctions into both subcontract and procurement auctions. This is for a future research.

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