Detection of Collusive Behavior

Ranon Chotibhongs[1] and David Arditi, M.ASCE[2]

Abstract: Collusion is an insidious issue in the construction industry. Even though it is widely acknowledged as unethical and illegal, there are not many research studies conducted to detect collusive bidding. This study proposes a step-by-step method to detect collusive bidding by analyzing historical bidding data provided by a construction owner. The construction owner in this study is a public agency that commissioned 108 construction projects that were worth $1.3 billion during a 10-year study period (2001–2010). The number of bidders (80 in total) was small considering that a total of 108 contracts were awarded in the study period. Five of the 80 bidders jointly undertook 72% of the total contracts awarded by this public agency during the study period. The proposed detection method is on the basis of a regression model and involves identifying the potential cartel bidders using two tests called the residual test and the cost structure stability test. After conducting the study, it was found that two of the six potential cartel bidders that were identified in this study had been audited by the public agency for bid fraud, and that another potential cartel bidder had been found guilty by the courts and forbidden from doing business with the public agency.
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Introduction

Most public construction projects are procured through competitive bidding in the United States. Collusion is a pervasive problem sometimes encountered in competitive bidding. Successful collusion causes a decrease in the number of bidders, an increase in the average bid price, and a reduction in bid variance (Zarkada-Fraser and Skitmore 2000). Collusion among cartel bidders creates a noncompetitive bidding environment in the market to the detriment of the owner. Canon #8 of the Code of Ethics of the American Society of Professional Estimators (American Society of Professional Estimators 2011) indicates, "Professional estimators and those in training to be estimators shall not enter into any agreement that may be considered acts of collusion or conspiracy (bid rigging) with the implied or express purpose of defrauding clients." Although collusion is widely accepted as an unethical and illegal practice in construction bidding, there is little empirical literature on collusion in sealed bid auctions (Pesendorfer 2000), probably because there is no reliable test that allows owners to detect collusion (Porter and Zona 1993).

Some of the most significant cases of collusion occur in bidding for public construction works. McMillan (1991) exposed the negotiations among cartel bidders in Japanese public construction projects. Allen and Mills (1989) reported the efforts of the Virginia Department of Transportation to prevent collusive bidding. Ishii (2006) reported on collusive behavior in the paving market in Japan. Bajari (2001) claimed that there are criminal bid-rigging cases in New York City and Chicago for school construction, bridge repair, interior remodeling, paving, and many other types of construction. Doree (2004) reported on the widespread use of cartels and structural bid rigging within the Dutch public construction industry. Vee and Skitmore (2003) and Bowen et al. (2000) observed the collusive bids in the public sectors of Australia and South Africa, respectively.

Research on the detection of collusion has concentrated on the development of statistical methods to determine pricing irregularities. For example, Porter and Zona (1993) applied rank-ordered multinomial logit analysis to detect collusion in highway construction projects, Pesendorfer (2000) investigated the differences in cost structures in sealed bid first-price auctions, and Bajari and Ye (2003) used a regression model to predict collusion by considering only three independent variables.

Other research has concentrated on examining the administrative and legal aspects of collusion. For example, Zarkada-Fraser and Skitmore (1998) concluded in their study that Australian estimators have a teleological orientation in their approach to moral decision making relative to bidding practices, Porter (2005) discussed the factors that facilitate or inhibit collusive schemes as well as the circumstances where detection of collusive behavior is possible, and Porter and Zona (2008) explored the incentives to enter into collusive agreements, the payoffs from continuing participation, and payoffs from ceasing participation.

While there is no single tool commonly used to detect collusion in the industry, this study aims to capitalize on previous researchers' works and to develop a new model that is effective, reliable, and easy to use. A multiple regression analysis-based approach is proposed to help detect noncompetitive bidding behavior. An effort is made to consider all controlling factors in the analysis in order to generate a reliable result. The collusive behavior of construction companies bidding in response to a public agency's solicitations during a 10-year study period (2001–2010) is investigated. This public agency awarded 108 contracts during this period for a total of $1.3 billion. The data used in the analysis are collected from the public agency's website.

[1]Graduate Student, Illinois Institute of Technology, Dept. of Civil, Architectural, and Environmental Engineering, Chicago, IL 60616.

[2]Professor, Illinois Institute of Technology, Dept. of Civil, Architectural, and Environmental Engineering, Chicago, IL 60616 (corresponding author). E-mail: arditi@iit.edu

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Proposed Model

Collusion is an agreement among a group of firms called cartel members. Successful collusion will increase cartel members' profits above the normal competitive level (Bajari and Summers 2002). The Department of Justice observes that some patterns of cartel bidding behavior contrast with competitive market behavior and suggests some possible signs of collusion ("Price Fixing" 2010):

- The same bidder always wins a particular bid. This can be more suspicious if one or more bidders continue submitting bids that are not reasonable and never win any bid.
- The same group of bidders submits bids, and the bidders in the group take turns being the lowest bidder.
- Some bids are much higher than previous bids by the same bidders or engineer's estimates for the same type and same project's conditions.
- A bidder bids significantly higher on some bids than on other bids, with no perceptible cost differences to explain the price increase.
- Bidders submit higher bids to local owners than to distant owners, indicating that bids may be fixed.
- Bid prices drop whenever a new or infrequent bidder submits a bid.
- The bidder who is awarded the bid subcontracts work to competitors that submitted unsuccessful bids on the same project. (This is not related to this research.)
- There are fewer bidders compared to normal bidding instances.
- Bidders submit identical bids where (1) prices stay identical for long periods of time, (2) previous prices were different, and (3) increasing price does not appear to be related to increased costs.

The fact that collusive behavior can take many forms, such as those mentioned above, inhibits the formulation of an all-inclusive universal model that can detect all types of collusive bidding behaviors. The recognition of this difficulty is the likely reason for the very few researchers tackling this problem. However, given the particular characteristics of the construction industry, and the common rules governing the bidding process in most public agencies, it should be possible to develop a model that detects potentially collusive bidders in the construction industry.

In the construction industry, competitive bidders determine an optimized bid by calculating their own likely costs and by considering the distribution of other firm's bids (Porter and Zona 1993; Bajari and Ye 2003). The following assumptions are made in developing the proposed regression model of the cost structure of a construction bid:

- Bidders compete only on price. Under the terms of contract, the winning bidder is responsible for labor, materials, and equipment and provides an output with specified characteristics.
- The set of bidders on any particular bid is common knowledge. Typically, the bidders who are interested in submitting a bid are those who have responded to the agency's request for qualification that is issued before the bidding.
- Bidding costs for bidder i on project t are random with a known pricing distribution.
- Bidding costs are independently distributed among the bidders.
- The cost estimate is private information to each bidder. Bidder i knows its own cost estimate but does not know the precise cost estimate of bidder j, just as bidder j does not know bidder i's cost estimate.

Bidders are risk neutral.

It is critical that all possible independent variables that may affect the offers made by bidders are included in the regression model because a misspecified model is likely to generate unreliable findings. The competitive model is presented in Eq. (1). This model makes use of the basic cost structure used by Bajari and Ye (2003) but augments it with six additional independent variables that are considered to be of importance in the formulation of the cost structure of a bid. Also the dependent variable is taken as the natural logarithm of the offer made by the bidder (BID), rather than the offer/engineer's estimate ratio (BID/EST) used by Bajari and Ye (2003).

Bajari and Ye's (2003) model includes three independent variables. (1) The distance from the bidder's address to the project site (DIST) is considered to be of importance because it affects the operation cost of the company. Bidders who are closer to the construction project should have lower transportation and setup costs. (2) The minimum distance of the other bidders to the project site excluding the bidder itself (MDIST) is included in the model because it represents the transportation cost of the competitors to the project site. (3) The ratio of the bid to the total value of work done by the bidder for the same owner in the study period prior to the bid (WON) is the third independent variable, presumably because a higher amount of prior work done for the same owner will pull project cost down.

The six independent variables added to Bajari and Ye's (2003) model include the following: (1) The duration of the construction (DUR) is included in the model because the duration of the construction project could reflect the size and sometimes complexity of the construction project, which in turn are related to the capabilities of the bidder and hence the size of the offer. (2) The ratio between the lowest bid and the mean bid (RATIO) could be an indication of the variance of the bid distribution; the higher the ratios, the lower the bidders' offers. (3) The number of bidders (NOBID) is an indicator of the intensity of the competition in the market. The larger the number of bidders, the higher the competition, and the lower the bids. (4) The average of the bids submitted by a bidder over a period of one year (AVERAGE) is an indicator of the average capacity of the bidder. Bidders with higher capacity are expected to be less conservative in their offers. (5) The variable TOTAL represents the total amount of the bids submitted by a bidder in the entire study period and reflects the extent of the bidder's participation in the agency's market. (6) The variable (ECON) is an indicator of the health of the economy as measured by the Dow Jones Industrial Index. It is added to the model because bids are likely to be higher in good economic times than bids in economic crisis situations since few construction companies compete for many projects in good times, whereas many companies compete for few projects in bad times.

Assuming the competitive bidding behavior satisfies the log-liner bidding rule, the cost structure of a bid could be formulated as shown in Eq. (1)

$$\begin{aligned}\mathrm{LN}(\mathrm{BID}_{i,t}) = {} & \beta_0 + \beta_1 \mathrm{LN}(\mathrm{EST}_t) + \beta_2 \mathrm{LDIST}_{i,t} + \beta_3 \mathrm{LMDIST}_{i,t} \\ & + \beta_4 \mathrm{LN}(\mathrm{TOTAL}_i) + \beta_5 \mathrm{LN}(\mathrm{RATIO}_t) + \beta_6 \mathrm{NOBID}_t \\ & + \beta_7 \mathrm{LN}(\mathrm{AVERAGE}_i) + \beta_8 \mathrm{DUR}_t + \beta_9 \mathrm{LN}(\mathrm{WON}_{i,t}) \\ & + \beta_{10} \mathrm{LN}(\mathrm{ECON}_{i,t}) + \varepsilon_{i,t} \qquad (1)\end{aligned}$$

where $\mathrm{BID}_{i,t}$ = bid amount quoted by bidder i for project t; EST_t = engineer's estimate for project t; $\mathrm{DIST}_{i,t}$ = distance from bidder i's branch address (or the address shown in the document) to the middle point of project t; $\mathrm{LDIST}_{i,t} = \log(\mathrm{DIST}_{i,t} + 1.0)$; $\mathrm{MDIST}_{i,t}$ = minimum distance from all firms' headquarters excluding bidder i to the middle point of project t; $\mathrm{LMDIST}_{i,t} = \log(\mathrm{MDIST}_{i,t} + 1.0)$; RATIO_t = ratio of the lowest bid to the average bid on project t; TOTAL_i = bidder i's total amount of bids for the entire study period; NOBID_t = number of bidders on project t;

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$\mathrm{AVERAGE}_i$ = average bid amount that bidder i bids each year; DUR_t = duration of project t estimated by bidder i in working days; $\mathrm{WON}_{i,t}$ = ratio of the bid to the total value of work done by bidder i in the study period prior to the bid; and ECON_t = economic conditions at bidding as measured by the Dow Jones Industrial Index.

DIST, MDIST, WON, TOTAL, and AVERAGE are bidder-specific effects when bidding on a project, while EST, RATIO, NOBID, DUR, and ECON constitute project-specific information. The coefficients $\beta_1, \beta_2, \ldots, \beta_{10}$ are the elasticity of the bids with respect to the independent variables, that is, the percentage change in bid price for a given small percentage change in the independent variables (Gujarati 1995). The residual $\varepsilon_{i,t}$ represents the variation in bids that is not explained by the variables included in the regression model for bidder i on project t. Some of this unexplained variation in bids is due to differences in bidder-specific information.

Acquisition of Data for the Study

The data used in this research were collected directly from a public agency's website that contains contract number, project name, project location, type of work, bid opening date, engineer's estimate, project duration, number of bidders, and bidders' names with their bid amount. This public agency procures only building construction projects through competitive bidding. A total of 108 contracts were awarded during the 10-year study period of 2001 to 2010. Table 1 shows the total amount of awarded contracts by year during the period 2001–2010. The average project duration is 344 calendar days, with the longest duration being 762 days and the shortest 30 days.

The public agency investigated in this study awards projects through an open competitive bidding process. Bidders compete only on their bid prices. The contract is awarded to the qualified lowest bidder. This public agency was selected for the study because some observations were perceived as signs of a collusive environment. For one, the number of companies that bid during the 10-year study period is quite small. Another observation was that the same group of bidders submits bids and the bidders in the group seem to take turns being the lowest bidder. Also, some pairs of bidders submit very close bids.

All bidders have to sign a noncollusive affidavit, which states, "The Contractor, its agents, officers or employees have not directly or indirectly entered into any agreement, participated in any collusion, or otherwise taken any action in restraint of free competitive bidding in connection with this proposal or contract. Failure to attest to this section as part of the bid will make the bid nonresponsive and not eligible for award consideration."

The total amount of contracts awarded within the study period was \$1,293,188,324. The highest, lowest, and average contract values are \$72,589,000, \$108,520, and \$11,973,966, respectively.

Table 1. Total Amount of Awarded Contracts by Year

Year	Total contract amount
2001	\$92,791,239
2002	\$155,431,479
2003	\$173,093,703
2004	\$49,514,308
2005	\$7,712,999
2006	\$14,965,550
2007	\$187,479,516
2008	\$291,102,780
2009	\$99,486,059
2010	\$221,610,691
Total	\$1,293,188,324

Table 2. Number of Bidders

Number of bidders	Number of contracts	Number of bids
2	7	14
3	20	60
4	26	104
5	16	80
6	11	66
7	9	63
8	6	48
9	8	72
10	3	30
11	2	22
	Total: 108	Total: 559

There were 80 bidders who bid these 108 contracts. Most of the bidders were local companies. A total of 559 bids were submitted in response to the 108 solicitations issued in the period 2001–2010, a minimum of 2, a maximum of 26, and an average of 5 bids per contract (Table 2).

Thirty-seven of the 80 bidders won at least one contract, but only 14 were awarded more than 1% of the total \$1.3 billion. Table 3 shows the bid statistics of these 14 bidders. The top 5 of the 14 bidders (bidders 21, 25, 45, 54, and 77) jointly held 72% of the total amount of work done for this agency. These five bidders also had high winning percentages.

Analysis of the Data

Data for only 71 contracts were used in this study because engineers' estimates were not available for the remaining 37 contracts. A total of 369 bids were submitted by bidders in response to these 71 solicitations (only 218 bids for the top 14 bidders listed in Table 3). As far as multicollinearity is concerned, the correlation matrix in Table 4 was inspected as this is a common method for analyzing the data of the independent variables included in Eq. (1). According to Gujarati (1995), multicollinearity is a problem if pairwise correlation coefficients are higher than 0.80. Two independent variables, TOTAL (the sum of a bidder's bids over the study period) and DUR (project duration) were eliminated from the competitive bidding model because of high correlation coefficients with other independent variables that were higher than 0.80 (see Table 4). Eq. (1) was then reformulated using only eight independent variables, as shown in Eq. (2).

$$\begin{aligned}\mathrm{LN}(\mathrm{BID}_{i,t}) = {} & \beta_0 + \beta_1\mathrm{LN}(\mathrm{EST}_t) + \beta_2\mathrm{LDIST}_{i,t} + \beta_3\mathrm{LMDIST}_{i,t} \\ & + \beta_4\mathrm{LN}(\mathrm{RATIO}_t) + \beta_5\mathrm{NOBID}_t \\ & + \beta_6\mathrm{LN}(\mathrm{AVERAGE}_i) + \beta_7\mathrm{LN}(\mathrm{WON}_{i,t}) \\ & + \beta_8\mathrm{LN}(\mathrm{ECON}_{i,t}) + \varepsilon_{i,t} \qquad (2)\end{aligned}$$

The results of the regression estimation of Eq. (2) using ordinary on 369 observations indicated that about 99% of the variation in the dependent variable is explained ($R^2 = 0.9908$, adjusted $R^2 = 0.9906$), and the standard error is low (0.1358). The t-statistics displayed in Table 5 are high except for LDIST and LMDIST. The lower t-statistics for LDIST and LMDIST can be explained by the fact that the distance between the location of bidder's office and the location of the project site does not significantly affect the bidders' offers because 95% of the bidders are local companies. All coefficients listed in Table 5 display reasonable signs. For example, when the NOBID increases, bidders decrease their bid prices in this highly competitive environment. Conversely, bidders increase their bid prices when the Dow-Jones Industrial Index

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Table 3. Statistics of 14 Bidders with Large Market Share

Bidder ID	Number of contracts bid	Percentage of contracts bid	Number of winning bids	Percentage of winning bids	Amount of contracts won	Market share (%)	Average bidding/year
21	77	13.77	12	15.58	$305,287,518	23.61	$118,653,448
25	28	5.01	11	39.29	$300,381,944	23.23	$109,826,212
45	19	3.40	6	31.58	$154,829,123	11.97	$70,397,024
77	27	4.83	5	18.52	$88,152,911	6.82	$96,980,839
54	28	5.01	12	42.86	$76,576,298	5.92	$18,602,538
27	4	0.72	2	50.00	$51,625,220	3.99	$20,999,129
50	9	1.61	4	44.44	$45,421,866	3.51	$28,738,486
10	23	4.11	3	13.04	$42,391,175	3.28	$53,487,395
73	20	3.58	5	25.00	$41,605,614	3.22	$30,988,157
37	24	4.29	1	4.17	$25,444,700	1.97	$43,772,563
9	11	1.97	3	27.27	$22,565,000	1.74	$27,122,879
5	4	0.72	2	50.00	$16,924,127	1.31	$11,249,766
19	7	1.25	4	57.14	$13,471,315	1.04	$10,463,021
24	39	6.98	6	15.38	$12,738,469	0.99	$23,128,562

Table 4. Correlation Matrix

Independent variables	EST	TOTAL	LDIST	LMDIST	RATIO	ECON	NOBID	DUR	AVERAGE	WON
EST	1									
TOTAL	0.65	1								
LDIST	0.10	−0.01	1							
LMDIST	0.12	0.12	0.32	1						
RATIO	−0.39	−0.36	−0.20	−0.27	1					
ECON	0.01	0.05	0.09	0.10	0.11	1				
NOBID	−0.02	−0.08	0.11	−0.17	−0.14	−0.36	1			
DUR	0.91[a]	0.61	0.14	0.16	−0.44	0.02	−0.02	1		
AVERAGE	0.66	0.89[a]	0.03	0.10	−0.37	0.05	−0.02	0.64	1	
WON	0.18	0.40	−0.15	0.10	−0.15	−0.02	0.00	0.21	0.33	1

[a]Correlations higher than 0.80.

Table 5. Reduced-Form Bid Function

Independent variables	Coefficient	*t*-statistic
Intercept	−0.866123487	−1.872792041
LN(EST)	0.994742347	144.2799639
LDIST	0.016535739	0.739203799
LMDIST	−0.039300764	−1.401526389
LN(RATIO)	−0.250694915	−2.758558274
NOBID	−0.014875449	−4.289010147
LN(AVERAGE)	−0.0150476	−1.849642787
LN(WON)	−0.001739122	−1.875827493
LN(ECON)	0.144219515	2.928875041

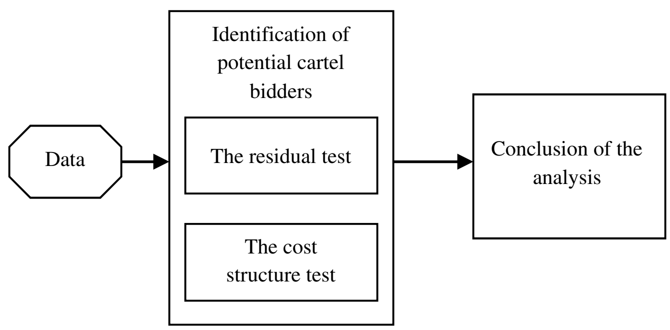

Fig. 1. Proposed model for collusion analysis

(ECON) shows a positive sign, implying many jobs and few bidders. If the bidder has won a contract from this public agency in the past (WON), the bidder's offer decreases because the bidder has specialty experience and specific equipment required in this public agency's projects.

The residual and the cost stability tests are performed as illustrated in Fig. 1. The residual test assesses the correlation of the residuals of the regression equations between bidders. The cost structure stability test determines whether bidders react the same way when facing the same cost structure.

Residual Test

The bids of various competitive firms should not be correlated. Before submitting a bid, bidders normally estimate their costs for the project. In doing so, they may make use of public information that is available to all bidders, which may increase the correlation between bidders' offers. Also, bidders may make use of quotes provided by the same subcontractors, hence again increasing the correlation between bidders' offers. However, a bidder's offer is largely affected by internal company information, particularly when the bidder plans to self-perform a large enough portion of the project. If a group of firms in the industry are cartel members and submit a phony bid to give the outward appearance of competition, the bids may be correlated in a manner that can be detected using appropriate statistical methods. Porter and Zona (1993) and Bajari and Ye (2003) indicate that the residuals from estimated bid functions for cartel bidders are more highly correlated with each other than the residuals of the regression equation of competitive bidders.

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Suppose the coefficient of correlation between the residual of bidder i's bids and bidder j's bids is ρ_{ij}. Note that ρ_{ij} can be calculated only when the number of bids that bidder i bids against bidder j is greater than 3. The following null hypothesis is considered for the residual test:

$$H_0\colon \rho_{ij} = 0 \tag{3}$$

The Fisher transformation is used to test the hypothesis in Eq. (3) because the Fisher transformation is appropriate for a nonparametric distribution (that has more than three projects bid by both bidders i and j). The Fisher transformation converts the Pearson's correlation (r) to the normally distributed variable Z. The Pearson's correlation coefficient (r) is calculated from the sample data. The Fisher r-to-z transformation is formulated as seen in Eq. (4)

$$Z = \frac{1}{2}\ln\frac{1+r}{1-r} \tag{4}$$

The distribution of Z is approximately normal with a mean μ_Z and a standard deviation σ_z expressed in Eqs. (5) and (6), respectively

$$\mu_Z = \frac{1}{2}\ln\frac{1+\rho}{1-\rho} \tag{5}$$

$$\sigma_z = \frac{1}{\sqrt{n-3}} \tag{6}$$

where n = number of cases in the sample.

The z-statistic can be expressed as in Eq. (7)

$$z = \frac{(Z-\mu_Z)}{\sigma_z} \qquad z = (Z-\mu_Z)\sqrt{n-3} \tag{7}$$

Eq. (7) approximately follows the standard normal distribution. Under the null hypothesis of $\rho_{ij} = 0$ and $\mu_{Zj} = 0$, the statistic can be written as in Eq. (8)

$$z = Z\sqrt{n-3} \tag{8}$$

for each pair of bidders as long as the number of simultaneous bids are more than three ($n > 3$).

The null hypothesis is rejected if the calculated $z \geq z_\alpha$. Hence, the Bonferroni's Correction (Blackwell 2008) is conducted to address the problem of multiple tests. When α_g is the type I error rate (the error of rejecting a null hypothesis when it is actually true) for the multiple tests and α is the same rate for each individual test, then Bonferroni's inequality can be derived as in Eq. (9)

$$\alpha_g \leq \alpha \times n \tag{9}$$

where n = number of tests.

First, a significance level for the overall test is defined, and then the significance levels for each individual test are calculated by using Eq. (8). The significance level α_g is set as 0.05 for the residual test. Therefore, the individual significance level can be calculated as $\alpha = 0.05/n$. For example, in the first entry in Table 6, the number of simultaneous bids is 7 for bids between bidder 9 and bidder 21; for an overall significance level of 0.05, the individual significance level is $\alpha = 0.05/7 = 0.007143$; the critical two-tailed test yields

Table 6. Results of the Residual Test

Pairs of bidders	Number of simultaneous bids (n)	Pearson's correlation coefficient (r)	z statistic	Significance level (α/n)	z critical	Test result
9 versus 21	7	0.923134882	3.21966	0.007143	2.690101	Fail
10 versus 19	4	0.854457001	1.272438	0.0125	2.497705	Pass
10 versus 21	16	0.514695257	2.051906	0.003125	2.955167	Pass
10 versus 24	9	0.963711291	4.888061	0.005556	2.772895	Fail
10 versus 45	4	−0.354846656	−0.37098	0.0125	2.497705	Pass
10 versus 54	5	0.976348676	3.129363	0.01	2.575829	Fail
10 versus 73	8	0.931112546	3.726829	0.00625	2.734369	Fail
10 versus 77	5	0.702487769	1.23347	0.01	2.575829	Pass
19 versus 73	4	0.283236664	0.291198	0.0125	2.497705	Pass
21 versus 19	4	0.788837207	1.068346	0.0125	2.497705	Pass
21 versus 24	11	0.750899926	2.75776	0.004545	2.837629	Pass
21 versus 25	19	0.906407331	6.028047	0.002632	3.007738	Fail
21 versus 37	16	0.819251008	4.162737	0.003125	2.955167	Fail
21 versus 45	13	0.826638876	3.723354	0.003846	2.890524	Fail
21 versus 50	6	0.903174726	2.579345	0.008333	2.638271	Pass
21 versus 54	12	0.850436036	3.773179	0.004167	2.865235	Fail
21 versus 73	10	0.767696258	2.684626	0.005	2.807034	Pass
21 versus 77	18	0.85447574	4.928399	0.002778	2.991292	Fail
24 versus 54	5	0.784950827	1.05814	0.01	2.575829	Pass
24 versus 73	9	0.884944768	3.424682	0.005556	2.772895	Fail
25 versus 37	10	0.610339208	1.877059	0.005	2.807034	Pass
25 versus 45	8	0.839559583	2.727286	0.00625	2.734369	Pass
25 versus 54	5	0.980438122	3.265059	0.01	2.575829	Fail
25 versus 77	13	0.79339805	3.416957	0.003846	2.890524	Fail
37 versus 54	6	0.841084207	2.121533	0.008333	2.638271	Pass
37 versus 77	6	0.425226069	0.786445	0.008333	2.638271	Pass
45 versus 37	4	0.989450162	2.619752	0.0125	2.497705	Fail
45 versus 54	5	0.964377473	2.835465	0.01	2.575829	Fail
45 versus 77	9	0.710644774	2.176336	0.005556	2.772895	Pass
54 versus 73	4	0.958328838	1.925019	0.0125	2.497705	Pass

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$z_{0.007143} = 2.690101$; since the z statistic is larger than the critical z, the test fails for bidders 9 and 21.

The results of the residual tests for 30 pairs of bidders are presented in Table 6. These pairs represent bidding activity for the 14 bidders presented in Table 3 that did most of the work for the agency. Five pairs of bidders, i.e., pairs (21, 25), (21, 37), (21, 45), (21, 54), and (21, 77) bid against each other more than 10 times. Out of the total of 30 pairs of observations, the following 14 pairs of bidders have high correlations between their residuals: pairs (9, 21), (10, 24), (10, 54), (10, 73), (21, 25), (21, 45), (21, 37), (21, 54), (21, 77), (25, 54), (25, 77), (24, 73), (45, 37), and (45, 54); the remaining pairs of bidders have statistically low correlations. On the basis of this finding, it can be stated that the bidding behavior of 10 bidders (9, 10, 21, 24, 25, 37, 45, 54, 73 and 77) is suspicious.

Cost Structure Stability Test

Competitive bidders behave identically when facing the same cost structure (Bajari and Ye 2003). Pesendorfer (2000) and Porter and Zona (1993) also agree that the coefficients of the cost structure model must be identical in a competitive bidding environment. Let the coefficients $\beta_1, \beta_2, \ldots, \beta_8$ be the average effect of each factor in the reduced-form bid function. The cost structure stability test can be performed by using the hypothesis given in Eq. (10)

$$H_0\colon \beta_{ik} = \beta_{jk} \tag{10}$$

for bidders i and j when $i \neq j$, and for all k (k is the total number of independent variables). The Chow test (Chow 1960) is commonly used to test whether the coefficients of a regression model are equal to the coefficients of another regression model. The variances of the disturbance term are assumed to be equal in both regressions. If the sample is large, the Chow test will be suitable whether the variances of the disturbance are the same in both regressions or not. The steps in running the F statistic for the Chow test are the following:

- Run the regression using all the bid data, and record the sum of the squared errors in the constrained model (SSR_C). The constrained regression pools two of the main firms together.
- Run two separate regressions on each pair of bidders, and record the sum of the squared errors in the unconstrained model (SSR_U).
- Using these two values, calculate the test statistic using the relationship in Eq. (11)

$$F = \frac{(\mathrm{SSR}_C - \mathrm{SSR}_U)/k}{\mathrm{SSR}_U/(n-2k)} \tag{11}$$

  where k = total number of independent variables; and n = total number of observations.
- The test statistic follows the F distribution with k and $n-2k$ degrees of freedom.
- The null hypothesis is rejected if the calculated $F \geq F_{\alpha,k,n-2k}$. $F_{\alpha,k,n-2k}$ is 2.60 for $\alpha = 0.01$, $k = 8$ independent variables, and $n = 218$ bids for the top 14 bidders listed in Table 3.

The results of the cost structure stability test are represented in Table 7. Among the 30 pairs of bidders listed in Table 3 who bid against each other at least four times, there are only six pairs that failed the cost structure stability test: pairs (10, 21), (10, 24), (10, 77), (21, 37), (21, 45), and (21, 54). As a result, six bidders (10, 21, 24, 37, 45, and 77) are considered to have been involved in suspicious bidding behavior.

Table 7. Results of the Cost Structure Stability Test

Pairs of bidders	Number of simultaneous bids (n)	F statistic	Test result
9 versus 21	7	2.045235	Pass
10 versus 19	4	0.858366	Pass
10 versus 21	16	2.849573	Fail
10 versus 24	9	3.990068	Fail
10 versus 45	4	0.965078	Pass
10 versus 54	5	0.832467	Pass
10 versus 73	8	1.158817	Pass
10 versus 77	5	3.857906	Fail
19 versus 73	4	0.456033	Pass
21 versus 19	4	0.21953	Pass
21 versus 24	11	2.188275	Pass
21 versus 25	19	2.122115	Pass
21 versus 37	16	3.084192	Fail
21 versus 45	13	2.624223	Fail
21 versus 50	6	1.077773	Pass
21 versus 54	12	2.980875	Fail
21 versus 73	10	1.003613	Pass
21 versus 77	18	1.873963	Pass
24 versus 54	5	0.378241	Pass
24 versus 73	9	1.889507	Pass
25 versus 37	10	1.3468	Pass
25 versus 45	8	1.017174	Pass
25 versus 54	5	0.492648	Pass
25 versus 77	13	1.155417	Pass
37 versus 54	6	1.025016	Pass
37 versus 77	6	0.570473	Pass
45 versus 37	4	0.537085	Pass
45 versus 54	5	1.266868	Pass
45 versus 77	9	0.869631	Pass
54 versus 73	4	0.413402	Pass

The Combined Results of the Residual Test and the Cost Structure Stability Test

The summary of the combined test results is provided in Table 8. Table 8 also presents the market share of each bidder. The four pairs of bidders who failed both tests are pairs (10, 24), (21, 45), (21, 37), and (21, 54). The six bidders involved, namely, bidders 10, 21, 24, 37, 45, and 54 are identified as potential cartel bidders.

Table 8. Results of the Residual Test and the Cost Structure Stability Test

Bidder ID	Market share (%)	Bidder ID	Market share (%)	Number of pairwise simultaneous bids	Residual test	Cost structure stability test
9	1.74	21	23.61	7	Fail	Pass
10	3.28	21	23.61	16	Pass	Fail
10[a]	3.28	24[a]	0.99	9	Fail	Fail
10	3.28	54	5.92	5	Fail	Pass
10	3.28	73	3.22	8	Fail	Pass
10	3.28	77	6.82	5	Pass	Fail
21	23.61	25	23.23	19	Fail	Pass
21[a]	23.61	37[a]	1.97	16	Fail	Fail
21[a]	23.61	45[a]	11.97	13	Fail	Fail
21[a]	23.61	54[a]	5.92	12	Fail	Fail
21	23.61	77	6.82	18	Fail	Pass
24	0.99	73	3.22	9	Fail	Pass
25	23.23	54	5.92	5	Fail	Pass
25	23.23	77	6.82	13	Fail	Pass
45	11.97	37	1.97	4	Fail	Pass
45	11.97	54	5.92	5	Fail	Pass

[a]Pairs of bidders that failed both tests.

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These potential cartel bidders bid against each other on average 12 times during the study period (see Table 8) confirming Porter and Zona's (1993) observations that the cartel bidders regularly bid against each other. The potential cartel bidders held about half of the public agency's market during the 10-year study period (about \$600 million). Bidders 10, 21, 24, 37, 45, and 54 bid 23, 77, 39, 24, 19, and 28 times in 108 contract lettings, respectively.

After the two tests were conducted, a search was conducted to see wether any of the 80 bidders who bid the 108 projects let by the public agency in the 10-year study period had been involved in any bidding irregularities. It was found that bidders 21 and 24 were audited by the public agency for bid fraud. Also bidder 10 pleaded guilty for a bid-rigging case and was suspended from participating in any federal contracts and prohibited from bidding on the public agency's projects. None of the remaining bidders' names came up when relevant investigations in the period 2001–2010 were searched. This evidence justifies the results of this study. The fact that three of the six bidders identified in this study as suspected collusive bidders have been investigated by authorities for bidding irregularities validates the two tests proposed in the study. On the other hand, the fact that the remaining three of the six suspected bidders have never been investigated by authorities may mean that they managed not to get detected by regular police methods.

Conclusion

Collusion is widely accepted as a major unethical and illegal practice in the construction industry. It is impossible to predict whether bidders are colluding unless there is legal evidence of compromising communications among the bidders prior to the bid deadline. This research introduces a tool to detect noncompetitive bidding practices.

The construction owner in this study is a public agency that commissioned 108 building construction projects worth \$1.3 billion during a 10-year study period (2001–2010). The number of bidders (80 in total) was small considering that a total of 108 contracts were awarded in the study period.

By using the residual and the cost structure stability tests, six bidders are categorized as potential cartel bidders since they fail both tests. The residual test assesses the correlations between the residuals of Eq. (2). The cost structure stability test investigates whether bidders behave the same way when they are confronted with the same cost structure. These six bidders possess almost 50% (47.75%) of the public agency's market during the study period 2001 to 2010. They bid against each other 12 times on average during this time.

Of the six potential cartel bidders who failed both the residual and the cost structure stability tests, two were audited by the public agency relative to bid fraud, while another was found guilty by a court of law for bid rigging and banned from doing business with the public agency. None of the remaining bidders' names were mentioned in the news as having been involved in bidding irregularities. This information was found after the model was set up and run, quite independently of the study reported in this paper. It was welcome news as it partially supported the findings of the study.

An important limitation of this study is that the proposed model cannot detect collusive bidding at the time it happens; it is able to detect suspected collusion in the past and only if the analyst has access to detailed historical information about the independent variables listed in Eq. (2). The larger the number of contracts awarded, the higher the likelihood that the model will result in reliable findings. Another limitation of the model is that it relies heavily on the engineer's estimate, and yet the accuracy of the engineer's estimate is sometimes debatable (Beeston 1999). Indeed, engineers often rely on past bid tabulations and, consequently, their estimates may be affected by undetected collusive bids in the past. Finally, it must be stated that the model will not work if cartel bidders replicate the bidding environment that passes both the residual and the cost structure stability tests.

While there is no single method that can be used to detect potential collusive behavior (Bajari and Ye 2003; Porter and Zona 1993), this study proposes a comprehensive step-by-step method that systematically analyzes the available historical bid data provided by an owner, and that identifies suspected cartel bidders. When implemented to 71 contracts awarded by a public agency in a 10-year period, the findings are quite convincing despite the limitations mentioned in the preceding paragraph.

Formulating a model that is composed of a series of two complementary methods that rely on an elaborate regression model is the major contribution of this study to the collusion-related literature. The proposed model detects collusive behavior in competitive bidding of construction works and identifies the potential cartel bidders in a two-step process that enhances the reliability of the outcome. The practical implication of the proposed model is that it can be used by large construction owners that have accumulated historical bidding information to identify the bidders that were involved in collusive behavior in the past and avoid doing business with these contractors in the future.

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