Optimal information disclosure in license auctions*

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Abstract

The literature on license auctions in oligopoly assumed that the auctioneer reveals the winning bid prior to the oligopoly game and stressed that this gives firms an incentive to signal strength through their bids, to the benefit of the innovator. In the present paper we examine whether revealing the winning bid is optimal. We consider three disclosure rules: full, partial, and no disclosure of bids, which are closely linked with standard auction formats. We show that more information disclosure increases the total surplus divided between firms and the innovator. More information disclosure also increases bidders' payoff. However, no disclosure maximizes the innovator's expected revenue.

KEYWORDS: Auctions, innovation, licensing, information sharing.

JEL CLASSIFICATIONS: D21, D43, D44, D45

1 Introduction

An outside innovator auctions the right to use a cost reducing, non-drastic innovation to a firm in a Cournot oligopoly. Should he choose an auction rule that discloses some or all bids prior to the oligopoly game? The present paper explores this issue and identifies the optimal auction.

The recent literature on license auctions assumed that the innovator reveals the winning bid and stressed that, in a Cournot oligopoly, this induces firms to signal strength through their bids, which

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contributes to increase equilibrium bids. However, the literature never examined whether revealing the winning bid is actually optimal.

The analysis of license auctions in oligopoly was initiated by Kamien and Tauman (1986) and others who showed that the interests of the innovator are best served if he auctions a limited number of licenses (see the survey by Kamien, 1992). License auctions were shown to be more profitable than other selling mechanisms such as royalty licensing.[1] One limitation of their analysis was the assumption that firms' cost reductions induced by the innovation are completely known to all firms prior to bidding.

Later, Jehiel and Moldovanu (2000) introduced incomplete information at the auction stage, but maintained that cost reductions become known after the auction and before the oligopoly game is played. This gap was closed by Das Varma (2003) and Goeree (2003) who assumed that firms can only indirectly infer the winner's cost reduction by observing the winning bid. They showed that, in a Cournot oligopoly, the incentive to signal strength leads to pointwise higher equilibrium bids than under complete information as in complete information model by Jehiel and Moldovanu (2000).[2] This comparison between equilibrium bids under complete and incomplete information should however not be confused with the claim that revealing the winning bid increases the innovator's revenue.[3]

The analysis of information disclosure rules in license auctions also bears a relationship to the earlier literature on information sharing in oligopoly. That literature assumed that firms can commit to reveal their private information concerning their cost before that cost is observed. The main finding was that in a Cournot oligopoly firms have an incentive to reveal their private information (see Shapiro, 1986; Gal-Or, 1985; Vives, 1990; Vives, 1984). The problematic part of that literature is the assumption that firms can commit to reveal information and that this information is verifiable. However, this problem can be resolved in license auctions where the auctioneer can commit to indirectly reveal cost information by choosing an auction rule that reveals some bids or no bid. Information sharing is thus a byproduct of bidding, which also bypasses the verifiability required in the information exchange literature.

In the present paper we consider three information disclosure rules: full information disclosure which happens to be equivalent to revelation of the winning bid, partial disclosure which is equivalent to revealing the second-highest bid, and no information disclosure. These disclosure rules are intimately linked to standard auction formats, ranging from the open, decreasing bid Dutch auction, the open, ascending bid English auction, and the standard sealed-bid auction (either first-price or Vickrey). Similar to the literature on information exchange in oligopoly we find that more information disclosure increases the total surplus divided between firms and the innovator. More information disclosure also increases bidders' payoff. However, no disclosure maximizes the innovator's expected revenue. Hence, the different standard auctions are not revenue equivalent, and the innovator is well advised not to reveal any bids.

Interestingly, in our analysis two kinds of signaling effects - to which we refer as first- and second-order signaling effects - occur. The *first-order signaling effect* is the effect of player A's observed

[1] However, Giebe and Wolfstetter (2008) showed that the profitability of license auctions can be increased by awarding royalty contracts to the loser's of the auction.

[2] They also showed that in models of Bertrand competition when goods are substitutes, bidders have an incentive to signal weakness, which may prevent existence of an equilibrium with monotone increasing bid functions.

[3] Similarly, our own contributions to licensing mechanism under incomplete information that award both unrestricted licenses and royalty licenses we assumed that the innovator reveals the winning bid (see Fan, Jun, and Wolfstetter, 2013b; Fan, Jun, and Wolfstetter, 2013a).

action on player B's belief about A's type; the *second-order signaling effect* is the effect of A's observed action on B's belief about A's belief about B's type. Under full information disclosure, the winning bid entails a first-order signaling effect on the losers of the auction. Whereas under partial information disclosure, the highest losing bid entails a second-order signaling effect on the winner of the auction because it allows the winner to update his beliefs about the beliefs of the highest losing bidder.

The plan of the paper is as follows. The model is stated in Section 2. We analyze the relevant duopoly subgames and the bidding games under full, partial, and no information disclosure in Sections 3 to 5. In Section 6 we provide intuitive interpretations for the differences between equilibrium bid functions across disclosure rules. Finally, in Section 7 we show that the different information disclosure rules can be ranked unambiguously according to the total surplus (to be shared by firms and the innovator), bidders' payoffs, and the innovator's revenue, and we identify the optimal standard auction.

2 The Model

Suppose an outside innovator employs a first-price auction[4] to sell the exclusive right to use a non-drastic innovation to one of two firms that interact in a duopoly market. The innovator sets an information disclosure rule that commits him to reveal some or all or no bids. After the outcome of the auction has been disclosed, the two firms play a Cournot duopoly game.

Three information disclosure rules are considered: Either the innovator reveals

- the winning bid (full information disclosure)[5], or
- only the losing bid (partial information disclosure), or
- neither the winning nor the losing bid (no information disclosure).

The timing of the licensing game is as follows: 1) The innovator announces the information disclosure rule. 2) Firms simultaneously submit their bids. 3) The innovator awards the license to the highest bidder who pays his bid (the losing bidder pays nothing), and discloses information concerning bids according to the announced disclosure rule. 4) Firms play a homogeneous goods Cournot duopoly game.

Prior to the innovation, firms have the same unit cost c. Using the innovation reduces unit costs by an amount x_i that depends on who uses it. Potential cost reductions are firms' private information, unknown to their rival and to the innovator. They are *i.i.d.* random variables, drawn from the *c.d.f.* $F : [d, c] \to [0, 1]$ with positive *p.d.f.* everywhere.

Firms and the innovator are risk neutral, inverse market demand is linear in aggregate output, Q, $P(Q) := 1 - Q$, and the probability distribution of cost reductions F is the uniform distribution. These simplifying assumption of linear demand is commonly used in the information sharing in oligopoly literature (see, for example Shapiro, 1986).

[4] As one can easily confirm, first- and second-price auctions are payoff equivalent, provided the auctioneer reveals the same information about bids. Therefore, considering the first-price auction is without loss of generality.

[5] As will become clear later on, revealing the winning bid is as informative as revealing the winning *and* the losing bid.

3 Full information disclosure

If equilibrium bid functions are strictly increasing (which we will confirm later), observing the winning bid reveals the winner's cost reduction to the losing bidder. The loser's cost is common knowledge. Therefore, if the innovator discloses the winning bid the innovator has revealed all relevant information, which is why we refer to this as full information disclosure.

The information disclosure has a first-order signaling effect because when the loser observes the winning bid he is able to update his prior beliefs about the cost reduction of the winner. Bidders may thus have an incentive to strategically inflate their bids in order to signal strength. Of course, in equilibrium bid "high". Of course, such "misleading" signaling is deterred.

In the following we solve the equilibrium expected payoffs of firms and the innovator. For this purpose we need to find the equilibrium bid function and firms' equilibrium expected profits in the duopoly subgames.

We employ the following procedure to solve the equilibrium bid function β_f. Consider one firm that unilaterally deviates from equilibrium bidding. We then state conditions concerning the β_f function that make deviations unprofitable. These conditions yield a unique β_f function.

Unilateral deviations from equilibrium bidding lead into duopoly subgames that are off the equilibrium path. Therefore, in order to compute the payoff of the firm that deviates from equilibrium bidding, we must first solve all relevant duopoly subgames.

3.1 Downstream duopoly "subgames"

Consider a firm, say firm 1, that had drawn the cost reduction x but bid $\beta_f(z)$, as if it had drawn cost reduction z, while the other firm 2 had played the strictly monotone increasing equilibrium bidding strategy, β_f. In the continuation duopoly game, the following "subgames" occur, depending upon the pretended cost reduction of firm 1, z, and the cost reduction parameter of firm 2, denoted by y.

3.1.1 When firm 1 won the auction (z ≥ y)

In that case firm 1 privately knows that its cost reduction is x, whereas firm 2 (the loser) believes that firm 1's cost reduction is z. Therefore, firm 2 believes to play a duopoly subgame with unit costs $(c_1, c_2) = (c - z, c)$. Denote the associated equilibrium strategies of the game that the loser believes to play by

$$(q_W^*(z), q_L^*(z)) = \left(\frac{1 - 2c_1 + c_2}{3}, \frac{1 - 2c_2 + c_1}{3}\right). \tag{1}$$

Firm 1 anticipates that the loser plays $q_L^*(z)$. But because firm 1 privately knows that its cost reduction is x rather than z it plays the best reply:

$$q_W^f(x,z) = \arg\max_q \,(1 - q - q_L^*(z) - c + x)\, q = \frac{2 - 2c + 3x + z}{6}. \tag{2}$$

The reduced form profit function of firm 1, conditional on winning, is

$$\pi_W^f(x,z) := q_W^f(x,z)^2. \tag{3}$$

3.1.2 When firm 1 lost the auction (z < y)

In that case firms play a duopoly subgame with unit costs $(c_1, c_2) = (c, c - y)$, with equilibrium strategies $(q_L^*(y), q_W^*(y))$.

Hence, the reduced form profit function of firm 1 conditional on losing is

$$\pi_L^f(y) := q_L^*(y)^2. \tag{4}$$

3.2 Equilibrium bid strategy

Using the above solution of the duopoly subgames, the expected payoff of a bidder with cost reduction x who bids as if his cost reduction were equal to z, while his rival follows the equilibrium strategy β_f, is:

$$\Pi_f(x,z) = F(z)\left(\pi_W^f(x,z) - \beta_f(z)\right) + \int_z^c \pi_L^f(y)dF(y). \tag{5}$$

For β_f to be an equilibrium, it must be such that $x = \arg\max_z \Pi_f(x,z)$. Using the first-order condition, one must have:

$$F'(x)\left(\pi_W^f(x,x) - \beta_f(x)\right) + F(x)\left(\partial_z \pi_W^f(x,x) - \beta_f'(x)\right) - F'(x)\pi_L^f(x) = 0, \tag{6}$$

which can be written in the form:

$$(\beta_f(x)F(x))' = F'(x)\left(\pi_W^f(x,x) - \pi_L^f(x)\right) + F(x)\partial_z \pi_W^f(x,x). \tag{7}$$

Because $\partial_{zx}\Pi_f(x,z) = {}^{(2-2c-d+3x+2z)}/_{6(c-d)} > 0$, the function $\Pi_f(x,z)$ is pseudoconcave. Hence, the first-order conditions yield global maxima.

Integration of (7) yields:

$$\begin{aligned}\beta_f(x) &= \int_d^x \left(\pi_W^f(y,y) - \pi_L^f(y)\right)\frac{F'(y)}{F(x)}dy + \int_d^x \partial_z \pi_W^f(y,y)\frac{F(y)}{F(x)}dy \\ &= \frac{d(15-15c+4d)}{54} + \frac{21-21c+4d}{54}x + \frac{5}{27}x^2\end{aligned} \tag{8}$$

Obviously, $\beta_f(x)$ is strictly increasing; hence, the assumed monotonicity confirms, which proves that $\beta_f(x)$ is the equilibrium bid function.

The equilibrium requirement (7) has a nice interpretation: whereas its RHS states the marginal benefit of a higher z its LHS states its marginal cost. In equilibrium, the bid function must be such that the marginal benefit equals the marginal cost, so that it does not pay to deviate from bidding $\beta_f(x)$, for all x.

The marginal benefit has two components: as z is increased, it becomes more likely to win rather than lose the auction (first term) and, in the event of winning, the rival is lead to believe that he faces a stronger player, with a higher cost reduction, which makes him reduce his output – to the benefit of the winner. The latter reflects the fact that signaling strength is profitable in the event of winning.

4 Partial information disclosure

We now consider the case of partial information disclosure. Because revealing only the winning bid implies full information disclosure, partial information disclosure means revealing only the losing bid.

If equilibrium bid functions are strictly increasing (which we will confirm later), the losing bid informs the winner about the loser's assessment of the winner's cost reduction. Therefore, revealing the losing bid has a second-order signaling effect.

A higher losing bid indicates to the winner that he is seen as stronger, which has an adverse effect on the loser's profit. Taking this into account, bidders have an incentive to strategically deflate their bids in order to "hide" the extent to which losing makes them more pessimistic.

In the following we solve the equilibrium expected payoffs of firms and the innovator. For this purpose we need to find the equilibrium bid function and firms' equilibrium expected profits in the duopoly subgames.

We employ the following procedure to solve the equilibrium bid function β_p. Consider one firm that unilaterally deviates from equilibrium bidding. We then state conditions concerning the β_p function that make deviations unprofitable. These conditions yield a unique β_p function.

Unilateral deviations from equilibrium bidding lead into duopoly subgames that are off the equilibrium path. Therefore, in order to compute the payoff of the firm that deviates from equilibrium bidding, we must first solve all relevant duopoly subgames.

4.1 Downstream duopoly "subgames"

Suppose firm 1 has drawn the cost reduction x but bids $\beta_p(z)$, as if it had drawn cost reduction z, while firm 2 has played the strictly increasing equilibrium bid strategy, β_p. In the continuation duopoly game, the following "subgames" occur, depending upon the pretended cost reductions of firm 1, z, and the cost reduction of firm 2, y.

4.1.1 When firm 1 won the auction (z > y)

In that case firm 1 privately knows that its cost reduction is x, whereas firm 2 (the loser) believes that firm 1's cost reduction is in the set $(y,c]$, and firm 1 knows this because it observes $\beta_p(y)$. Denote the equilibrium strategies by $(q_W^p(x,y), q_L^p(y))$. They must solve the following conditions:

$$q_W^p(x,y) = \arg\max_q q\left(1-q+q_L^p(y)-c+x\right) \tag{9}$$

$$q_L^p(y) = \arg\max_q q\int_y^c \left(1-q+q_W^p(x,y)-c\right)dF(x). \tag{10}$$

This yields the equilibrium strategies and the reduced form profit function of firm 1, conditional on winning:

$$q_W^p(x,y) = \frac{1}{12}(4-3c+6x+y) \tag{11}$$

$$q_L^p(y) = \frac{1}{6}(2-3c-y) \tag{12}$$

$$\pi_W^p(x,y) = q_W^p(x,y)^2. \tag{13}$$

4.1.2 When firm 1 lost the auction (y > z)

In that case firm 1 believes that firm 2's cost reduction is in the set $(z, c]$, and firm 2 knows this.

By the above reasoning (reversing the roles of firms 1 and 2) we find that the equilibrium strategy of firm 1 is $q_L^p(z)$ and that of firm 2 is $q_W^p(y,z)$. Therefore, the reduced form profit function of firm 1, conditional on losing, is

$$\pi_L^p(z) = q_L^p(z)^2. \tag{14}$$

4.2 Equilibrium bid strategy

Using the above solution of the duopoly subgames, the expected payoff of a bidder with cost reduction x who bids as if his cost reduction were equal to z, while his rival follows the equilibrium strategy β_p, is:

$$\Pi_p(x,z) = \int_d^z \left(\pi_W^p(x,y) - \beta_p(z)\right) dF(y) + (1 - F(z))\pi_L^p(z). \tag{15}$$

For β_p to be an equilibrium, it must be such that $x = \arg\max_z \Pi_p(x,z)$. Using the first-order condition, one must have:

$$F'(x)\left(\pi_W^p(x,x) - \beta_p(x)\right) - \beta_p'(x)F(x) + (1 - F(x))\pi_L^{p\prime}(x) - F'(x)\pi_L^p(x) = 0. \tag{16}$$

Equation (16) can be written in the form:

$$(\beta_p(x)F(x))' = F'(x)\left(\pi_W^p(x,x) - \pi_L^p(x)\right) + (1 - F(x))\pi_L^{p\prime}(x). \tag{17}$$

Integration yields the equilibrium bid function

$$\begin{aligned}\beta_p(x) &= \int_d^x \left(\pi_W^p(y,y) - \pi_L^p(y)\right)\frac{F'(y)}{F(x)}dy + \int_d^x \pi_L^{p\prime}(y)\frac{1-F(y)}{F(x)}dy \\ &= \frac{3c(8-41d) + d(132+37d) - 9c^2}{432} + \frac{132 - 123c + 37d}{432}x + \frac{37}{432}x^2.\end{aligned} \tag{18}$$

The equilibrium requirement (17) has the following interpretation: its RHS states the marginal benefit of z; the LHS states its marginal cost. In equilibrium, the bid function must be such that the marginal benefit equals the marginal cost, so that it does not pay to deviate from bidding $\beta_p(x)$, for all x.

The marginal benefit has two components: as z is increased from z to z' 1) it becomes more likely to win rather than lose the auction (this is captured by the first term); 2) in the event of losing, the set of rivals' types (who win) is changed from $(z, c]$ to $(z', c]$; therefore, firm 1 infers that it faces a stronger rival whose average output is greater, which reduces firm 1's expected profit.

Like in the case of full disclosure, bidding has a signaling aspect. However, unlike in the case of full disclosure, a signal is sent only in the event of losing (rather than winning), the signaling effect is a second-order (rather than first-order) effect, and signaling entails an incentive to strategically deflate (rather than inflate) bidding.

5 No information disclosure

If no information is disclosed, bids cannot convey information. However, updating of prior beliefs occurs, responding to the events of winning and losing. In particular, the loser can infer a lower bound of the winner's cost reduction, and the winner can draw an inference concerning the loser's belief about the winner's cost reduction. These updated beliefs affect the play in the continuation duopoly subgames.

In order to solve the equilibrium bid function we first need to solve the duopoly subgames that may occur if a bidder unilaterally deviates from equilibrium bidding, on and off the equilibrium path of the bidding game.

Firms play output strategies, $(q_W^n(x), q_L^n(x))$, conditional on either winning or losing.

5.1 Duopoly subgame on the equilibrium path of the game

Consider a firm with cost reduction x that faces a rival with (unknown) cost reduction y. Denote the equilibrium output strategies on the equilibrium path by $q_W^{n^*}(x), q_L^{n^*}(x)$. They must solve the following requirements:

$$q_W^{n^*}(x) = \arg\max_q q \int_d^x \left(1 - q - q_L^{n^*}(y) - c + x\right) \frac{F'(y)}{F(x)} dy \tag{19}$$

$$q_L^{n^*}(x) = \arg\max_q q \int_x^c \left(1 - q - q_W^{n^*}(y) - c\right) \frac{F'(y)}{(1 - F(x))} dy. \tag{20}$$

As one can easily confirm, these conditions have a linear solution, as follows:

$$q_W^{n^*}(x) = \frac{1}{45}(15 - 11c + 2d) + \frac{8}{15}x \tag{21}$$

$$q_L^{n^*}(x) = \frac{1}{45}(15 - 23c - d) - \frac{2}{15}x. \tag{22}$$

5.2 Duopoly subgames off the equilibrium path

Consider a firm with cost reduction x that unilaterally deviated from equilibrium bidding and bid $\beta_n(z)$, whereas the rival followed the equilibrium bid strategy. If that firm won the auction, its equilibrium output strategy, $q_W^n(x,z)$, solves the condition:

$$q_W^n(x,z) = \arg\max_q q \int_d^z \left(1 - q - q_L^{n^*}(y) - c + x\right) \frac{F'(y)}{F(z)} dy. \tag{23}$$

Whereas if it lost the auction, its equilibrium output strategy, $q_L^n(z)$, solves the condition:

$$q_L^n(z) = \arg\max_q q \int_z^c \left(1 - q - q_W^{n^*}(y) - c\right) \frac{F'(y)}{(1 - F(z))} dy = q_L^{n^*}(z). \tag{24}$$

This yields:

$$q_W^n(x,z) = \frac{1}{45}(15 - 11c + 2d) + \frac{1}{2}x + \frac{1}{30}z \tag{25}$$

$$q_L^n(z) = \frac{1}{45}(15 - 23c - d) - \frac{2}{15}z \tag{26}$$

$$\pi_W^n(x,z) = q_W^n(x,z)^2 \tag{27}$$

$$\pi_L^n(z) = q_L^n(z)^2. \tag{28}$$

5.3 Equilibrium bid strategy

Using the above solution of the duopoly subgames, the expected payoff of a bidder with cost reduction x who bids as if his cost reduction were equal to z, while his rival follows the equilibrium strategy β_n, is:

$$\Pi_n(x,z) = F(z)\left(\pi_W^n(x,z) - \beta_n(z)\right) + (1 - F(z))\pi_L^n(z). \tag{29}$$

For β_n to be an equilibrium, it must be such that $x = \arg\max_z \Pi_n(x,z)$. Using the first-order condition, one must have:

$$F'(x)\left(\pi_W^n(x,x) - \beta_n(x)\right) + F(x)\left(\partial_z \pi_W^n(x,x) - \beta_n'(x)\right) - F'(x)\pi_L^n(x) + (1 - F(x))\pi_L^{n\prime}(x) = 0,$$

which can be written in the form:

$$(\beta_n(x)F(x))' = F'(x)\left(\pi_W^n(x,x) - \pi_L^n(x)\right) + F(x)\partial_z \pi_W^n(x,x) + (1 - F(x))\pi_L^{n\prime}(x). \tag{30}$$

Because $\partial_{zx}\Pi_n(x,z) = (30-22c+d+45x+6z)/90(c-d) > 0$, the function $\Pi_n(x,z)$ is pseudoconcave. Hence, the first-order conditions yield global maxima.

Integration of (30) yields:

$$\begin{aligned} \beta_n(x) &= \int_d^x \left(\pi_W^n(y,y) - \pi_L^n(y)\right)\frac{F'(y)}{F(x)}dy + \int_d^x \partial_z \pi_W^n(y,y)\frac{F(y)}{F(x)}dy + \int_d^x \pi_L^{n\prime}(y)\frac{1-F(y)}{F(x)}dy \\ &= \frac{c(120 - 377d) + 15d(27 + 8d) - 88c^2}{1350} + \frac{375 - 347c + 122d}{1350}x + \frac{4}{45}x^2. \end{aligned} \tag{31}$$

Obviously, $\beta_n(x)$ is strictly increasing; hence, the assumed monotonicity confirms, which proves that $\beta_n(x)$ is the equilibrium bid function.

The equilibrium requirement (30) has the following interpretation: the RHS states the marginal benefit of z and the LHS states its marginal cost. In equilibrium, the bid function must be such that the marginal benefit equals the marginal cost, so that it does not pay to deviate from equilibrium bidding $\beta_n(x)$, for all x.

The marginal benefit has three components: as z is increased to z', 1) it becomes more likely to win rather than lose the auction (this is captured by the first term), 2) in the event of winning, the set of rival's types (who lose) is increased from $[d,z)$ to $[d,z')$; because losers' output is decreasing in their type parameter, it follows that the rival's average output diminishes, to the benefit of the winner (this is captured by the second term); 3) in the event of losing, the set of rivals' types (who win) is reduced from $(z,c]$ to $(z',c]$; therefore, one infers that one faces a rival who is on average stronger and produces higher output, which reduces the own expected profit.

6 Comparison of equilibrium bid functions

We now summarize and interpret the relationship between the equilibrium bid functions.

Proposition 1. *No disclosure implies more aggressive bidding than partial disclosure, $\beta_n(x) > \beta_p(x)$, whereas $\beta_n(x) > \beta_f(x)$ for x below a threshold $\hat{x}$ level and $\beta_n(x) < \beta_f(x)$ for all $x > \hat{x}$.*[6]

Proof. 1) Compute $\phi(x) := \beta_n(x) - \beta_p(x)$, which gives a strictly convex function of x that is decreasing and positive valued at $x = c$. Hence, $\phi(x) > 0$ for all $x \in [d, c]$.

2) Compute $\psi(x) := \beta_n(x) - \beta_f(x)$, which gives a strictly concave function of x that is decreasing and positive valued at $x = d$ and negative valued at $x = c$. Hence, $\psi(x) = 0$ has exactly one root $\hat{x} \in (d, c)$. □

The relationship between the equilibrium bid functions is illustrated in Figure 1.

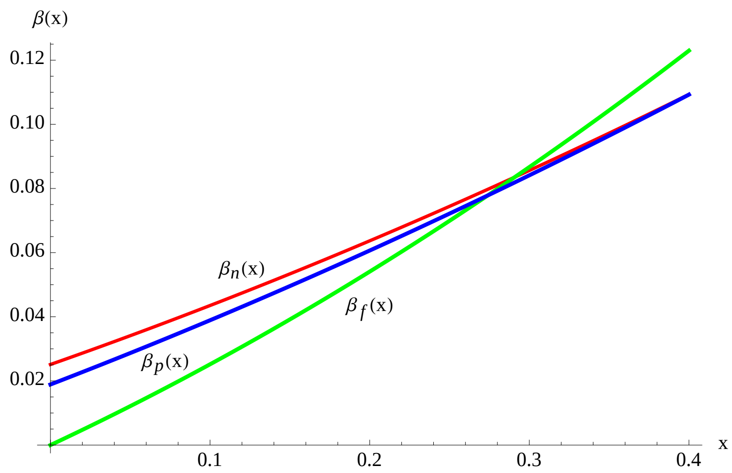

Figure 1: Equilibrium bid functions (assuming $c = 0.4, d = 0$)

The relationship between the bid functions can be interpreted by comparing the distinct terms of the bid functions. All bid function have in common a component that reflects the profit premium of winning the license, $E\left(\pi_W(X_{(2)}) - \pi_L(X_{(2)}) \mid X_{(2)} < x\right)$.[7] However, this profit premium differs across disclosure rules. Focusing on the most relevant comparison between full and no disclosure, we find that this profit premium is higher under no disclosure than under full disclosure. This contributes to make $\beta_n(x)$ greater than $\beta_f(x)$.

Interestingly, if the winning bid is not revealed, the profit premium is positive even for $x = d = 0$, which reflects in the positive intercepts of β_n and β_p in Figure 1. The reason for this paradoxical property is that the winner benefits from the uncertainty of the loser about the winner's cost reduction. Moreover, at $x = d$ the profit premium is higher under no than under partial disclosure. The reason is as follows: under partial disclosure the loser's type becomes common knowledge. Starting from no disclosure, the loser with the lowest cost reduction equal to d would like to inform the winner about his type because that would induce the winner to produce less output. Therefore, $\pi_L^p(d) > \pi_L^n(d)$ and $\pi_W^p(d,d) < \pi_W^n(d,d)$. This explains why for low cost reduction the

[6] Similarly, β_p intersects β_f from above exactly once.

[7] $X_{(2)}$ denotes the second highest order statistics of the sample of two *i.i.d.* random variables.

profit premium is higher under no disclosure than under partial disclosure, which contributes to make $\beta_n(d) > \beta_p(d)$, as depicted in Figure 1.

The β_f function has one other term which reflects the benefit from signaling strength that contributes to increase β_f. Whereas the β_n function has two other terms. Both of these terms reflect the benefit and cost of experimentation. Specifically, the term $\partial_z \pi_W^n(x,x)F(x)$ represents the fact that, in the event of winning, a slightly inflated bid, $\beta_n(z) > \beta_n(x)$, informs the bidder that he faces a rival (the loser) whose type set is increased from $[d,x)$ to $[d,z)$. Because the loser's output is decreasing in his type parameter, the outcome of this experimentation tells the bidder that his rival's average output is lower, which is why this term is positive. Similarly, the term $\pi_L^{n\prime}(x)(1-F(x))$ represents the fact that in the event of losing a slightly inflated bid informs the bidder that he is facing a rival (the winner) whose type set is reduced from $(x,c]$ to $(z,c]$. Because the winner's output is increasing in his type parameter, the outcome of this experimentation tells the bidder that his rival's average output is higher, which is why this term is negative.

Computing the difference between the signaling term in the β_f function and the sum of terms that reflect the benefit and cost of experimentation in the β_n function, one finds that the signaling term exceeds the experimentation term and that the difference between these terms is increasing in x. This explains why for high x full disclosure yields higher equilibrium bids than no disclosure.

The relationship between the equilibrium bid functions does not indicate immediately which disclosure is optimal. However, the disclosure rules can be ranked unambiguously.

7 Optimal information disclosure

We now characterize the disclosure rule that is optimal for the innovator and examine whether there is a conflict of interest between firms and the innovator. Because different disclosure rules affect the size of the total surplus, firms' preference order is not necessarily the opposite of the innovator's preference, and we also provide the ranking by total surplus.

The innovator's equilibrium expected revenues in the different regimes, $R_i := \int_d^c \beta_i(x)2F(x)dF(x)$, $i \in \{f,p,n\}$, are:

$$R_f = \frac{1}{54}\left(2c(7-8d)+d(22+7d)-9c^2\right) \tag{32}$$

$$R_n = \frac{1}{2025}\left(c(555-557d)+d(795+271d)-389c^2\right) \tag{33}$$

$$R_p = \frac{1}{864}\left(c(224-254d)+d(352+111d)-145c^2\right). \tag{34}$$

The corresponding equilibrium expected profits of firms, $\Pi_i^* := \int_d^c \Pi_i(x,x)dF(x)$, $i \in \{f,p,n\}$, are:

$$\Pi_f^* = \frac{1}{54}\left(6-11d-13(1-d)c+11c^2\right) \tag{35}$$

$$\Pi_p^* = \frac{1}{288}\left(32-48d-7d^2-(80-62d)c+73c^2\right) \tag{36}$$

$$\Pi_n^* = \frac{1}{4050}\left(450-645d-112d^2-(1155-839d)c+1073c^2\right). \tag{37}$$

Using the above results, and the fact that the total surplus is equal to $S_i := R_i + 2\Pi_i^*$, it is easy to confirm the following rankings of disclosure rules.

Proposition 2. *The disclosure rules are ranked as follows:*

$$R_n > R_f > R_p \quad \textit{(innovator's revenue ranking)} \tag{38}$$

$$\Pi_f^* > \Pi_p^* > \Pi_n^* \quad \textit{(firms' ranking)} \tag{39}$$

$$S_f > S_p > S_n \quad \textit{(surplus ranking).} \tag{40}$$

Evidently, more information improves efficiency. While firms also prefer more information, the innovator most prefers the least efficient regime of no information disclosure. This indicates a sharp conflict of interest, except that all parties agree that full disclosure is preferable to partial disclosure. Of course, the latter could not occur if the total surplus were not affected by the disclosure rule.

The ranking of disclosure rules by total surplus can be interpreted as follows. The expected total surplus can be written as $S = E((1-Q)Q) - E(cq_L + (c-X)q_W), Q := q_W + q_L$, which in turn can be rewritten as:

$$S = (1 - E(Q))E(Q) - Var(Q) - \bar{C}, \quad \bar{C} := E(cq_L + (c-X)q_W). \tag{41}$$

Using the above solution of q_W^i, q_L^i for $i \in \{n, p, f\}$ one finds that the expected value of aggregate output is the same for all three disclosure rules, whereas the variance of aggregate output and the expected value of aggregate aggregate cost decrease as more information is disclosed:[8]

$$E(Q^n) = E(Q^p) = E(Q^f), \quad Var(Q^n) > Var(Q^n) > Var(Q^f), \quad \bar{C}^n > \bar{C}^p > \bar{C}^f. \tag{42}$$

This explains why the expected value of total surplus increases as more information is disclosed.[9]

The intuition for the rankings of disclosure rules from the perspective of the innovator and bidders is less transparent. However, using the surplus and the innovator's revenue rankings it is easy to see why bidders least prefer the disclosure rule that is most preferred by the innovator, as follows:[10]

$$\Pi_n^* = \frac{1}{2}(S_n - R_n) > \frac{1}{2}(S_f - R_n) > \frac{1}{2}(S_f - R_f) = \Pi_f^*. \tag{43}$$

Disclosure rules are intimately connected to auction formats. In an open, descending bid (Dutch) auction the highest bid is automatically revealed to bidders, and in an open, ascending bid (English) auction the second highest bid is revealed to bidders, whereas in sealed-bid auctions bids are invisible (unless the auctioneer chooses to reveal information). Because first- and second-price sealed auctions are revenue equivalent if in both cases the same information is disclosed, we find the following revenue ranking of auction formats which indicates that revenue equivalence fails.

Corollary 1. *The revenue ranking of standard auction formats in terms of the innovator's revenue is:*

$$\textit{Sealed-bid (1-st or 2-nd price)} \succ \textit{Dutch} \succ \textit{English}. \tag{44}$$

Hence, due to differences between the implicit information disclosure, the standard auctions are not revenue equivalent and the sealed-bid auction is the optimal auction.

fails.

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[8]Specifically, $E(Q) = (6-4c+d)/9$, $Var(Q^f) = (c-d)^2/162$, $Var(Q^p) = Var(Q^f) + (5(c-d)^2)/864$, $Var(Q^n) = Var(Q^p) + (19(c-d)^2)/21600$, $\bar{C}^f = (4c-5c^2-d-d^2)/9$, $\bar{C}^p = \bar{C}^f + (c-d)^2/144$, $\bar{C}^n = \bar{C}^p + (c-d)^2/2160$.

[9]This interpretation is similar to Shapiro (1986) who compared the incentives for full vs. no disclosure assuming that firms can commit in advance to exchange verifiable information.

[10]Note, viewed from behind the "veil of ignorance", bidders' expected payoff is equal to one half of what is left of the total surplus after deducting the innovator's expected revenue.

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