# Single and Multi-Winner Auctions with Performance Obligation

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**Abstract**

Auctioning off access rights towards private providers following a process of competitive tendering has become a core element of governments' toolbox to regulate markets and public services, protecting public interests. This market-based management of public access, however, effectively creates a monopolist with all the associated negative consequences for consumer welfare and market functioning. We design an experiment to test the two most prominent policy tools to remedy this predicament, i.e. ensuring competition also after the auction and/or explicitly defining a minimum production standard. Our results indicate that production standards are comparatively more powerful in improving total welfare, mainly via increased market output.

***Keywords***— Second Price Auction; Market Design; Market Experiment; Industry Regulation; Performance Obligation

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# 1 Introduction

Over the last decades, governments have shifted towards increasing competition in the provision of public services to secure public interests (Armstrong & Sappington, 2006; Wolswinkel, Jansen, & van Ommeren, in press).[1] While authorities granting licenses to operate on a market have a variety of methods at their disposal (e.g., administrative processes, lotteries and first-come-first-served principles), auctions are a typical method for distributing these licenses (Börgers & Van Damme, 2004; Gupta, 2002).[2] Gas stations, airport slots, spectrum rights and $CO_2$ emission permits have been put up for bid (see, e.g., Ball, Berardino, & Hansen, 2018; McAfee & McMillan, 1996). In contrast to other procurement alternatives, competitive tendering of government services via auctions provides a set of advantages (Amaral, Saussier, & Yvrande-Billon, 2009; Hawkins, 2020; Park, Lee, & Choi, 2011). Most importantly, auctions can achieve efficiency by assigning the operating rights to the party that values these rights most while generating some government revenue in the process (McMillan, 1995, 1994). Auctioning off an operating license, however, may come at a social cost as this state-certified barrier to entry sustains one firm in a monopoly position which will result in a deadweight loss for society at the expense of consumer welfare (Leslie, 2006; Posner, 1975; Rey & Salant, 2017; Jehiel & Moldovanu, 2003).[3]

To address this issue, governments may decide to maintain some competition after the auction by admitting more than one firm to the market (Cramton, Kwerel, Rosston, & Skrzypacz, 2011; Dana Jr & Spier, 1994). An alternative, more regulatory approach includes an enforceable performance obligation when operating on the market, like for example a "universal service" (Economides, 1999) or "use it or lose it" (Cave, 2010) requirement. [4] As such, competitive tendering of services has received attention in recent years both in the public debate (Evans, 2019; Gryta & Flint, 2017), the academic discourse (i.e. Amaral et al., 2009; Lin, Chang, Chang, & Zheng, 2020; McMillan, 1995; Wolswinkel, 2013; Van Ommeren, 2004), as well as with policymakers.[5]

Despite the popularity of auctions for government tendering, we only know little about the direct effects of these policies on firms' valuation for market access and their output on the market. Our study responds to this knowledge gap by presenting results from an incentivised laboratory experiment on performance obligations in single-winner and multi-winner auctions. Our design allows to manipulate

[1]Historically, public services were either provided by government itself, or licensed through administrative decision (McMillan, 1994). In the context of spectrum rights in the United States, for example, interested parties would file an application with the Federal Communications Commission, which then assigned licenses at random via lottery (Kwerel & Williams, 1993; McMillan, 1994; Hazlett, 1998).

[2]Subject to natural or technical limitations of capacity, public authorities are legally obliged to apply a selection procedure to potential candidates that provides full guarantees of impartiality and transparency including, in particular, adequate publicity about the launch, conduct and completion of the procedure (Van Ommeren, 2004; Wolswinkel, van Ommeren, & Den Ouden, 2019; Adriaanse, van Ommeren, Den Ouden, & Wolswinkel, 2016). The same link between transparency and impartiality had already been emphasised by the Court of Justice of the European Union in Telaustria, supra n. 17, para. 61.

[3]Auriol and Picard (2009) demonstrate that under certain conditions, even a monopolist servicing the market can be preferred to the government operating on the market itself. For example, in very poor countries or in markets that render high franchise fees, governments use market access fees to liquidate its debt.

[4] In the Netherlands, for example, license holders are obliged to actually perform the licensed activity as deterrent for spectrum hoarding.

[5]Federal communications Commissions 'Auctions of Upper Microwave Flexible Use License for Next Generation Wireless Services; Notice and Filing Requirements, Minimum Opening Bids, Upfront Payments, and Other Procedures for Auctions 101 (28 GHz) and 102 (24 GHz)' https://www.fcc.gov/document/fcc-establishes-procedures-first-5g-spectrum-auctions-0; Parliamentary papers 2001/02, 24 036, nr. 254; Don, Drahmann, and Rutten (2020) and EU Emissions Trading System (Directive 2003/87/EC).

the market organisation while keeping constant the general demand structure a firm faces. This level of control regarding the market design would be unparalleled in a field setting, which enables us to measure the true cost and benefit of post-auction competition or production standards. By employing an $n$-price Vickrey auction (Vickrey, 1961), participants' dominant strategies are to bid their true valuation for market access independent of risk attitudes (Kagel, Harstad, & Levin, 1987).

Indeed, aligning with results from earlier experiments (e.g., Kagel & Roth, 2020), we find that aggregate bidding levels coincide with the equilibrium prediction for all treatments. Individual bids, by contrast, can deviate significantly from the equilibrium, in particular for players who produce relatively efficiently. Concerning production levels, our findings indicate some overproduction with respect to the equilibrium prediction for most treatments. Only the unconstrained single-winner produces at equilibrium level, which for this treatment is at a socially inefficient low level. Both maintaining competition on the market and explicit performance obligations lead to an increase in output, which translates into an increase in consumer surplus and overall social welfare.

We extend prior work on the differentiation of multi-unit and single-unit auctions which sought to identify their unique characteristics (see, for example Wilson, 1979; Ausubel, Cramton, Pycia, Rostek, & Weretka, 2014). Our study is the first to test the effects of performance obligations on the bidding and production behaviour of single-unit vis-à-vis multi-unit auctions. Prior studies have either studied auctions in which winning firms get licenses to operate in an aftermarket (Janssen & Karamychev, 2009; Offerman & Potters, 2000; Kasberger, 2020) or the effect of the price paid for licences on the aftermarket (Cambini & Garelli, 2017; Park et al., 2011) in isolation. We contribute to this literature by adding an explicit investigation of the impact of performance obligations and by varying the market structure after the auction.

Our article is structured as follows. Section 2 presents the experimental design. Then we present the underlying theory and formulate hypotheses in Section 3 before discussing our results in Section 4. We conclude by discussing the policy implications and potential avenues for future research in Section 5.

## 2 Experimental Design

We present a two-stage experiment in which firms first compete for market access via a sealed bid $n$-price Vickrey auction and then set a quantity to be sold on that market, if successful in the first stage (Vickrey, 1961). Using a $2 \times 2$ design, we vary whether there exists a minimum quantity obligation and/or post-procurement competition on the market to investigate their effect on valuation for market access and consequences for output and prices.

For the first stage, we employ principles from the affiliated private value (APV) auction design, as in Kagel et al. (1987) and Milgrom and Weber (1982), to design a market with affiliated private *production costs*. In contrast to the seminal independent private value (IPV) and the pure common value (CV) paradigms, the APV relaxes a set of strong assumptions required for the IPV and the CV approach, respectively. Under IPV, each individual bidder knows her private value for the object, but others do not have this information at all. Instead, they only know their own valuation, which is independent of anybody else's valuation. Empirically, this appears to be a very strong assumption.[6]

[6]For a standard equipment contract, the bidders can usually accurately anticipate their own costs to determine the best offer (Klein, 1998). For many concessions and licenses, however, bidders may need to value

The CV approach assumes that the auctioned object is valued at exactly the same rate for all bidders, but this rate is unknown to all bidders, who are only endowed with private estimates of this common rate (Paarsch, 1992; Hansen, 1985). This complete homogeneity in the valuation of the auctioned object is an equally strong assumption, empirically. Instead, APV as we employ in this study, does incorporate differences in individual preferences, and does assume that the independence of these private valuations is unrealistic (see Li, Perrigne, & Vuong, 2002). In brief, APV models individual valuations as a additively separable function of a common value shared by all agents (here: $c_0$) and an individual noise term around $c_0$, which we call $\varepsilon_i$. We discuss the specific implementation of APV for our auction in Subsection 2.1.

Figure 1 provides an overview of our treatments, which we will explain in detail in the remainder of this section. In each session, participants submit bids in an auction for market access, which only a subset of all participants can get. The treatments vary in whether one or two participants gain access to the market, and whether or not there exists a minimum production threshold. In the experiment, participants play for tokens (denoted as ¤), which will be converted into individual earnings at a rate of €0.1 for 1 token, at the end of the experiment.

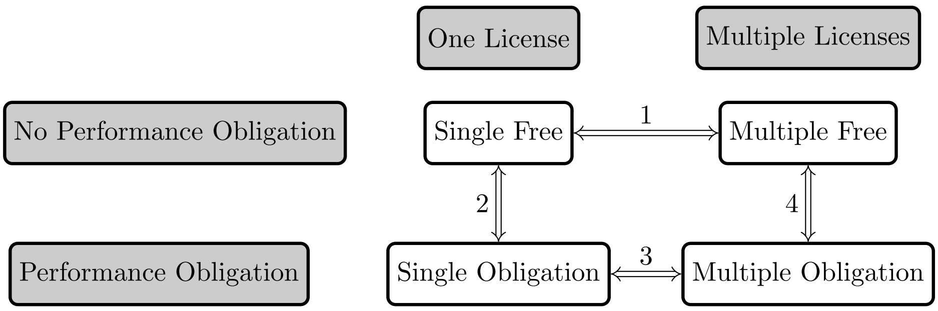



**Figure 1:** Overview of the $2 \times 2$ design varying the number of licenses to be won and whether or not winning a license comes with a performance obligation

## 2.1 Single Free Treatment

We start by describing the procedure for the *Single Free* treatment, before zooming in on the other treatments and how they differ from this benchmark. Figure 2 summarises the structure of an experimental session, which is identical for all treatments. Subsequent to instructions, a risk aversion test using methods by Eckel and Grossman (2002) and a trial round, participants engage in a 10 round bid for market access with subsequent Production Phase (in partner matching). At the end of the experiment, one round will be selected at random to be payment relevant. Earnings from the other rounds will not be paid out. This avoids hedging behaviour between the rounds and makes sure participants approach each round as if it was the payment-relevant one (Charness, Gneezy, & Halladay, 2016).

The experimental session is concluded by a brief questionnaire and collection of payment information. To begin, we will focus on the two phases of the experiment which are central to our research design: The Bidding Phase and the Production Phase, as indicated in grey background colour in Figure 2.

the right to the concession or license, which depends not just on their own skill, but also on factors affecting all bidders, such as consumers' willingness to pay and regulators' future behaviour.

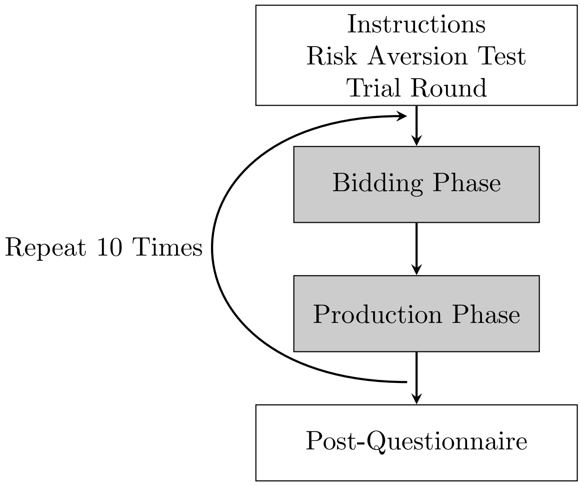



**Figure 2:** Experimental Setup

### Phase 1: Bidding Phase

Participants interact in groups of three (partner matching). Each participant receives 100 tokens at the start of each round, which she can use for bidding in the auction. Using a second-price, sealed-bid procedure, three (3) participants bid for one (1) access permit to a market. This means the participant submitting the *highest bid* will win the auction and pay the *second-highest* bid to access the market. The bidding procedure in this treatment is close to the Second-Price Private Information Condition in Kagel et al. (1987). When bidding for market access, participants are informed of the individual production cost $c_i$, the inverse demand function for *Single Auctions*, $p_S(x_i)$, and the bandwidth from which the noise parameter $\varepsilon_i$ is drawn, all of which will be explained in what follows.

### Phase 2: Production Phase

The participant who has won the auction proceeds to the Production Phase to produce and sell units in the market subject to the following inverse demand function:

$$p_S(x_i) = 21 - x_i. \tag{1}$$

This translates into a decreasing price per unit $(x_i)$, depending on the total number of units in the market, as outlined in Table 1 for selected values of $x_i$. While producers are real participants in the experiment, buyers are simulated using the inverse demand function.

**Table 1:** Single treatments – inverse demand function represented in table format

| **Units Produced** $x_i$ | **Price per Unit** $p_S(x_i)$ |
|---|---|
| 5 | ¤16 |
| 10 | ¤11 |
| 15 | ¤ 6 |
| 20 | ¤ 1 |

In each auction round, individual marginal production cost ($c_i$) is determined in a two-step procedure. For legibility, we omit time indices. First, an uneven random integer ($c_0$) is drawn from the discrete uniform distribution $[\underline{c}, \overline{c}] = [5, 13]$. This means only five numbers can be drawn, being 5, 7, 9, 11 or 13. In practice, our software picked each of these values exactly twice (without replacement), making sure each $c_0$ happens exactly twice in a random order over the course of the 10 rounds.

Next, private values $c_1 \ldots c_3$ are drawn at random from a uniform distribution around $c_0$, such that

$$c_i = c_0 + \varepsilon_i$$

with $\varepsilon_i$ drawn from $[\underline{\varepsilon}, \overline{\varepsilon}] = [-2, 2]$ at a precision of one decimal. In other words, in each round, each player $i$ has private individual marginal production cost $c_i$, which is comprised of a general marginal production cost component $c_0$ drawn between 5 and 13, and a noise parameter $\varepsilon_i$, which is drawn between -2 and 2. Hence, the individual market production cost $c_i$ lies between 3 and 15. Participants learn their private value or $c_i$ and hence, have perfect information about their personal valuation of the market when placing a bid (Bulow, Levin, & Milgrom, 2009; Kasberger, 2020). In addition, players know the bandwidth from which $\varepsilon_i$ is drawn (i.e. $[-2, 2]$). The value of $c_0$ and the individual marginal production cost of other players $c_{-i}$, by contrast, are not disclosed to the participants. After every round, participants will be informed about whether they have won and what their price is for market access.

We allow non-negative bids up to a precision of one decimal. Ties will be broken by a randomisation device (i.e., virtual coin toss). Let $b_{i,k}$ be the bid of player $i$, ordered by the size of the bid from highest ($k = 1$) to lowest ($k = 6$). Earnings for the highest bidder then are

$$\pi_i = 100 + p_S(x_i) \cdot x_i - c_i \cdot x_i - b_{j,2} \tag{2}$$

with $i, j \in I$ and $i \neq j$. This is the token endowment of 100 from the bidding phase, plus the player's revenue from production, minus the production cost, minus the bid of the second-highest bidder. All other players keep their endowment of 100 from the auction round as flat fee earnings for this round.

## 2.2 Multiple Free Treatment

The *Multiple Free* treatment proceeds as the *Single Free*, with the exceptions outlined in this subsection. As before, the experiment is preceded by instructions, a risk aversion measure and a trial round. Then participants interact for 10 rounds in partner matching for the main part of the experiment. As before, one round will be randomly selected as payment-relevant at the end of the experiment.

### Phase 1: Bidding Phase

Instead of one winner as in the *Single Free* treatment, we now have six (6) participants and two (2) winners per auction round. Again, each participant receives an endowment of 100 tokens, which she can use to place bids. Participants cast their individual bids in the same way as in the *Single Free* treatment, subject to the same information set: i.e., knowing own individual marginal production cost $c_i$, the bandwidth from which the noise parameter $\varepsilon_i$ is drawn, and the inverse demand function for both *Multiple* treatments $p_M(x_i, x_j)$. To accommodate for the higher number of winners, the market for the Production Phase in the *Multiple* treatments is scaled upwards by a factor of two: i.e., twice as much production can be realised.

In contrast to the *Single Free* treatment, two bidders will be selected as auction winners and receive access to the market. In a multi-unit 'Vickrey auction', the two highest bids are accepted at the price of the third bid. This pricing rule is a direct generalisation of the one-unit Vickrey-rule (as in Vickrey, 1961). This way, in both the *Single* and the *Multiple* treatments, the auction procedure selects $k$ winners who have placed the highest bid at a price of the bid ranked at position $k+1$.

### Phase 2: Production Phase

Equivalent to the *Single Free* treatment, both winners from the auction round will proceed to the Production Phase. Individual marginal production cost $c_i$ with $i \in \{1, \ldots, 6\}$ will have been determined each round from $c_0$ and $\varepsilon_i$ as in the *Single Free* treatment. The winning participants proceed to Phase 2 to produce and sell units on the market subject to the following inverse demand function for a duopolistic market that is twice as large as in the single-item auction:

$$p_M(x_i, x_j) = 21 - 0.5(x_i + x_j) \tag{3}$$

Accordingly, the market price is a decreasing function of both $i$'s and $j$'s output. When entering the Production Phase, winners do not receive information about the other market participant's individual marginal cost $c_{-i}$ nor about $c_0$. Table 2 presents an overview of the mapping of the aggregate output $(x_i + x_j)$ into the price per unit $(p_M(x_i, x_j))$ for selected values. Accordingly, firms now face a coordination problem in that each of the two producers who have gained access to the market individually determine their production $x_{i,j}$, while the price per unit depends on the sum of their joint production $x = x_i + x_j$. Let $b_{l,k}$ be the bid of player $l$, ordered by the size of the bid from highest $(k = 1)$ to lowest $(k = 6)$, with $i, j, k \in I$ and $i \neq j$. Earnings for each market participant then are determined by the endowment, plus the revenue from the market, minus the production cost, minus the cost for market access. Formally:

$$\pi_i = 100 + \overbrace{(21 - 0.5(x_i + x_j))}^{p_M(x_i,x_j)} \cdot x_i - c_i \cdot x_i - b_{l,3} \tag{4}$$

**Table 2:** Multiple treatments - inverse demand function in table format

| **Units Produced** $x_i + x_j$ | **Price per Unit** $p_M(x_i, x_j)$ |
|---|---|
| 5 | ¤18.5 |
| 10 | ¤16 |
| 15 | ¤13.5 |
| 20 | ¤11 |
| 25 | ¤ 8.5 |
| 30 | ¤ 6 |
| 35 | ¤ 3.5 |
| 40 | ¤ 1 |

## 2.3 Single Obligation Treatment

The *Single Obligation* treatment proceeds as the *Single Free* one, with the addition of a performance obligation for the winning party. Hence, all parameters are equivalent between these two treatments (see Subsection 2.1), with the exception of what is outlined in the following.

### Phase 1: Bidding Phase

Each participant receives an endowment of 100 tokens and places a bid for market access. When placing a bid, participants know their individual marginal production cost $c_i$ and the inverse demand function $p_S(x_i)$, which are both determined as described in Subsection 2.1. Participants also know the performance obligation $\underline{x}^{SO}$ at this stage, which has been determined at the point that maximises consumer surplus.[7] When admitted to the Production Phase, participants have to produce at least $\underline{x}^{SO}$.

### Phase 2: Production Phase

This phase proceeds as in the *Single Free Auction* with the exception that the participant who has won access to the market cannot produce less than the performance obligation $\underline{x}^{SO}$. The participant may, however, decide to produce more than $\underline{x}^{SO}$, subject to her individual marginal production cost $c_i$ and the inverse demand function $p_S(x_i)$.

## 2.4 Multiple Obligation Treatment

The *Multiple Obligation* treatment is a combination of the *Multiple Free* and the *Single Obligation* ones. All parameters remain equivalent, except now there will be multiple winners (i.e., two) per bidding round, and a performance obligation applies for all winners. Also here, the performance obligation $\underline{x}^{MO}$ will be determined at the point that maximises consumer surplus.[8] Each producer will have

[7] See Section 3.3 for details on the consumer surplus in this market.

[8] See Subsection 3.4 for the consumer surplus in this market.

to contribute at least 50% of this output level, irrespective of the other's output level, such that $\underline{x}_i^{MO} = 0.5 \cdot \underline{x}^{MO}$. A player's production exceeding $\underline{x}_i^{MO}$ does not compensate for the other player's performance obligation. Each player independently has to fulfil her performance obligation.

### 2.5 Procedures

We ran this computerised experiment[9] with 252 participants (60.7 % female, average age 21.5) at the CentERlab of Tilburg University, the Netherlands, between February and May 2022. The experiment lasted approximately 75 minutes including instructions, the main experiment, a short survey and payment invoicing. Average earnings per participant were €12.81 (sd = 2.65). Participants sat in a computer cubicle visually separated from each other. Further, participants completed a trial run with on-screen instructions to familiarise with the interface and the game concept.[10] The instructions and screen shots can be downloaded from the online repository.

## 3 Theory and Hypotheses

The market we employ in our experiment extends the standard symmetric linear quantity-setting monopoly/duopoly for homogeneous products towards one with a minimum output level established by a principal. We start our analysis by looking at the *Single Free* treatment. First, we determine the level of output, which informs the bidding strategy based on the player's valuation for market access. We will then turn to the *Multiple Free* treatment, again first focusing on the level of output before discussing bidding strategies based on the valuation for market access. Finally, we discuss both the *Single Obligation* and the *Multiple Obligation* cases in the same order of analysis.

Throughout this section, we focus on the predictions for market behaviour. In Appendix A, we provide the associated formal derivations underlying the results presented in this section. We conclude this section with hypotheses grounded in the established behavioural predictions in Subsection 3.5.

### 3.1 Single Free Treatment – Market Access Valuation and Bidding Strategies

When entering the market, the monopolist determines her output, motivated by the profit function (Equation 2) derived from the inverse demand function and the cost function, as described in Subsection 2.1. Depending on the individual marginal production cost $c_i$ for the auction winner, profit is maximised at a level of output equal to

$$x_i^{SF} = \frac{21 - c_i}{2}. \tag{5}$$

Milgrom and Weber (1982) show that for an $n$-price Vickrey auction (like, for example, the second

[9] The programme was written in z-Tree (Fischbacher, 2007).

[10] Prior to the experimental market, we measured participants' level of risk aversion using methods by Eckel and Grossman (2002).

price auction), a player's optimal strategy is to bid her true valuation for the good. This is true, independent of the bidder's risk preferences, the number of rival bidders, initial wealth levels, or other bidders' strategies. Lusk and Shogren (2007) provide an intuitive illustration of the underlying dynamics, leading to this theorem: "If a bidder submits a bid greater than his value, he runs the risk that the second highest bid will exceed his value, which would cause him to lose money; if he submits a bid less than his value, he runs the risk that someone could outbid him, causing him to miss out on a profitable opportunity. Over- and under-bidding one's value runs the risk of either paying too much or missing out on a good deal, which drives the bidder toward simply bidding his true value." Accordingly, players would bid their true valuation for market access at a level of

$$b_i^{SF} = \frac{1}{4} (21 - c_i)^2 . \tag{6}$$

We provide a formal derivation in Appendix A.1.

## 3.2 Multiple Free Treatment – Market Access Valuation and Bidding Strategies

When compared to the *Single Free* treatment, two auction winners gain access to the market now, competing in a duopoly – a textbook case of Cournot quantity competition between two sellers (Ruffin, 1971). Under this duopolistic competition, each market participant $i$ independently maximises expected earnings (Equation 4) at an output of

$$x_i^{MF} = \frac{2(21 - c_i)}{3}. \tag{7}$$

Concerning the bidding strategy, the argument from Subsection 3.1 applies to demonstrate that a player's optimal strategy is to bid her true valuation for market access, which is a corollary of the total (expected) output on the market. As individual marginal production cost is distributed around $c_0$ for all players, this true mean constitutes the expected value both for her own and for other players' marginal production cost. Hence, in expectation we have $E(c_0) = E(c_{-i}) = c_i$. This allows us to determine the valuation for market access at a level of

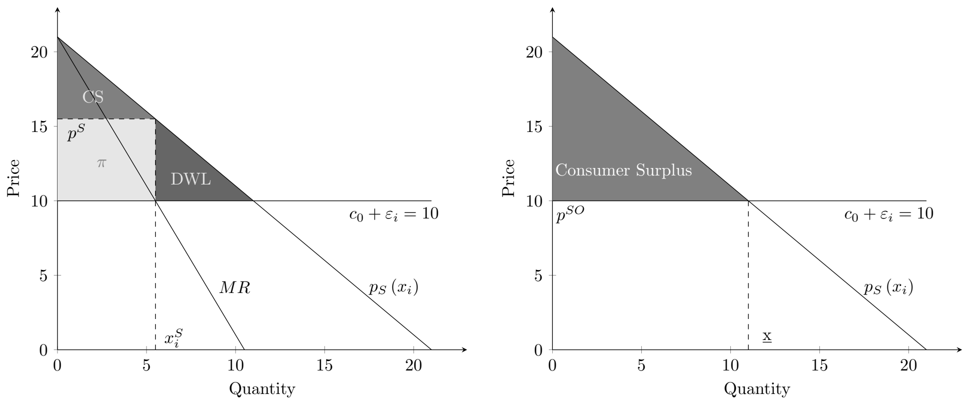
$$b_i^{MF} = \frac{2}{9} (21 - c_i)^2 . \tag{8}$$

We provide a formal derivation in Appendix A.2.

Under collusive behaviour (i.e., both producers behave as one (large) monopolist), the two market participants would jointly produce twice the amount of output and realise individual earnings at the same value as the monopolist in the *Single Free* treatment, if both produce the same collusive output. Hence, if both producers in the *Multiple Free* treatment collude and share their earnings equally, their individual profit would equal that of the monopolist in the *Single Free* case. Consequently, a player expecting to enter a market under collusion should submit the same bid as a player in the *Single Free* treatment (Equation 6), making the two baseline treatments very similar to each other.

### 3.3 Single Obligation Treatment – Market Access Valuation and Bidding Strategies

In both the *Single Obligation* and the *Multiple Obligation* treatments, there is a mandatory minimum production level $\underline{x}$ associated with granting entry into the market. The output in the Production Phase may not be lower than this quantity. We assume that this minimum quantity is set by the government which is concerned with consumer welfare (Jehiel & Moldovanu, 2003). In this standard market, consumer surplus is maximised at a point in which the marginal production cost is equal to the inverse demand function, as illustrated in Figure 3.[11] To minimise market distortions while safeguarding consumer surplus, government sets $\underline{x}$ at the highest possible threshold for marginal production cost $c_0 + \bar{\varepsilon}$, which is $c_0 + 2$ under the calibrations of our experiment. At this point, all firms are able to produce the required output at non-negative profits. Figure 3 illustrates the market situation with or without minimum production requirements at a hypothetical cost level of $c_i = c_0 + \bar{\varepsilon} = 10$. Higher cost levels would shift up the horizontal curve $c_0 + \varepsilon_i$, reducing output quantity and increasing price in the process. Inversely, lower cost levels would shift down the horizontal curve $c_0 + \varepsilon_i$, increase output quantity and reduce price.




**(a)** Monopolist without minimum production

**(b)** Monopolist with minimum production

**Figure 3:** The market situation without and with minimum production at a hypothetical level of $c_0 + \varepsilon_i = 10$. CS is consumer surplus; DWL is deadweight loss; $\pi$ is monopolist profit; and MR is marginal revenue.

In Appendix A.3, we show that consumer surplus will be maximised at a minimum production level $\underline{x}$ of

$$\underline{x}^{SO} = 21 - c_0 - \bar{\varepsilon}. \tag{9}$$

Note that under the conditions of this market, $\underline{x}^{SO}$ is always binding. Hence, players will produce at $x_i^{SO} = \underline{x}^{SO}$ and bid their true valuation for market access for this level of output, being

$$b_i^{SO} = \left(21 - \underline{x}^{SO} - c_i\right) \underline{x}^{SO}. \tag{10}$$

In Appendix A.3 we provide formal derivations.

[11] Our results are robust as to the alternative assumption that government is concerned with total welfare instead. In this market, the result from maximising consumer surplus is equivalent to maximising total welfare.

## 3.4 Multiple Obligation Treatment – Market Access Valuation and Bidding Strategies

This treatment combines elements from both the *Multiple Free* and *Single Obligation* treatments in that there will be multiple (i.e., two) producers on the market who will both face minimum production requirements. We present associated formal derivations in Appendix A.4. Government sets the minimum production level $\underline{\mathrm{x}}^{MO}$ to maximise consumer surplus. To simplify, and as the government does not know the producers' individual cost functions, each producer has to contribute to the minimum production level at the same rate, meaning that every producer has to produce at least half of the minimum production number in our duopoly setting. Hence, $\underline{\mathrm{x}}_i^{MO} = \underline{\mathrm{x}}_j^{MO} = 0.5 \cdot \underline{\mathrm{x}}^{MO}$. Accordingly, the minimum production level for each agent $i$ and $j$ in the market remains unchanged with respect to the *Single Obligation* treatment at a level of

$$\underline{\mathrm{x}}_i^{MO} = \underline{\mathrm{x}}_j^{MO} = 21 - c_0 - \bar{\varepsilon}. \tag{11}$$

In the Appendix, we show that for colluding players who behave as one (large) monopolist, the minimum production level is always binding, hence output and bids would remain at the same level as in the *Single Obligation* treatment.

Also under duopolistic competition, the minimum production level is binding for most realisations of the marginal production cost. There exist combinations of high levels of $c_0$ together with low $c_i$ for which the unconstrained duopolistic output (as in the *Multiple Free* case) exceeds the minimum production level. Figure 19 illustrates how unconstrained duopolistic output exceeds the minimum production level only for specific cases. Hence, we formalise the equilibrium output as

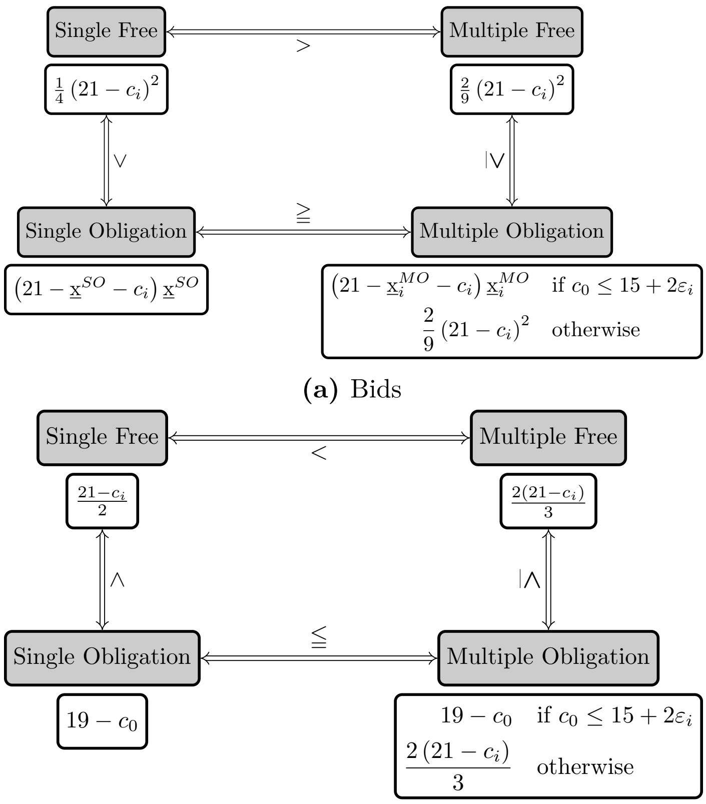
$$x_i^{MO} = \begin{cases} \underline{\mathrm{x}}_i^{MO} & \text{if } c_0 \leq 15 + 2\varepsilon_i \\ \frac{2(21-c_i)}{3} & \text{otherwise.} \end{cases} \tag{12}$$

As argued before, players bid their true valuation for market access having the same expectations about the distribution of other players' cost, meaning $E(c_{-i}) = c_i$ as all $\varepsilon_i$ are distributed around zero. As discussed, participants mostly produce at the minimum output requirement, exceeding this production level only for specific values of individual production cost $c_i$. Hence, participants' bidding behaviour mostly parallels that of players from the *Single Obligation* treatment (as in Equation 10, while some players will bid as in the *Multiple Obligation* treatment (as in Equation 8). We can describe this as

$$b_i = \begin{cases} \left(21 - \underline{\mathrm{x}}_i^{MO} - c_i\right) \underline{\mathrm{x}}_i^{MO} & \text{if } c_0 \leq 15 + 2\varepsilon_i \\ \frac{2}{9}\left(21 - c_i\right)^2 & \text{otherwise.} \end{cases} \tag{13}$$

## 3.5 Hypotheses

We have established predictions for equilibrium bids and output for all treatments, as summarised in Figure 4a.[12] The *Single Free* treatment allows the producer to operate on the market as monopolist without competition or exogenous production threshold. In the *Multiple Free* treatment, we introduce a second producer to the market, transforming the market from monopolistic market to duopolistic quantity competition. Third, the *Single Obligation* treatment exposes the monopolist to a minimum output level, introduced by the principal to maximise consumer surplus. Lastly, the *Multiple Obligation* treatment combines both features, such that players find themselves in a duopolistic quantity competition while being confronted with a minimum output level. The $2 \times 2$ character of our experimental design allows us to isolate each effect and test the hypotheses that we formulate in this subsection (see also Figure 1).



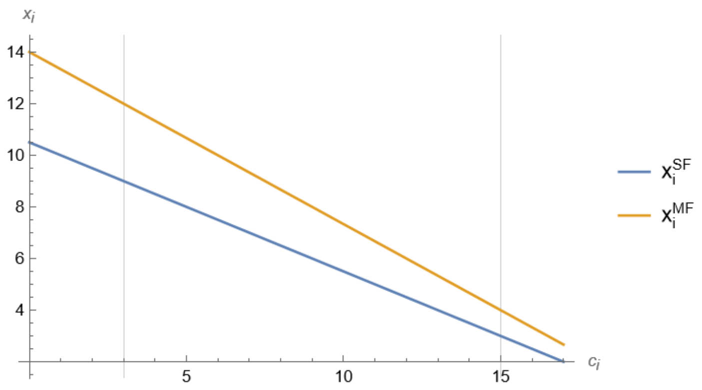

**(a)** Bids

**(b)** Output

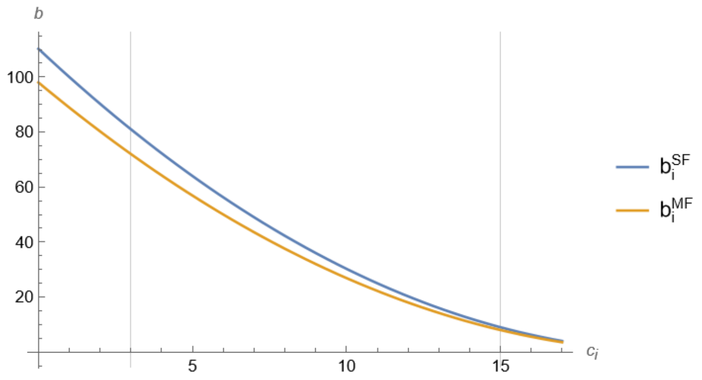
**Figure 4:** Overview of bids and output under standard assumptions for each treatment. We differentiate between "$\geq$ / $\leq$" to indicate that we expect the *inequality* to be most prevalent and "$\geqq$ / $\leqq$" when we expect the *equality* to be more prevalent.

We start by discussing the effect from introducing a second producer in the market, corresponding to the arrow indicated as "1" in Figure 1. In Figure 5, we present visual representations for the difference in equilibrium output and equilibrium bid levels between the treatments. Subfigure 5a illustrates equilibrium output as a function of player $i$'s marginal production cost $c_i$ for both treatments. Then Subfigure 5b shows equilibrium bids for both tretments as a function of $c_i$.

[12]We preregistered our hypotheses at the Open Science Framework, available at osf.io/mqjd4.




**(a)** Equilibrium *output* as a function of own individual marginal production cost $c_i$.




**(b)** Equilibrium *bid* as a function of individual marginal production cost $c_i$.

**Figure 5:** Visual representation of the output and bidding levels for the *Single Free* and *Multiple Free* treatments. Vertical lines at $c_i = 3$ and $c_i = 15$ indicate the upper and lower bound for $c_i$ under the configuration of our experiment.

The figures illustrate that our the results from our equilibrium analysis predict a lower output in the *Single Free* treatment, with a smaller treatment difference for higher cost levels. Consequently, we predict higher bids in the *Single Free* treatment, again with a smaller treatment difference for high cost levels. We develop the underlying hypotheses formally in Appendix B.1.

Note that we get this result despite the upscaling of the *Multiple* environment by a factor of two. This means that in the *Multiple Free* treatment, two players enter a market of exactly twice the size of the market a single player enters in the *Single Free* case. As such, our equilibrium predictions purely capture the effect of competition on the market, controlling for market size.

**Hypothesis 1a** Participants place higher bids in the *Single Free* than in the *Multiple Free* treatment. This difference corresponds negatively with the individual marginal cost $c_i$.

**Hypothesis 1b** Participants produce less in the *Single Free* than in the *Multiple Free* treatment. This difference decreases for higher cost levels $c_i$.

Next, we consider the effect from introducing a minimum production level in a monopolist market, which corresponds to the arrow indicated as "2" in Figure 1. We have argued that the minimum production level introduced at an output that maximises consumer surplus will have a binding character for the monopolist. As such, introducing a minimum output level increases output, which leads to a lower valuation for market access by the monopolist. Subfigure 6a illustrates equilibrium output as a function of the general cost factor $c_0$ and Subfigure 6b depicts equilibrium bids for both treatments on the vertical axis as a function of both individual marginal cost $c_i$ and the general cost component $c_0$.

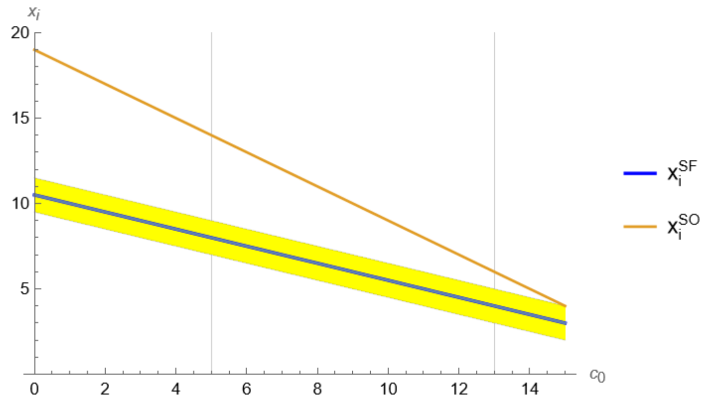
The figures intuitively illustrate how 1) the equilibrium output for the *Single Free* treatment $x_i^{SF}$ is *below* output for the *Single Obligation* $x_i^{SO}$ for all cost levels (Figure 6a). This difference is smaller for large levels of $c_0$. Then, 2) this image presents itself inverted for the valuation for market access, in which the equilibrium bid in the *Single Free* treatment $b_i^{SF}$ is *above* the bid in the *Single Obligation* $b_i^{SO}$ for all cost levels (Figure 6b). Ceteris paribus, this difference is more pronounced for higher levels of $c_i$. We develop these treatment differences predictions formally in Appendix B.2.

**Hypothesis 2a** Players place higher bids in the *Single Free* as compared to the *Single Obligation* treatment. This difference corresponds negatively with the individual marginal cost $c_i$.

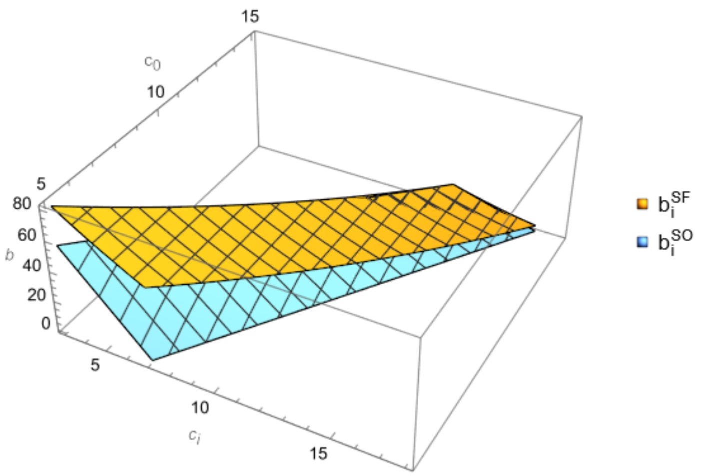
**Hypothesis 2b** Output in the *Single Free* is lower than in the *Single Obligation* treatment. This difference decreases with individual marginal production cost $c_i$.

Third, consider introducing competition in an environment with a minimum production level. This comparison corresponds to the arrow indicated as "3" in Figure 1 and a comparison of behaviour between the *Single Obligation* and *Multiple Obligation* treatment. Subfigure 7a illustrates equilibrium output as a function of general marginal production cost $c_0$, including a bandwidth around the output for the *Multiple Obligation* treatment $\left(x_i^{MO}\right)$ to illustrate the effect of the bandwidth $\varepsilon_i$. Subfigure 7b shows equilibrium bids on the vertical axis as a function of individual marginal production cost $c_i$ and the general cost parameter $c_0$.

The graphs illustrate how in terms of output, the minimum production level is binding for most realisations of $c_i$ and $c_0$ and that only for a high-$c_0$-environment combined with low $c_i$ would a player

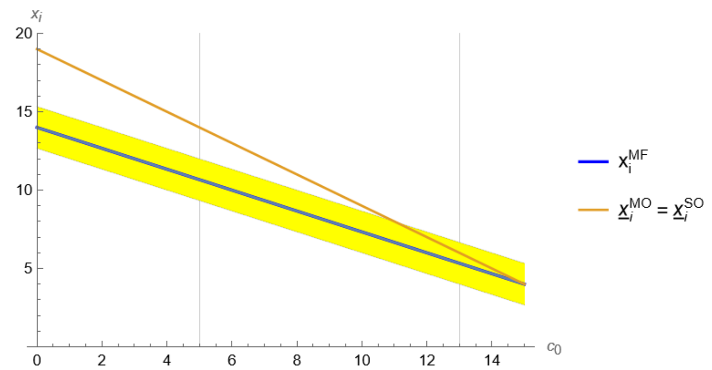



**(a)** Equilibrium *output* as a function of general marginal production cost $c_0$. The yellow bandwidth around $x_i^{SF}$ indicates the lower and upper bound taking into account $\varepsilon$. Vertical lines at $c_0 = 5$ and $c_0 = 13$ indicate the upper and lower bound for $c_0$ under the configuration of our experiment.

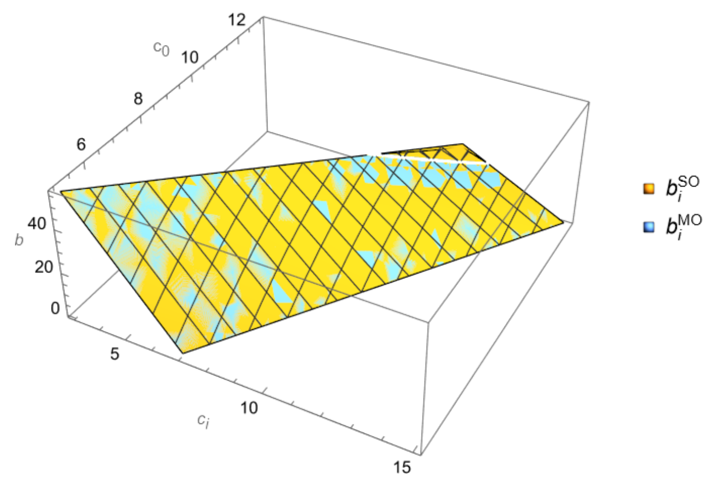



**(b)** Equilibrium *bid* as a function of individual marginal production cost $c_i$ and general marginal production cost $c_0$.

**Figure 6:** Visual representation of the output and bidding levels for the *Single Free* and *Single Obligation* treatments.




**(a)** Equilibrium *output* as a function of general marginal production cost $c_0$. The yellow bandwidth around $x_i^{MF}$ indicates the lower and upper bound taking into account $\varepsilon$. Vertical lines at $c_0 = 5$ and $c_0 = 13$ indicate the upper and lower bound for $c_0$ under the configuration of our experiment.




**(b)** Equilibrium *bid* as a function of individual marginal production cost $c_i$ and general marginal production cost $c_0$.

**Figure 7:** Visual representation of output and bidding levels for the *Single Obligation*, *Multiple Free* and *Multiple Obligation* treatments.

exceed the minimum production level. Naturally, this means that for most of the $c_i$-$c_0$ space, bids are the same between the *Single Obligation* and *Multiple Obligation* treatments. Only for players with low $c_i$ in a high $c_0$-environment, bids exceed those in the *Single Obligation* treatment. We provide a formal discussion in Appendix B.3.

**Hypothesis 3a** Players place mostly equal and sometimes higher bids in the *Single Obligation* as compared to the *Multiple Obligation* treatment.

**Hypothesis 3b** Output in the *Single Obligation* is mostly equal and sometimes lower than output in the *Multiple Obligation* treatment.

As last step, we analyse the introduction of a minimum production level in a duopolist setting. For this, we compare output and bidding in the *Multiple Free* and the *Multiple Obligation* treatment, which is represented conceptually by the arrow indicated as "4" in Figure 1. We can again use Subfigure 7a as visual illustration for the relationship between output and marginal cost in the *Multiple Free* and *Multiple Obligation* treatments. Finally, Figure 8 illustrates bids for the two treatments on the vertical axis as function of individual marginal cost $c_i$ and the general cost component $c_0$.

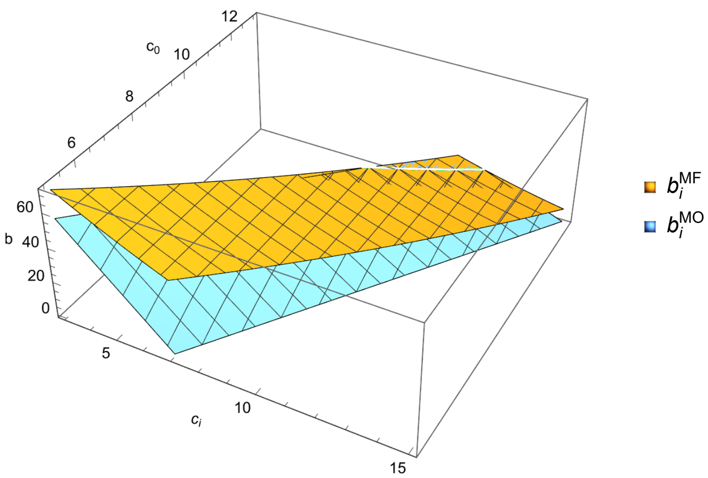



**Figure 8:** Visual representation of bidding levels for the *Multiple Free* and *Multiple Obligation* treatments as a function of individual marginal production cost $c_i$ and the general component $c_0$.

In the graphs, it becomes visible that output in the *Multiple Free* is mostly below that in the *Multiple Obligation* treatment. Only for specific low values of $c_i$ in a high-$c_0$-environment, outputs in both treatments are equal. This translates into equilibrium predictions for the bids such that for the vast majority of realisations, bids are lower in the *Multiple Free* than in the *Multiple Obligation* treatment. We approach this in a formal equilibrium discussion in Appendix B.4.

**Hypothesis 4a** Bids in the *Multiple Free* are mostly higher than and sometimes equal to bids in the *Multiple Obligation* treatment.

**Hypothesis 4b** Output in the *Multiple Free* is mostly smaller than and sometimes equal to output in the *Multiple Obligation* treatment.

# 4 Results

We start by providing a general overview of participants' bidding behaviour and output per treatment. Then we zoom in more closely on bidding and contribution behaviour and the factors influencing participants' decisions in this experimental market, including a discussion of the hypotheses. We close this section by an outline of the welfare implications of each policy on consumers, producers and the government revenue from the auction.

For hypothesis testing employing three or more groups, we use the non-parametric Kruskall-Wallis test (KW) (Kruskal & Wallis, 1952) and Dunn's post-hoc test (Dunn, 1964) with false discovery rate (FDR) adjustment by (Benjamini & Hochberg, 1995). For regressions, we use a GLS random effect panel regression and assess the distance between the resulting parameters using a Wald test.

## 4.1 Results Overview

Sub-Figure 9a illustrates average bids per individual for each treatment, which shows significant heterogeneity between the treatments (KW Test, $N = 252,\ \chi^2 = 49.759,\ p = 0.0001$). Participants place the highest bids for market access as monopolist in the absence of output requirements (*Single Free* treatment). Bids for access to the duopolist market are significantly lower, as evidenced by a post-hoc Dunn's test (pairwise comparisons) with Benjamini-Hochberg correction for multiple hypotheses testing (Sub-Table 3a). Introducing a performance obligation further reduces the average bid, both for monopolist and duopolist markets. Only between the two markets with output obligation, there does not seem to be a robust difference in bidding levels overall, yet substantial directional suggestive evidence. As such, there exists a hierarchy in bid levels such that

$$b_i^{SF} > b_i^{MF} > b_i^{SO} \geq b_i^{MO}.$$

**Table 3:** Dunn's pairwise comparisons using Benjamini-Hochberg false discovery rate adjustment.

| Column mean - row mean $z$-test statistic ($p$-value) | **Single Free** | **Multiple Free** | **Single Obligation** |
|---|---|---|---|
| **Multiple Free** | 2.661** (0.006) | | |
| **Single Obligation** | 4.467*** (0.000) | 2.497** (0.008) | |
| **Multiple Obligation** | 6.48*** (0.000) | 4.677*** (0.000) | 1.322 (0.093) |

** $p < 0.05$, *** $p < 0.01$

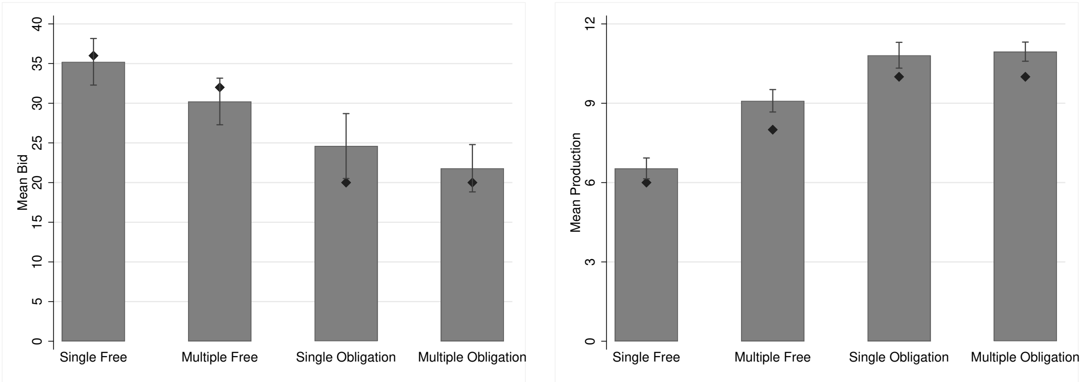
**(a)** Dunn's pairwise comparison of average *bids* for market access per participant by treatment.

| Column mean - row mean $z$-test statistic ($p$-value) | **Single Free** | **Multiple Free** | **Single Obligation** |
|---|---|---|---|
| **Multiple Free** | −4.396*** (0.000) | | |
| **Single Obligation** | −6.537*** (0.000) | −3.126*** (0.001) | |
| **Multiple Obligation** | −8.27*** (0.000) | −4.792*** (0.000) | −0.882 (0.189) |

*** $p < 0.01$

**(b)** Dunn's pairwise comparison of average *production* if winning market access by treatment.

Similarly, Sub-Figure 9b illustrates the heterogeneity in output/production per treatment, which




**(a)** Average bids per individual for each treatment.

**(b)** Average production per treatment.

**Figure 9:** Aggregate bids and production levels per treatment. Black squares indicate equilibrium prediction averaged over all rounds.

we confirm via non-paramteric test (KW Test, $N = 228,\ \chi^2 = 78.169,\ p = 0.0001$). We only consider *actual* production here, meaning we take only the production decision of winning participants in a given round for our analysis of production behaviour. In Appendix C, we discuss hypothetical production decisions of non-winning participants. We find that output is the lowest in the *Single Free* treatment and the highest in the two *Obligation* treatments, with the *Multiple Free* treatment in between. Sub-Table 3b confirms this relationship using a pairwise non-parametric Dunn's test, which we can summarise as

$$x_i^{SF} < x_i^{MF} < x_i^{SO} \leq x_i^{MO}.$$

## 4.2 Bidding Behaviour

The underlying theory presented in Section 3 suggests a negative relationship between bidding and individual production cost. As such, we investigate bidding behaviour using GLS random effect panel regressions. In particular, we describe individual $i$'s bid in Round $t$, $\text{Bid}_{it}$, by the following model:

$$\begin{aligned} \text{Bid}_{it} &= \mu \\ &+ \beta_1 \text{ Multiple} \\ &+ \beta_2 \text{ Obligation} \\ &+ \beta_3 \text{ Multiple} \times \text{Obligation} \\ &+ \beta_4 \ c_{it} \\ &+ \beta_5 \ c_{it}^2 \\ &+ \beta_6 \text{ Period}_t \\ &+ \beta_7 \text{ Controls} + \varepsilon_{it}, \end{aligned} \tag{14}$$

where $\mu$ is the average bid for the entire set of participants across all treatments. This regression allows us to isolate the effect of introducing competition ($\beta_1$) or a minimum production level ($\beta_2$) into the market. Further, it allows to investigate the combination of duopolistic competition and minimum production levels ($\beta_3$). The analysis further controls for individual linear ($\beta_4$) and quadratic production cost ($\beta_5$), as well as Period effects ($\beta_6$) and controls ($\beta_7$). In Table 4, Regressions (1)-(3) present the results from the regression in Equation 14. Regression (4) extends this by investigating the respective sensitivity with respect to individual production cost for each treatment using interaction effects.

**Table 4:** Random effects model regressing individual bids on treatment dummies and controls.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | | **Bid**$_{i,t}$ | | |
| Multiple | $-5.003^{**}$ | $-3.007$ | $-2.321$ | $-6.161^{*}$ |
| | (2.45) | (2.33) | (2.34) | (3.64) |
| Obligation | $-10.622^{***}$ | $-11.624^{***}$ | $-11.707^{***}$ | $-29.068^{***}$ |
| | (2.83) | (2.69) | (2.66) | (4.05) |
| Multiple $\times$ Obligation | 2.205 | 1.921 | 1.525 | $8.584^{*}$ |
| | (3.46) | (3.29) | (3.28) | (5.04) |
| $c_i$ | | $-4.606^{***}$ | $-4.560^{***}$ | $-3.737^{***}$ |
| | | (0.62) | (0.62) | (0.26) |
| $c_i^2$ | | $0.107^{***}$ | $0.104^{***}$ | |
| | | (0.03) | (0.03) | |
| Period | | | $-0.030$ | $-0.060$ |
| | | | (0.10) | (0.10) |
| Multiple $\times$ $c_i$ | | | | 0.514 |
| | | | | (0.32) |
| Obligation $\times$ $c_i$ | | | | $2.060^{***}$ |
| | | | | (0.36) |
| Multiple $\times$ Obligation $\times$ $c_i$ | | | | $-0.951^{**}$ |
| | | | | (0.44) |
| Constant | $35.224^{***}$ | $66.232^{***}$ | $53.141^{***}$ | $54.537^{***}$ |
| | (2.00) | (3.24) | (6.46) | (6.25) |
| Controls | *No* | *No* | *Yes* | *Yes* |
| Number of observations | 2,520 | 2,520 | 2,520 | 2,520 |
| Number of panels | 252 | 252 | 252 | 252 |
| Within-model R-squared | 0.000 | 0.224 | 0.224 | 0.238 |
| Between-model R-squared | 0.130 | 0.210 | 0.240 | 0.248 |
| Overall R-squared | 0.055 | 0.217 | 0.231 | 0.242 |

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Standard errors in parentheses.

The output shows that without controlling for individual production cost levels $c_{it}$, introducing competition appears to reduce the bids for market access ("Multiple" factor in Regression (1)), yet when including individual production cost (Regression (2)) and controls (Regression (3)), this renders the effect of duopolistc competition on bids not significantly different from zero. Lastly, when allowing for heterogeneous effects of production cost in Regression (4), the effect of introducing competition is significantly different from zero again. Throughout all regressions – despite varying significance levels – $\beta_1$ consistently has a negative effect of about 2-6 points, providing some suggestive evidence for a negative effect from competition.

Furthermore, Regression (4) shows that $c_i$ does not have a significantly different effect between the *Single Free* and *Multiple Free* treatments (factor "Multiple $\times$ $c_i$"). The coefficient in question displays the right directionality, but fails to pass a significance test at any conventional significance level. This means that the treatment difference between bids in the two treatments does not change with $c_i$, refuting the second part of Hypothesis 1a.

**Result 1a** We find some evidence for higher bids in the *Single Free* treatment. This disappears when controlling for production cost. This difference is not affected by the cost levels $c_i$.

Introducing a production obligation appears to have a robust negative effect on bidding levels both with and without controls ($\beta_2$). Regressions (1)-(3) suggest that bids are about 10 points lower when there is a minimum production obligation, which translates into an effect size of roughly 2-3 times larger than that from introducing competition. When taking into account treatment differences in the reaction to cost levels, as in Regression (4), this treatment difference appears to be at a magnitude of even 29 points. The interaction effect "Obligation $\times$ $c_i$" shows that the gap between the treatments narrows for higher cost levels.

**Result 2a** We find evidence for higher bids in the *Single Free*, as compared to the *Single Obligation* treatment. This is true both in the presence and absence of controls. The treatment difference is smaller for high levels of individual marginal cost $c_i$.

Next, Regressions (1)-(3) suggest that combining duopolistic competition and a production obligation does not provide an extra benefit on top of what the two policy instruments deliver in separation. This notwithstanding, Regression (4) we find some weak evidence for an extra combination effect and a joint directionality of $\beta_3$ among the regressions. For Hypothesis 3a, we are interested in the relationship between bids in the *Single Obligation* and *Multiple Obligation* treatments to assess the effect of adding competition to an environment with minimum production level. Both when employing the coefficients from Regression (3) (Wald Test: $\beta_{\text{Multiple}} + \beta_{\text{Multiple}\times\text{Obligation}} = 0,\ \chi^2(1) = 0.12,\ p = 0.731$) or Regression (4) $\left(\chi^2(1) = 0.48,\ p = 0.487\right)$, we find no difference in bids between the two treatments. Figure 9a and the Dunn's test results from Table 3a paint the same picture, suggesting no difference between the bids for market access either as a monopolist or duopolist when minimum production levels exist in the market.

**Result 3a** There is no significant difference between bids in the *Single Obligation* and *Multiple Obligation* treatments. We find some suggestive directional evidence towards higher bids in the *Single Obligation* treatment.

Fourth, introducing a minimum production level in a duopolistic competition setting – i.e. comparing the *Multiple Free* and *Multiple Obligation* treatments – significantly reduces the level of bids for market access both when employing Regression (3) (Wald Test: $\beta_{\text{Obligation}} + \beta_{\text{Multiple}\times\text{Obligation}} = 0,\ \chi^2(1) = 28.87,\ p < 0.001$) or Regression (4) $\left(\chi^2(1) = 47.13,\ p < 0.001\right)$. Sub-Figure 9a and Sub-Table 3a complement this evidence.

**Result 4a** Bids in the *Multiple Free* are significantly higher than in the *Multiple Obligation* treatment.

As the equilibrium strategies devised in Section 3 predict, individual cost reduces the bids significantly ($\beta_4$). Intuitively, higher production cost decrease the potential earnings a potential producer could materialise on the market, which reflects in lowered valuations for market access. This effect appears to be convex, i.e. attenuated for higher cost levels ($\beta_5$). Figure 10 illustrates the quadratic prediction for bids on individual production cost for each treatment. The graph visualises the negative relationship between production cost and bidding. The graph further plots the equilibrium predictions from Figure 4a and demonstrates that bidding levels are fairly close to individual predictions. We observe some underbidding for low cost levels in the *Free* treatments and the inverse for *Obligation* treatments.

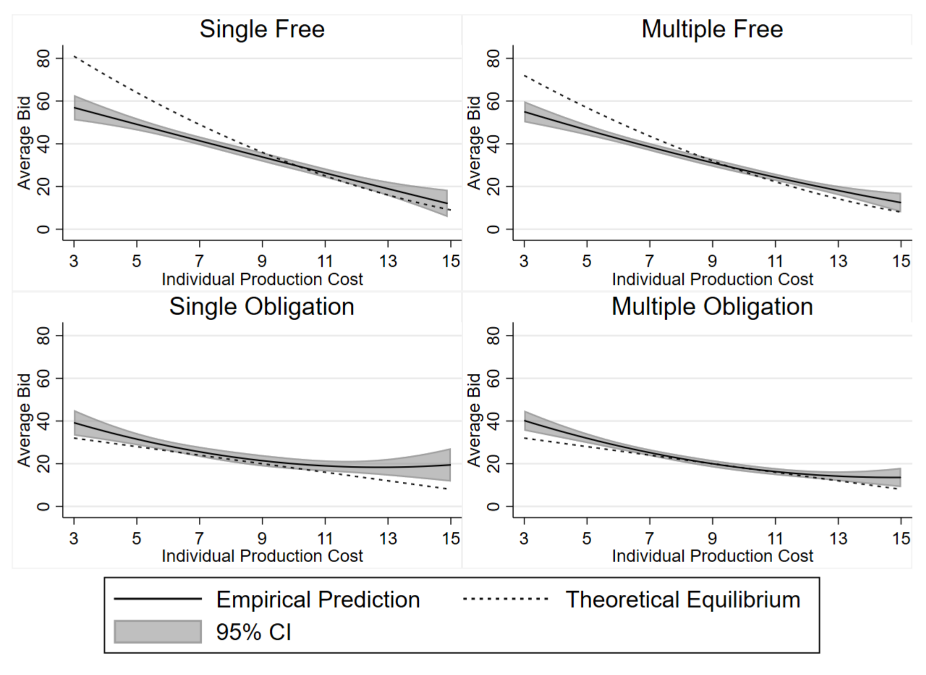



**Figure 10:** Average bids as a function of individual production cost per treatment

## 4.3 Production

Paramount in understanding what effect the policies have on the functioning of the market is to look at what is being produced after the Bidding Phase. In this subsection, we focus on actual production by winners from the auction. In Appendix C, we extend this to hypothetical production by those who ended up not winning the bidding round. Again, we use GLS random effect panel regressions to investigate production on the market as a function of various factors in the game. As compared to the model in Equation 14, we also control for the bid placed by the producer in a given round ($\beta_4$). Again, we extend the model towards heterogeneous treatment effects from marginal production cost in Regression (4). Let the production of individual $i$ in round $t$, Production$_{it}$ be described by the same factors as before, formalised as

$$
\begin{aligned}
\text{Production}_{it} &= \mu \\
&+ \beta_1 \text{ Multiple} \\
&+ \beta_2 \text{ Obligation} \\
&+ \beta_3 \text{ Multiple} \times \text{Obligation} \\
&+ \beta_4 \text{ Bid}_{it} \\
&+ \beta_5 \ c_{it} \\
&+ \beta_6 \ c_{it}^2 \\
&+ \beta_7 \text{ Period}_t \\
&+ \beta_8 \text{ Controls} + \varepsilon_{it}
\end{aligned} \tag{15}
$$

Table 5 shows the associated regression results. First, we find that, compared to the unconstrained monopolist, introducing duopolistic competition increases output by about 2.6-4.9 points ($\beta_1$). This increase confirms our results from Sub-Figure 9b and the Dunn's test results from Sub-Table 3b. Regression (4) further demonstrates that the treatment difference in output between the *Single Free* and *Multiple Free* treatments shrinks for higher production cost $c_i$, as $\beta_{\text{Multiple}\times c_i} < 0$.

**Result 1b** Participants produce significantly less in the *Single Free* than in the *Multiple Free* treatment. This difference corresponds negatively with the individual marginal cost $c_i$.

Second, introducing a production obligation increases production by about 4-8.2 points as compared to the output of an unconstrained monopolist ($\beta_2$). Also here, the treatment difference gets smaller for higher cost levels as $\beta_{\text{Obligation}\times c_i} < 0$.

**Result 2b** Output in the *Single Free* is significantly lower than in the *Single Free* treatment. This difference corresponds negatively with the individual marginal cost $c_i$.

Third, combining duopolistic competition with an output requirement in the *Multiple Obligation* case shifts the output to roughly the same level as in the *Single Obligation* treatment as confirmed by Regressions (3) (Wald Test: $\beta_{\text{Multiple}} + \beta_{\text{Multiple}\times\text{Obligation}} = 0,\ \chi^2(1) = 2.71,\ p = 0.1$) and (4) $\left(\chi^2(1) = 0.25,\ p = 0.615\right)$. The first Wald Test shows some directional suggestive evidence that output in the *Multiple Obligation* scenario is higher than in the *Single Obligation* treatment at a 90% confidence level, but is far from any reasonable significance level for the second test. Sub-Figure 9b and Sub-Table 3b confirm that output in the two treatments are too close to find statistical significance.

**Result 3b** Our results suggest that output in the *Single Obligation* is not significantly different than in the *Multiple Obligation* treatment, notwithstanding some suggestive evidence for lower output in the *Single Obligation* case.

Fourth and finally, the results both from Regression (3) (Wald Test: $\beta_{\text{Obligation}}+\beta_{\text{Multiple}\times\text{Obligation}} = 0,\ \chi^2(1) = 35.87,\ p < 0.001$) and (4) $\left(\chi^2(1) = 27.55,\ p < 0.001\right)$ confirm that introducing a minimum production level in a duopolist environment significantly increases output. Also here, Sub-Figure 9b and Sub-Table 3b add to the evidence from the regression analysis.

**Table 5:** Random effects model regressing individual production on treatment dummies and controls.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | | **Production**$_{i,t}$ | | |
| Multiple | 2.618*** | 2.957*** | 2.886*** | 4.886*** |
| | (0.36) | (0.32) | (0.33) | (0.72) |
| Obligation | 4.831*** | 4.032*** | 3.999*** | 8.233*** |
| | (0.42) | (0.37) | (0.38) | (0.81) |
| Multiple × | −2.390*** | −2.383*** | −2.352*** | −5.216*** |
| Obligation | (0.51) | (0.45) | (0.46) | (0.97) |
| Bid | 0.071*** | 0.025*** | 0.024*** | 0.031*** |
| | (0.01) | (0.00) | (0.00) | (0.00) |
| $c_i$ | | −0.830*** | −0.828*** | −0.354*** |
| | | (0.14) | (0.14) | (0.07) |
| $c_i^2$ | | 0.009 | 0.008 | |
| | | (0.01) | (0.01) | |
| Period | | | −0.043* | −0.037 |
| | | | (0.02) | (0.02) |
| Multiple × | | | | −0.247*** |
| $c_i$ | | | | (0.08) |
| Obligation | | | | −0.506*** |
| $\times i$ | | | | (0.09) |
| Multiple × | | | | 0.359*** |
| Obligation $\times c_i$ | | | | (0.10) |
| Constant | 3.130*** | 11.639*** | 12.322*** | 9.052*** |
| | (0.38) | (0.73) | (1.04) | (0.94) |
| Controls | *No* | *No* | *Yes* | *Yes* |
| Number of observations | 840 | 840 | 840 | 840 |
| Number of panels | 228 | 228 | 228 | 228 |
| Within-model R-squared | 0.175 | 0.571 | 0.574 | 0.588 |
| Between-model R-squared | 0.441 | 0.586 | 0.587 | 0.623 |
| Overall R-squared | 0.358 | 0.608 | 0.614 | 0.633 |

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Standard errors in parentheses.

**Result 4b** Output in the *Multiple Free* is significantly smaller than output in the *Multiple Obligation* treatment.

While the bid placed has a small but strongly significant effect ($\beta_4$), individual production cost has a significant negative effect on production output ($\beta_5$). Costs affect bids in a convex manner, but there is no evidence for a non-linear relationship between production and individual cost ($\beta_6$). Figure 11 plots the quadratic predictions for production output as a function of cost for each treatment. Again, this graph reproduces the negative relationship revealed by our regressions. It further illustrates a very high level of accuracy with respect to the equilibrium predictions, which are indicated as dotted lines in the graph. As most noteworthy deviation, the *Multiple Free* treatment displays some small degree of overproduction across the board, compared to the equilibrium prediction. Further, while there is some over-production for small cost levels in the *Single Obligation* treatment, in the *Multiple Obligation* scenario it is the producers with particularly high production cost that display some overproduction.

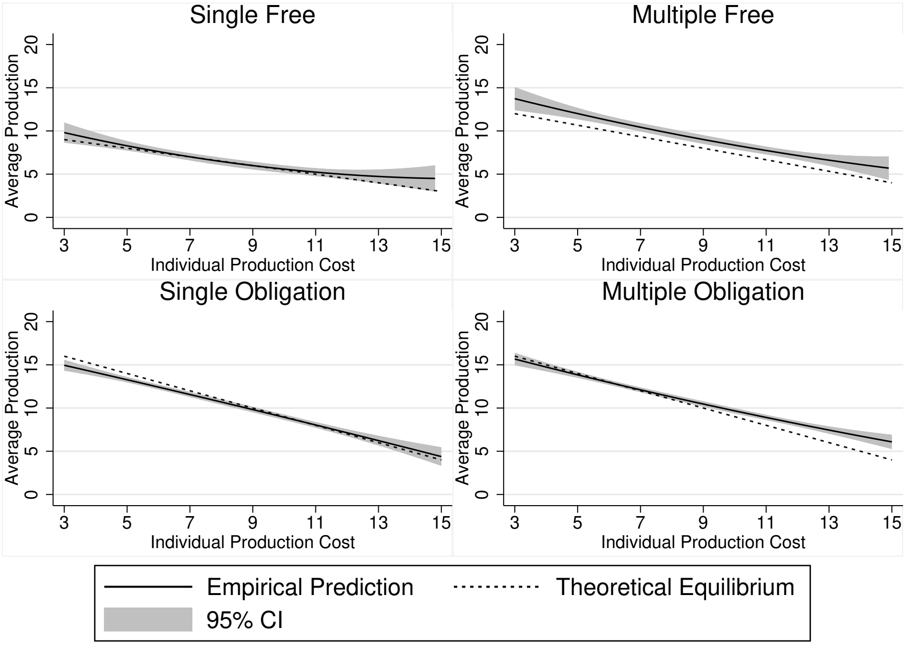



**Figure 11:** Average production as a function of individual production cost per treatment

## 4.4 Efficiency of Auction

Theory generally describes Vickrey auctions as efficient and demand-revealing under the most general circumstances (Ausubel, 2004). While evidence from induced value experiments show that a second-price auction can produce efficient outcomes at the aggregate (Kagel & Roth, 2020), it appears to have its problems at the individual level. In particular, participants whose bid is far below or above the market-clearing price appear to bid strategically, which hampers the Vickrey auction's demand-revealing function (Knetsch, Tang, & Thaler, 2001).

Despite our aggregate results (e.g. Figure 9a) showing average bids comparatively close to the theoretical equilibrium, particularly in the *Free* treatments we document some underbidding for lower price ranges (Figure 10). This raises the concern that players with lower individual cost may systematically underbid, which can hamper the auction mechanism's ability to allocate the most efficient producer to the market. This concern warrants a closer look at individual bidding behaviour, followed by an analysis on whether the auction mechanism actually succeeds in granting market access to the most efficient firms.

To learn more about individual bidding behaviour, we determine the difference between a player's actual bid in round $t$ and the associated theoretical equilibrium, which we will refer to as "Net Bid". Let $b_i$ be player $i$'s bid in round $t$ and $b_i^*$ be the respective equilibrium prediction for the given treatment and individual cost for player $i$. Then, $\textit{Net Bid} = b_i - b_i^*$. While a bid equal to the equilibrium prediction renders a Net Bid of zero, a positive Net Bid indicates overbidding, and a negative Net Bid underbidding. Figure 12 depicts the Net Bid as a function of the individual noise parameter $\varepsilon_i$.

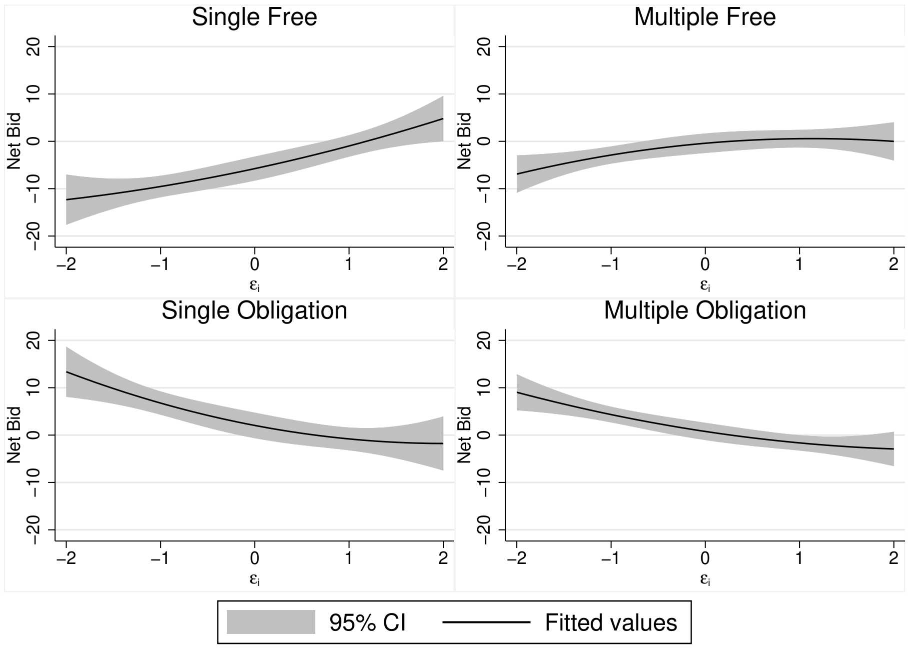



**Figure 12:** Deviation of bids from equilibrium prediction as a function of the noise parameter $\varepsilon_i$. A Net Bid of zero indicates that a player bids exactly the equilibrium prediction, a positive Net Bid implies overbidding, and a negative Net Bid underbidding.

The figure confirms the above-mentioned conjecture that players with relatively lower individual production cost – i.e. low $\varepsilon_i$-types – underbid in the *Free* treatments. By contrast, low $\varepsilon_i$-types in the *Obligation* treatments overbid with respect to the equilibrium prediction. At the same time, all treatments display a trend towards zero Net Bid, meaning that high $\varepsilon_i$-types tend to bid closer to the equilibrium prediction. As a consequence, we observe a positive slope in the Net Bids with respect to $\varepsilon_i$ for the *Free* treatments (Cuzick Test (Cuzick, 1985) at individual decision level separate for each treatment: $N \geq 420,\ z \geq 3.133,\ p \leq 0.0017$) and a negative trend for the *Obligation* treatments (Cuzick Test at individual decision level separate for each treatment: $N \geq 420,\ z \leq -6.59,\ p \leq 0.0001$). As such, our evidence indicates inefficient bidding behaviour at the individual level for low $\varepsilon_i$-types, but not for high $\varepsilon_i$-types. Most interestingly, while this inefficiency is manifested through underbidding in the *Free* treatments, we document the inverse, i.e. overbidding for low $\varepsilon_i$-types, in the *Obligation* treatments.

Next, we assess whether this has a bearing on the auction's aggregate efficiency, focusing on the intensive margin. By adapting Kagel et al. (1987)'s efficiency measure to our design, we get a measure of the intensity of the auctions' inefficiency. Formally, let $IN_I$ be the intensive margin inefficiency for group $I$; $\varepsilon_i\,(b_{i,k})$ be the noise parameter of player $i \in I$, ranked by the size of the bid from highest ($k = 1$) to lowest ($k = 3$ or 6, depending on the treatment); and $\varepsilon_{j,n}$ be player $j$'s noise parameter ordered by size with $m = 1$ the lowest and $m = 6$ or $m = 3$ the highest of the group, depending on the treatment. Note that $i, j \in I$, $i$ and $j$ may or may not represent the same player. Then:

$$IN_I = \begin{cases} \frac{\varepsilon_i(b_{i,1})-\varepsilon_{j,1}}{\varepsilon_{j,3}-\varepsilon_{j,1}} & \textit{Single} \text{ treatments} \\ \frac{\varepsilon_i(b_{i,1})-\varepsilon_{j,1}+\varepsilon_i(b_{i,2})-\varepsilon_{j,2}}{\varepsilon_{j,5}-\varepsilon_{j,1}+\varepsilon_{j,6}-\varepsilon_{j,2}} & \textit{Multiple} \text{ treatments} \end{cases} \tag{16}$$

We are interested in whether the auction allocates market access to the player(s) with the lowest marginal cost. For this, we take the difference between the winner's noise parameter $\varepsilon_i$ and the group's lowest $\varepsilon_i$, normalised by the distance between the group's highest and lowest $\varepsilon_i$ in the *Single* treatments. Note that the enumerator is zero when the auction is fully efficient, i.e. when it allocates market access to the most efficient player, and one if it allocates the market to the player with the lowest efficiency in the group. As there are two winners in the *Multiple* treatments, an efficient auction would allocate the market to the *two* players with the lowest marginal cost. Hence for these treatments, we generate the difference between the lowest two bidder's noise parameter $\varepsilon_i$ and the group's two lowest $\varepsilon_i$ in each round. We then normalise this by the distance between the group's two highest and two lowest $\varepsilon_i$.

Figure 13 illustrates the distributions of inefficiency rates for each treatment in a violin plot (Hintze & Nelson, 1998), including a marker for the median, and a box and spikes as in a box plot. While the medians for the *Single* treatments are at 0 (*Single Obligation*) and 10.6% (*Single Free*), the median inefficiency rates for the *Multiple* treatments are more than twice as large at, respectively, 27.7 (*Multiple Obligation*) and 34.6% (*Multiple Free*). The box plots show that even for a treatment with low median as the *Single Free*, inefficiency rates distribute across the whole domain from zero to one. This is also true for all other treatments, albeit to a lesser degree. Finally, the kernel density plot reveals a bimodal distribution for the two *Single* treatments, which is a corollary of the fact that next to allocating the market to the most efficient ($IN_I = 0$) or least efficient ($IN_I = 1$) player, in these treatments there exists only one intermediate other player who the auction mechanism could select for market access. By contrast, in the *Multiple* treatments, there are a total of four intermediate options.

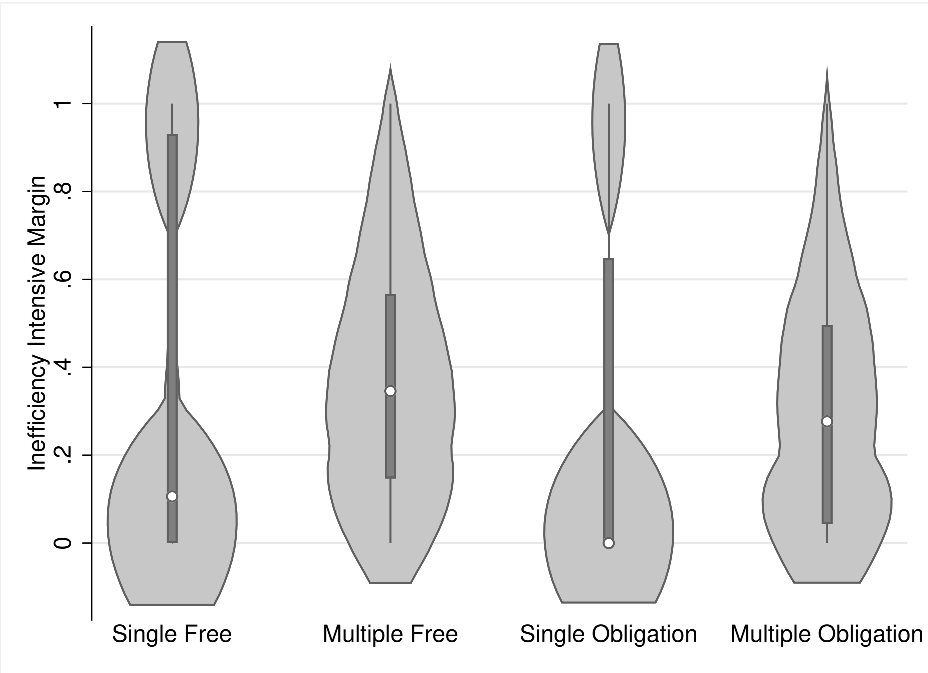



**Figure 13:** Violin plot illustrating the auction mechanism rate of inefficiency (intensive margin) normalised from fully efficient (0) to least efficient (1), including markers for the median of the data, a box indicating the interquartile range, and spikes extending to the upper- and lower-adjacent values, as in standard box plots.

Summing up, while more efficient players (low $\varepsilon_i$) structurally underbid in the *Free* treatments, they overbid in the *Obligation* treatments (cf. Figure 12). A reason for this may be the stark difference in equilibrium predictions for low production cost-levels between the *Free* and *Obligation* treatments (see e.g., Figure 10). While participants adjust their bidding levels, they do so less than our theoretical equilibrium predicts. Inefficient types, by contrast, place bids very close to the equilibrium prediction in all treatments. For high-cost types, the equilibrium prediction does not differ much between treatments, which our empirical results reproduce. When looking at the auctions' aggregate efficiency (Figure 13), we observe a significantly higher median inefficiency rate for the *Free* treatments, compared to the *Obligation* scenario (Mann-Whitney U test (MWU) (Mann & Whitney, 1947). H0: $IN_I$ in *Free* treatments $= IN_I$ in *Obligation* treatments, $N = 560,\ z = 2.641,\ p = 0.0083$). Furthermore, we can show that the auction mechanism allocates market access more efficiently in the *Single* treatments than in the *Multiple* case (MWU test. H0: $IN_I$ in *Single* treatments $= IN_I$ in *Multiple* treatments, $N = 560,\ z = -3.57,\ p = 0.0004$). As such, while a production obligation appears to improve the auction mechanism, mainly by encouraging bids from efficient types, competition introduces a strategic component to the production phase that percolates into the bidding phase, reflecting into lower allocative efficiency.

## 4.5 Social Welfare

Naturally, decisions of government agencies in protecting and ensuring public interests influence social welfare in the economy. In this auction design, social welfare can be dis-aggregated into consumer surplus, producer profit and direct government revenues from the auction. We first discuss each of the elements in separation before turning to an overall assessment of the market outcomes. In our experiment, the *Multiple* treatments are scaled upwards by a factor of two as compared to the *Single* treatments in order to make the decision environment comparable for participants (firms). Consequently, we need to normalise our social welfare analysis at the firm level.

**Consumer Surplus** As illustrated in Figure 3, the consumer surplus can be found in the triangle between the inverse demand function, the market price and the y-axis. Conceptually, it represents the difference between the maximum price a consumer is willing to pay and the actual price they do pay. Formally, let $p_t\left(x^{tot}\right)$ be the market price in round $t$ for a total output of $x_t^{tot}$. Consumer surplus in round $t$ can be determined by

$$CS_t^{Single} = 1/2\left(21 - p_t\left(x_t^{tot}\right)\right)x_t^{tot}.$$

As mentioned, we normalise consumer surplus at the firm level to make our treatments comparable, i.e. $CS_t^{Multiple} = CS_t^{Single}/2$. Figure 14 and Table 6 show consumer surplus for each treatment using one observation per group averaged over all ten rounds.

As expected, consumer surplus is lowest in a market with an unconstrained monopolist as in the *Single Free* treatment. Introducing competition (*Multiple Free*) almost doubles the level of consumer surplus generated by each firm. Even more, an output obligation leads to even higher consumer surplus in the *Single Obligation* and *Multiple Obligation* treatments. All differences are significant at the 95% confidence level in a pairwise Dunn's test ($p \leq 0.0144$), except for the latter two treatments (Dunn's

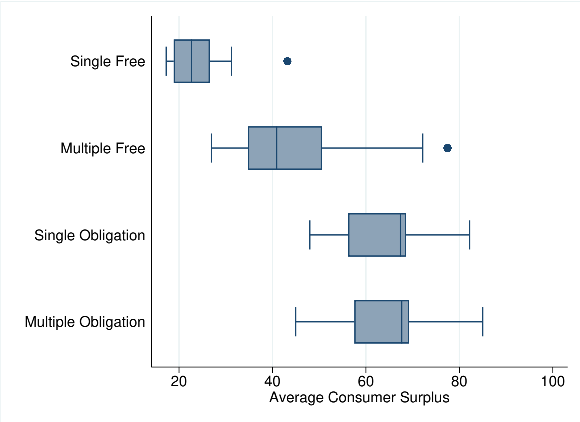



**Figure 14:** Consumer Surplus each firm generates on the markets.

| | |
|---|---|
| Single Free | 24.11<br>(6.850) |
| Multiple Free | 45.51<br>(15.07) |
| Single Obligation | 62.71<br>(9.721) |
| Multiple Obligation | 64.18<br>(11.61) |
| Total | 49.13<br>(19.7) |

**Table 6:** Average Consumer Surplus per firm for each treatment. Standard deviation in parentheses.

Test *Single Obligation* vs. *Multiple Obligation* treatments: $p = 0.427$).

**Producer Surplus** We use producers' individual earnings per period as base for measuring producer surplus as in Equations 2 and 4. As such, we use data from participants who have won the auction. To make the treatments comparable, we average the producer surplus of both firms in the *Multiple* treatments. Figure 15 and Table 7 use one observation per group averaged over all ten rounds to show how the different markets pan out for producers' profits.

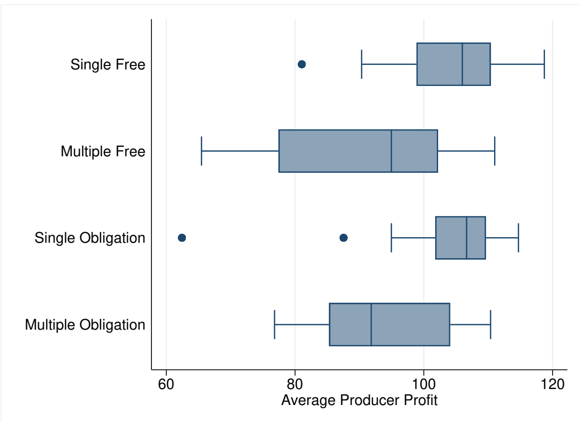



**Figure 15:** Producer Surplus per firm resulting from the output and prices on the markets.

| | |
|---|---|
| Single Free | 103.7<br>(9.435) |
| Multiple Free | 90.59<br>(14.73) |
| Single Obligation | 102.5<br>(13.22) |
| Multiple Obligation | 93.08<br>(10.27) |
| Total | 97.47<br>(13.36) |

**Table 7:** Average Producer Surplus per firm for each Treatment. Standard deviation in parentheses.

While on both markets with multiple firms (*Multiple Free* and *Multiple Obligation*), producers leave the market with less than their initial endowment, producers in the single markets (*Single Free* and *Single Obligation*) do make positive economic profits net of their initial endowment. Differences in producer surplus between both *Multiple* and both *Single* treatments, respectively, are not significantly different, by contrast when tested via Dunn's tests.

**Government Revenues** The winner of the auction pays for the right to access the market which creates revenues for the principal. We normalise this access price at the group level (per firm) and over all ten rounds of the game to illustrate the distribution of the associated government revenue in Figure 16 and Table 8.

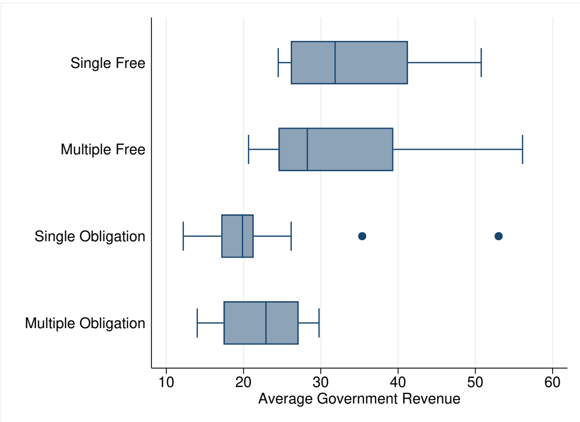



**Figure 16:** Government Revenue per firm resulting from auction payments.

| | |
|---|---|
| Single Free | 34.32 (7.808) |
| Multiple Free | 32.32 (10.37) |
| Single Obligation | 22.22 (10.16) |
| Multiple Obligation | 22.67 (5.198) |
| Total | 27.88 (10.22) |

**Table 8:** Average Government Revenue per firm for each Treatment. Standard deviation in parentheses.

We find that while monopolists and duopolists appear to value market access similarly (when comparing both *Free* or both *Obligation* treatments), the production obligation leads to significantly lower access prices, and in the consequence to lower government revenue (when comparing both *Single* or both *Multiple* treatments). Nevertheless, because we calculate the government revenue per firm, the government revenue for the *Multiple* treatments will be doubled, as two firms pay for access to the market.

**Total Welfare** When trading off the different market participants' surpluses, we aggregate consumer surplus, producer profit and government revenue as calibrated in our experiment. Again, note that this expresses the total welfare generated *per firm* averaged over all ten rounds. Figure 17 and Table 9 show that both *Free* treatments have a comparable level of total welfare per firm, lower than both *Obligation* treatments, which in turn also fare at a similar level of total welfare from each other. Zooming in on the two *Free* treatments, we can see that while the *Single Free* renders a higher producer surplus than the *Multiple Free* treatment, this comes at the expense of the consumer surplus. Usually, competition law either is concerned with aggregate welfare or with consumer welfare (e.g., Kaplow, 2011; Kaplow & Shapiro, 2007), suggesting a preference for the *Multiple Free* over the *Single Free* approach from the point of view of a market designer.

A public interest arises if the government takes up the promotion of a social interest in the belief

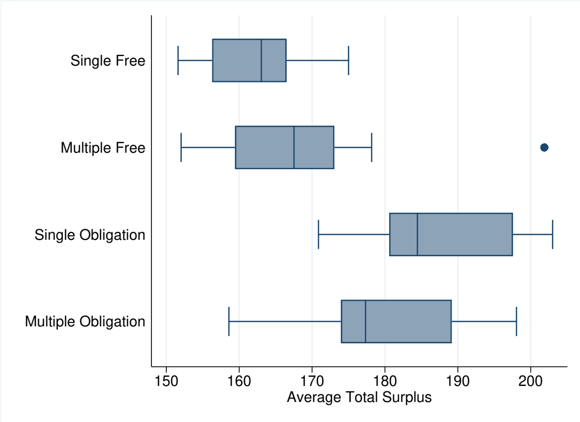



**Figure 17:** Total Surplus per firm. Total Surplus is the aggregate of consumer surplus, producer profit and government revenues from the auction.

| | |
|---|---|
| Single Free | 162.1 |
| | (7.017) |
| Multiple Free | 168.4 |
| | (11.68) |
| Single Obligation | 187.4 |
| | (9.793) |
| Multiple Obligation | 179.9 |
| | (11.39) |
| Total | 174.5 |
| | (14.12) |

**Table 9:** Average Total Surplus per firm for each Treatment. Standard deviation in parentheses.

that this interest will otherwise not be realised properly (Wolswinkel et al., in press). Introducing a minimum production level as in the *Obligation* treatments significantly increases total welfare created by each firm. This despite *1)* bids in the auction being about 65% lower, reducing government revenue from holding a competitive tender for market access, and *2)* similar producer surplus levels between both *Single* and *Multiple* treatments. The government has the option to prioritise consumer surplus by implementing a minimum production threshold as a key objective in its policy agenda. The high overall social surplus for the *Obligation* treatments is driven by a significant improvement in consumer surplus, which more than doubles, as compared to the *Single Free* scenario. This means, while producers bid less for market access, which fully compensates for their lower market revenue, producers gain tremendously from increased output and lowered prices due to the output obligation.

Comparing the *Single Obligation* and *Multiple Obligation* treatments, we find significant differences only concerning the producer surplus, for which the *Single Obligation* delivers a significantly better result (Dunn's Test: $p = 0.014$). Curiously, this does not translate into significantly different total surplus between the two treatments (Dunn's Test: $p = 0.114$).

## 5 Conclusion

A broad array of public markets are regulated by means of auctions for access rights to companies or other organisations. The 2016 United States wireless spectrum auction, for example, allocated about 100 MHz of Ultra High Frequency (UHF) spectrum, raising $19.8 billion (Gross, 2017). Other examples include the bi-annual capacity auction for the electricity market in the United Kingdom or the European Union Emissions Trading System. The underlying idea is that the auction allocates services to the most efficient party, triggering improvements in efficiency and innovation (Kates, 2017; Neumann, 2001).

While there exists a rich theoretical literature on regulation regimes for various types of monopolies (e.g., Baron & Myerson, 1982; Lewis & Sappington, 1988a, 1988b) and competitive procurement (Birulin & Izmalkov, 2022; Chakraborty, Khalil, & Lawarree, 2021), empirical evidence is scant. Our study addresses this gap in the literature. In our experimental study, we put various regulation regimes to an empirical test in a controlled environment and assess their effects on procurement bids, output and social welfare. We find that while both establishing a minimum production threshold and establishing competition on the market reduce procurement bids (which in turn reduces government earnings from the licence tendering), both regimes lead to a significant increase in output, drop in price and increase in consumer surplus. Importantly, we find that the output obligation is relatively more potent in achieving the policy goals.

This demonstrates a certain trade-off for policymakers between various aspects of public interest: government revenues, firm profits and consumer surplus. Our results show that a production obligation on a monopolist ensures a higher level of consumer surplus while maintaining about the same level of firm profit as in the unconstrained monopolist case. As such, firms anticipate their lower profit margin and place lower bids, which results in lower government revenue. In comparison, duopolistic competition leads to a moderate increase in consumer surplus. Both firms compete fiercely on the market and fail to secure positive economic profits net of the opportunity cost of staying out of the market. In contrast to the monopolist with production obligation, competing firms do not anticipate lowered profits from production, leaving government revenue relatively unaffected. Lastly, when both measures are combined, social welfare effects are comparable to what we see for a monopolist with production obligation with the exception of producer surplus. Also here, firms compete at a rate that would not be sustainable long term.

Another (indirect) public interest for policymakers is the efficiency of the auction (Arrowsmith, 2010), in which our treatments differ considerably. Despite the positive effects on consumers, introducing competition on the market reduces the efficiency of the auction mechanism significantly. Interestingly, a production obligation, by contrast, significantly improves the auction's efficiency in allocating the most cost-effective firms to the market. Most interestingly, the Single Obligation auction is even fully efficient at the median.

Our study contributes empirical evidence from a controlled environment to the lively policy debate on competition and market regulation (see, e.g., Priest, 1993; Pittman, 2007). Consensus has developed that the protection of consumer welfare should be an important aim of policy regulation (Hovenkamp, 2009), which in the US is reflected by the Sherman act and US Supreme Court rulings,[13] making consumer welfare focus the stated law of the land. There appears, however, to be some confusion and disagreement about what exactly is meant when referring to "consumer welfare" (Orbach, 2011). While some scholars equate the term "consumer welfare" with "consumer surplus," others argue for a broader interpretation as in "total surplus" (Heyer, 2014). We provide empirical evidence showcasing how different policy vehicles pan out for a consumer surplus versus total surplus perspective. Particularly the interpretation for the *Multiple Free* treatment differs considerably between the two perspectives. While it delivers positive consumer surplus effects, its results on total welfare compare to the benchmark from an unconstrained monopolist.

Our design shares a set of limitations common to experimental studies using a student sample,

[13] See, e.g., Nat'l Collegiate Athletic Ass'n v. Bd. of Regents of Univ. of Okla., 468 U.S. 85, 107 (1984); Arizona v. Maricopa County Med. Soc'y, 457 U.S. 332, 367 (1982); Reiter v. Sonotone Corp., 442 U.S. 330, 343 (1979).

particularly concerning the generalisability of the results. As we mostly employ students from business and economics programmes, our participants represent future managers who are being trained to make similar operational decisions for competitive corporations in the near future. For the purpose of our empirical test of different regulation regimes in a controlled environment, real managers could even prove to be a sub-optimal sample in our case, as they may inadequately react to the incentives offered in a controlled experiment. Increasing the financial incentives to a level adequate for top-level managers would come at the expense of sample size at a level that would present an even bigger threat to external validity. Future research may explore this frontier, e.g. by complementing our quantitative laboratory experiment by means of a natural field experiment or semi-structured qualitative interviews.

To allow comparability between markets with one or two producers at the firm level, we double the size of the markets with two producers. Scaling up the markets as such limits the scale at which we can interpret some of the social welfare implications, in particular when looking at government revenue. As such, we are able to make statements about the social welfare effects derived from each firm's activity, yet cannot simply compare market-level social welfare outcomes between treatments with one or two producers. When trading off internal consistency of firm-level behaviour across all treatments with aggregate welfare implications, we selected the conservative approach to try and keep the decision structure as comparable as possible at the level of individual study participant. Future studies could expand this perspective, e.g. by varying the number of firms admitted to the market while keeping market size fixed.

At the other dimension of our treatment variation, we designed a performance obligation geared at a predetermined minimum quantity to be provided by the producer. Governments often stipulate service-level agreements when outsourcing public services (Chen & Perry, 2003), yet while private business operates with the aim of providing the maximum financial return possible, the performance of government operations is usually assessed on multiple dimensions (Domberger, Jensen, & Stonecash, 2002). For example, Hodge (1999) identifies economic, social, democratic, legal and political performance dimensions for public sector enterprises. Our study abstracts from this multi-dimensionality and compounds these into a single observable dimension – the quantity produced. We regard this simplification as necessary to cleanly study how the introduction of a performance obligation and/or post-tender competition affects the market, which is at the core of our research question. Future research may expand on our model by presenting agents with multi-dimensional trade-offs.

# A Mathematical Appendix

In this section, we derive the equilibrium production levels and the associated bidding behaviour under standard assumptions and under collusion between the market agents. For legibility, we omit time indices throughout.

## A.1 Single Free Treatment

**Level of Output** A player's valuation for market access equals her expected earnings from the Production Phase of the game. Total earnings in this experiment are determined by the endowment plus the revenue from the Production Phase, minus the cost from producing, minus the bid of the second-highest bidder. We formalise this in Equation 2 as

$$\pi_i = 100 + p_S(x_i) \cdot x_i - c_i \cdot x_i - b_{j,2}. \tag{2}$$

Substituting $p_S(x_i) = 21 - x_i$ from Equation 1 and optimising with respect to $x_i$ delivers the optimal level of output:

$$x_i^{SF} = \frac{21 - c_i}{2} \tag{5}$$

**Bidding Strategy** Lusk and Shogren (2007) and Milgrom and Weber (1982) show that in this type of Vickrey auction, bidding the true valuation is a player's optimal strategy, irrespective of risk preferences, number of other bidders, wealth levels, or other players' strategies. Accordingly, player $i$ places a bid $b_i$ equal to her expected return from entering the market, which is

$$\left(21 - x_i^{SF} - c_i\right) x_i^{SF} = b_i. \tag{17}$$

Substituting Equation 5 into Equation 17 delivers

$$b_i^{SF} = \frac{1}{4}(21 - c_i)^2. \tag{6}$$

## A.2 Multiple Free Treatment

**Level of Output under Collusion** We now have two players, $i$ and $j$, on a market that is twice as large as the market in Subsection A.1. We first find the output if both players collude: i.e., if both players behave as if they were one (large) monopolist. We show that earnings in this case are exactly double the amount as in the *Single Free* treatment, which means that under an equal sharing rule, both players could realise the same earnings as in the *Single Free* treatment if they collude.

For simplicity, we assume that $c_i = c_j$, denoted simply as $c$ for the rest of this paragraph.[14] Furthermore, as players do not know the other's individual production cost, but that $E(\varepsilon_i) = E(\varepsilon_j) = 0$; Hence, $E(c_j) = c_i$. Further, let $x = x_i + x_j$. A (large) monopolist maximises joint earnings at

$$\pi = 200 + \overbrace{(21 - 0.5x)}^{p_M(x_i, x_j)} \cdot x - c \cdot x - 2 \cdot b_{l,3}. \tag{18}$$

[14] Ciarreta and Gutiérrez-Hita (2012) discuss collusive behaviour under cost asymmetries in a quantity competition market. Our purpose here is to simply demonstrate that the market of the *Multiple Free* treatment can generate earnings for both players that are equivalent to those of the market at the *Single Free* treatment, if players behave as one (large) monopolist.

Optimising with respect to $x$ delivers the optimal output at

$$x^{SC} = 21 - c, \tag{19}$$

which is exactly twice the output from the market in the *Single Free* treatment (cf. Equation 5).

**Bidding under Collusion** For a player expecting to enter a market under collusion, market access would be determined by

$$\left(21 - \frac{x^{SC}}{2} - c\right)\frac{x^{SC}}{2} = b_i. \tag{20}$$

Substituting the output under collusion from Equation 19 delivers

$$b_i^{SC} = \left(\frac{21 - c_i}{2}\right)^2, \tag{21}$$

which is exactly equal to the value for market access as monopolist in the *Single Free* treatment (cf. Equation 6).

**Level of Output under Duopolistic Competition** Both players independently set quantities that will have influence on each others' earnings. Both players have individual marginal production cost $c_i$ and $c_j$, which may or may not be equal. Their earnings are determined by the endowment, the revenue and cost from production, and the cost for market access. The latter is determined by the third-highest bid submitted. Let $b_{l,k}$ be the bid of player $l$, ordered by the size of the bid from highest ($k = 1$) to lowest ($k = 6$). Note that $i, j, k \in I$ and $i \neq j \neq k$. Accordingly, each player can realise earnings from the market as follows:

$$\pi_i = 100 + \overbrace{(21 - 0.5\,(x_i + x_j))}^{p_M(x_i,x_j)} \cdot x_i - c_i \cdot x_i - b_{l,3} \tag{4}$$

For players $i$ and $j$, the best response functions then derive at

$$x_i + \frac{1}{2}x_j = 21 - c_i \tag{22}$$

and

$$\frac{1}{2}x_i + x_j = 21 - c_j. \tag{23}$$

As argued before, while the other player's actual individual production cost is unknown, players form beliefs based on the distribution of the cost in the market. As $E(\varepsilon_i) = E(\varepsilon_j) = 0$, a player optimises output based on her expectation of own and the other player's cost function in the game at $E(c_j) = c_i$. Applying this to the best response functions (Equations 22 and 23), they intersect at

$$x_i^{MF} = \frac{2\,(21 - c_i)}{3}. \tag{7}$$

The result holds equivalent for player $j$.

**Bidding Strategy under Duopolistic Competition** Bidding their true valuation for market access (as argued for above), players take into account both their own production cost and the expected production cost of the other winner. Accordingly, a player will bid

$$(21 - 0.5\,(x_i + x_j) - c_i)\,x_i = b_i. \tag{24}$$

Note that $E\,(c_i) = c_0 + \varepsilon_i$ with $E\,(\varepsilon_i) = 0$, which is true for all $i \in I$. Accordingly, when assessing the value for market access, a player will assume $E\,(c_{-i}) = c_i\ \forall -i \in I$. Using this information and substituting Equation 7, a player bids

$$b_i^{MF} = \frac{2}{9}\,(21 - c_i)^2\,. \tag{8}$$

## A.3 Single Obligation Treatment

**Minimum Production Level** Government sets the minimum production at the level of $p_S\,(x) = c_0 + \overline{\varepsilon}$. Let $\underline{\mathrm{x}}^{SO}$ be the minimum production in a given round. We employ the inverse demand function from Equation 1 to find

$$\underline{\mathrm{x}}^{SO} = 21 - c_0 - \overline{\varepsilon}. \tag{9}$$

**Level of Output** As argued above, the monopolist maximises earnings at an output of $x^{SF}$ (Equation 5), which decreases in $c_i$, as illustrated in Figure 3a. To investigate the conditions for which the output obligation is binding, we are interested in the conditions for $x^{SF} \geq \underline{\mathrm{x}}^{SO}$. This inequality describes all cases at which the unconstrained monopolist as in the *Single Free* treatment produces more than the output obligation. Using Equations 5 and 9 and substituting $c_i = c_0 + \varepsilon_i$, we have:

$$\frac{21 - (c_0 + \varepsilon_i)}{2} \geq 21 - c_0 - \overline{\varepsilon}$$

Substituting $\overline{\varepsilon} = 2$ as in our experiment, this solves for:

$$c_0 \geq 17 + \varepsilon_i \tag{25}$$

As $\varepsilon_i \in [-2, 2]$, even in the "worst case", i.e. when $\varepsilon_i = -2$, $c_0$ would need to be at least 15 for the unconstrained monopolist to produce more than the minimum production level. In our experiment, $c_0$ is drawn from a uniform distribution on $[\underline{c}, \overline{c}] = [5, 13]$, so $\underline{\mathrm{x}}^{SO}$ is always binding for the calibrations we employ. A monopolist entering the market will not produce more than $\underline{\mathrm{x}}^{SO}$, but cannot go below $\underline{\mathrm{x}}^{SO}$. Figure 18 provides a visual representation. Formally:

$$x_i^{SO} = \underline{\mathrm{x}}^{SO} \tag{26}$$

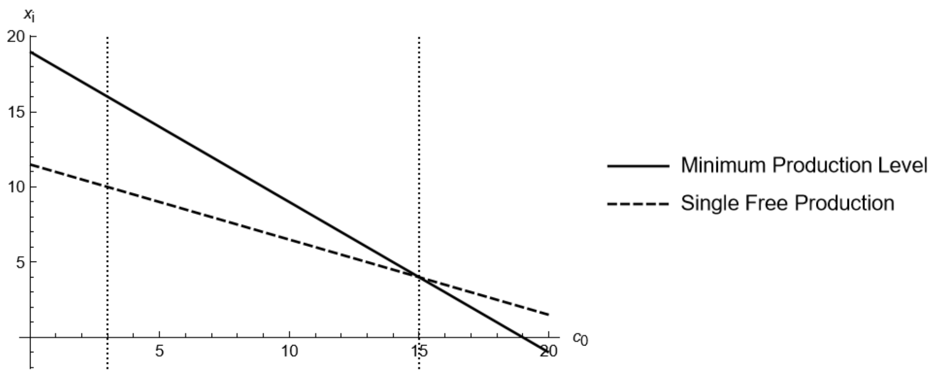



**Figure 18:** Equilibrium output $x_i$ for an monopolist (dashed line) and minimum production level (solid line) for different levels of $c_0$. We let $\varepsilon_i = -2$ and $\bar{\varepsilon} = 2$. Vertical dotted lines at 3 and 15 indicate the upper and lower bound for $c_i$ under the configuration of our experiment.

**Bidding Strategy** Players bid their true valuation for market access for an output of $\underline{x}^{SO}$, which is the expected return from entering the market at this output level. Formally:

$$b_i^{SO} = \left(21 - \underline{x}^{SO} - c_i\right) \underline{x}^{SO} \tag{10}$$

## A.4 Multiple Obligation Treatment

**Minimum Production Level** Similar to the *Single Obligation* treatment, the minimum production level $\underline{x}^{MO}$ will be at $p_M(x) = c_0 + \bar{\varepsilon}$, i.e. the point that maximises consumer surplus. We denote $\underline{x}^{MO}$ for the output of the entire market, with $\underline{x}_i^{MO}$ and $\underline{x}_j^{MO}$ the respective minimum production levels for producers $i$ and $j$. We assume both producers have to contribute to the minimum production level at the same rate, irrespective of their individual marginal production function. Hence, $\underline{x}_i^{MO} = \underline{x}_j^{MO} = 0.5 \cdot \underline{x}^{MO}$. Employing the inverse demand function from Equation 3, we find the minimum production level for both producers at

$$\underline{x}^{MO} = 42 - 2\left(c_0 + \bar{\varepsilon}\right), \tag{27}$$

which translates into individual minimum production levels of respectively

$$\underline{x}_i^{MO} = \underline{x}_j^{MO} = 21 - c_0 - \bar{\varepsilon}. \tag{11}$$

For each player, this delivers the same level of minimum output as in the *Single Obligation* treatment (cf. Equation 9).

**Collusion – Level of Output and Bidding Strategy** We demonstrate behaviour if both producers collude and behave as one (large) monopolist by combining steps from Appendices A.2 and A.3. Note that equivalent to the *Single Obligation* treatment, also here the minimum production level will be binding, as Equation 25 and its interpretation also apply to the case of collusion in this treatment. A player expecting to enter a market with collusion values market access at

$$\left(21 - 0.5\underline{x}_i^{MO} - 0.5\underline{x}_j^{MO} - c_i\right) \underline{x}_i^{MO} = b_i. \tag{28}$$

As $\underline{x}_i^{MO} = \underline{x}_j^{MO}$, we can simplify this to

$$b_i = \left(21 - \underline{x}_i^{MO} - c_i\right) \underline{x}_i^{MO}, \tag{29}$$

which is equivalent to the bid for the *Single Obligation* treatment as $\underline{x}^{SO} = \underline{x}_i^{MO}$.

**Level of Output under Duopolistic Competition** As discussed above, duopolists compete in a Cournot market, producing at a level of $x_i$ and $x_j$ as described in Equation 7, which is decreasing in own marginal production cost.

To show whether or not the minimum production level is binding, we are again interested in the case when individual production would be higher than the minimum production level, i.e. when $x_i^{MF} \geq \underline{x}_i^{MO}$ (equivalent for $j$). As $\varepsilon_i$ and $\varepsilon_j$ are distributed around zero, we can keep $E(c_j) = c_i$.[15] Using this and substituting $c_i = c_0 + \varepsilon_i$ we plug Equations 7 and 11 to get

$$\frac{2\left(21 - \left(c_0 + \varepsilon_i\right)\right)}{3} \geq 21 - c_0 - \overline{\varepsilon}. \tag{30}$$

Substituting $\overline{\varepsilon} = 2$ as in our experiment, this solves for

$$c_0 \geq 15 + 2\varepsilon_i. \tag{31}$$

Other than in the *Single Obligation* treatment, here the minimum production level is not always binding. For high levels of $c_0$ coupled with low $c_i$, equilibrium duopolist output may exceed the minimum production level in specific cases. We can formalise equilibrium output as

$$x_i^{MO} = \begin{cases} \underline{x}_i^{MO} & \text{if } c_0 \leq 15 + 2\varepsilon_i \\ \frac{2(21 - c_i)}{3} & \text{otherwise.} \end{cases} \tag{12}$$

As Figure 19 illustrates, $\underline{x}_i^{MO}$ is binding in most situations of our experiment. Only for high levels of $c_0$, a producer with comparably low levels of individual production cost $c_i$ will produce marginally more than the minimum production level.

**Bidding Strategy under Duopolistic Competition** As before, players bid their true valuation for market access under the same priors about the distribution of other players' cost, i.e. $E(c_{-i}) = c_i$, because both $\varepsilon_i$ and $\varepsilon_j$ are symmetrically distributed around zero with $E(\varepsilon_i) = E(\varepsilon_j) =$

[15] One might expect that we can use the same distribution argument from above to replace $c_0$ on the right-hand side by $c_i$. However, as $\underline{x}_i^{MO}$ is a parameter known to the producer when making the production decision, the actual right-hand side value of Equation 30 is known to the producer.

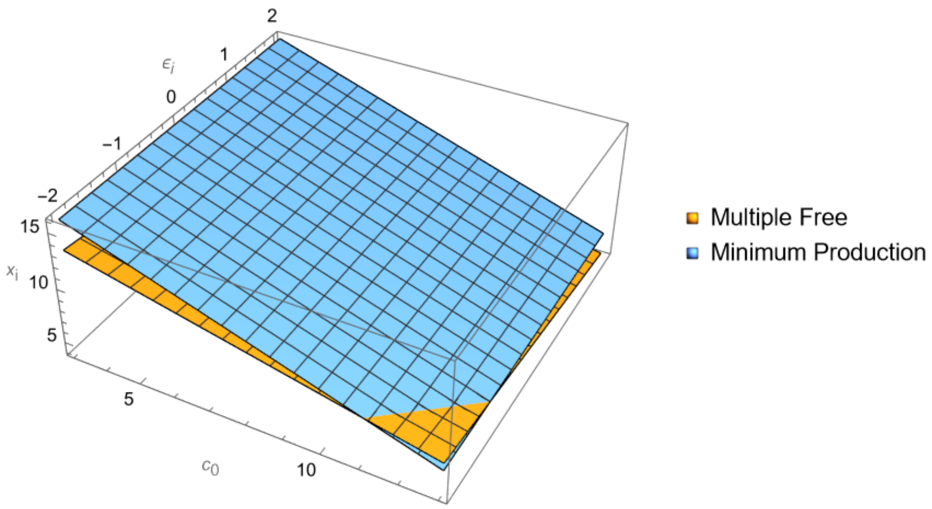



**Figure 19:** The figure depicts two planes in the a three-dimensional Cartesian space. For both planes, the level of output $x_i$ is a function of $c_0$ on the x-axis and $\varepsilon_i$ on the y-axis within the range defined in our experiment. The yellow plane illustrates equilibrium output in the *Single Free* treatment and the blue plane depicts the Minimum Production level.

0. As the minimum production level is *not* binding for specific combinations of $\underline{\mathrm{x}}_i^{MO}$ and $c_0$, we employ Equations 10 and 8 to describe bidding behaviour. That is, participants bid as in the Single Obligation treatment unless they are a producer with relatively low individual production cost in a high-cost environment, when one bids as in the *Multiple Free* treatment. Visually, this concerns players situated in the lower triangle in Figure 19 where *Single Free* output is higher than the minimum production level. Formally:

$$b_i = \begin{cases} \left(21 - \underline{\mathrm{x}}_i^{MO} - c_i\right) \underline{\mathrm{x}}_i^{MO} & \text{if } c_0 \leq 15 + 2\varepsilon_i \\ \frac{2}{9}\left(21 - c_i\right)^2 & \text{otherwise.} \end{cases} \tag{13}$$

# B Treatment Differences

## B.1 Single Free Compared to Multiple Free Treatment

**Output** We start by discussing treatment differences in terms of equilibrium output. Intuitively, we expect a monopolist output to be below that of a duopolist, which is echoed by what we see in Figure 5a. To investigate the cases for which this is true, we check

$$f\left(c_i\right) = \frac{2\left(21 - c_i\right)}{3} - \frac{21 - c_i}{2} \geq 0,$$

which is true for $c_i \leq 21$, hence for all values of the calibrations in our experiment. This means that $x_i^{SF}$ is lower than $x_i^{MF}$ for all cost levels. Further, $f'(c_i) = -11/6$, so the difference between $x_i^{SF}$ and $x_i^{MF}$ is lower for higher cost levels.

**Bidding** Next, Figure 5b illustrates that equilibrium bids in the *Single Free* treatment are higher than those in the *Multiple Free* treatment. Formally:

$$g(c_i) = \frac{1}{4}(21 - c_i)^2 - \frac{2}{9}(21 - c_i)^2 \geq 0,$$

which is always true for $c_i \in \mathbb{R}$. Also, $g'(c_i) = \frac{1}{18}(-21 + c_i)$, which is negative for $c_i \leq 21$. In other words, under the calibrations of this experiment, the equilibrium prediction for the difference in bids between the *Single Free* and the *Multiple Free* treatment is smaller, the higher the individual marginal production cost $c_i$.

## B.2 Single Free Compared to Single Obligation Treatment

**Output** Pursuant to Figure 6a, we first discuss the treatment differences in output. Using $\bar{\varepsilon} = 2$ we are interested in the points at which output in the *Single Obligation* treatment is higher than output in the *Single Free* treatment, which we formalise as

$$\frac{21 - c_i}{2} \leq 19 - c_0$$
$$\text{subject to} \quad c_0 \in [c_i - 2, c_i + 2].$$

This is true for

$$c_0 \leq 15 \quad \text{for } c_i \in [c_0 - 2, c_0 + 2], \tag{32}$$

meaning it is always true for the calibrations of our experiment. Next, let $c_0 = c_i - \varepsilon_i$ to represent the treatment difference in output as $f(c_i) = 19 - c_i + \varepsilon_i - \frac{21 - c_i}{2}$. As $f'(c_i) = -\frac{1}{2}$, the function has a negative slope throughout, so the treatment difference in output decreases with $c_i$.

**Bidding** Figure 6b depicts equilibrium bids for the two treatments. We formalise the difference between the two using Equations 6 and 10, substituting Equation 9 and $\bar{\varepsilon} = 2$ into the latter:

$$g(c_i) = \frac{1}{4}(21 - c_i)^2 - (c_0 + 2 - c_i)(19 - c_0) \geq 0.$$

which is true for $c_0 \in \mathbb{R}$ if $c_0 - 2 \leq c_i \leq c_0 + 2$. Next let $c_0 = c_i - \varepsilon_i$ to find $g'(c_i) = \frac{c_i - 21}{2} + 2 - \varepsilon$. As $g'(c_i) \leq 0$ if $c_i \leq 17 + 2\varepsilon_i$, the difference between the *Single Free* and *Single Obligation* treatment decreases with individual marginal cost level for almost all levels of $c_i$. Only for particularly high marginal cost levels ($c_i > 13$), $g'(c_i)$ is positive.

To sum up, our analysis shows that bids in the *Single Free* Treatment are higher than in the *Single Obligation* scenario and that this difference is smaller across the board for relatively inefficient firms with high individual marginal cost.

### B.3 Single Obligation Compared to Multiple Obligation Treatment

**Output** As discussed in Subsection A.4, the minimum production requirement $\underline{x}_i^{MO}$ is binding for most realisations of the cost levels in the *Multiple Obligation* treatment (see Equation 12 and Figure 19), while for certain cost levels we have $x_i^{MO} = x_i^{MF}$. We have established the equivalence of the minimum production requirements between the *Single Obligation* and *Multiple Obligation* treatments, hence $\underline{x}_i^{MO}$ and $\underline{x}_i^{SO}$. Further Subsection A.4 has shown how $x_i^{MO}$ *can* be higher than $x_i^{SO}$ under certain conditions.

**Bidding** Trivially, the "larger equal"-relationship in output between the two treatments translates into bids that are for the most part equal, yet may be higher in the *Single Obligation* treatments for certain values of $c_i$ as defined in Subsection A.4.

### B.4 Multiple Free Compared to Multiple Obligation Treatment

**Output** Similarly, we refer to the analysis from Subsection A.4 and Figure 19, which show that output in the *Multiple Obligation* treatment for the most part exceeds the level of output in the *Multiple Free* case. For some specific values of $c_i$ and $c_0$, the two are equal, as formalised in Equation 12.

**Bidding** In the same spirit and again applying results from Subsection A.4, bids in the *Multiple Free* scenario are mostly higher than in the *Multiple Obligation* treatment with the exception of specific values of $c_i$ and $c_0$, as defined in Equation 13, for which the two are equivalent.

## C Hypothetical Production

In a given round, only one third of all participants reach the Production Phase, i.e. one of three participants per group in the *Single* and two of six participants in the *Multiple* treatments. As a consequence, many participants make no actual production decision in a given round and receive a flat fee as earnings if the respective round was selected as payment relevant. Parallel to the auction winners determining their production, we ask the auction losers what they would have produced if they had won the auction round.[16] This decision was not incentivised, so the stated hypothetical production by the auction losers has no payment consequences, neither for themselves nor for other participants.

As such, we believe one of two strategies could surface (next to answering totally random). First, participants state their true preference for what they would have produced. If this is the case and if the auction works in selecting the most effective firms, we should observe that the hypothetical production is lower than the actual production. Second, alternatively, participants recognise the beneficial character of high output (meaning low prices) for consumers and give socially desirable

[16] The actual formulation in the experiment was: "Hypothetically, if you would have won, how many Units would you have wanted to produce?"

answers. If this is the case, we should observe that hypothetical production is higher than actual production.

Consider Figure 20, which parallels Figure 9b only now also with both hypothetical production, i.e what the auction losers say they produced had they gained access to the market. The figure shows how for the *Free* treatments, hypothetical production is lower than actual production, while for *Obligation* treatments, they are at the same level. This suggests that the first strategy is true. The auction selects more efficient firms into the market, so auction losers would produce less if they entered the market. For the *Obligation* treatments, by contrast, the minimum production level is binding in most cases, so even when entering the market, auction losers would have been required to produce at the threshold.

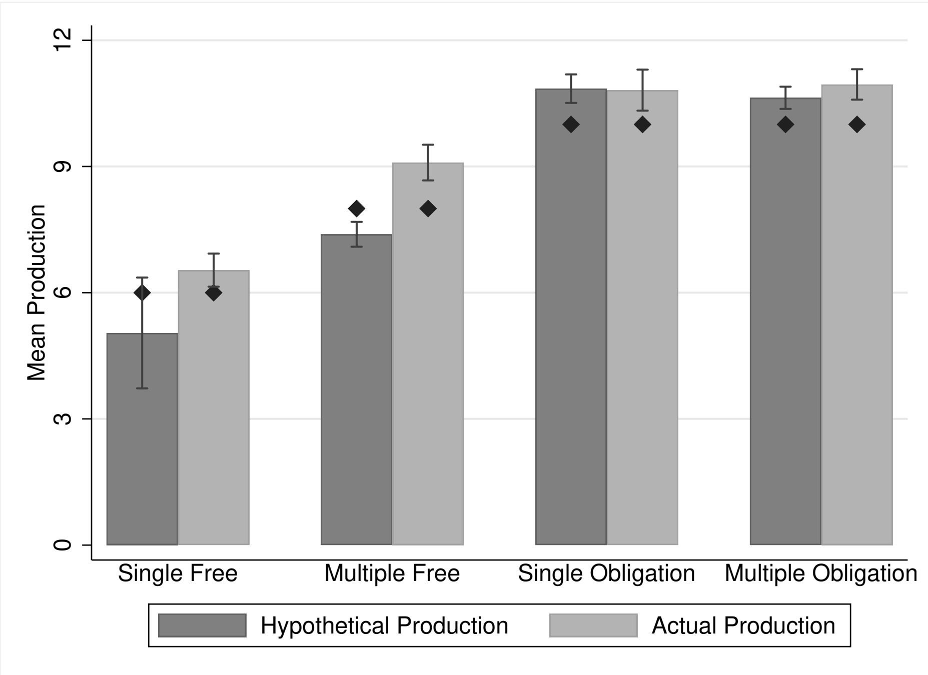



**Figure 20:** Hypothetical and actual average production per treatment. Black diamonds Indicate the equilibrium prediction over all rounds.

We reproduce the GLS random effect panel regression from Subsection 4.3, now both for hypothetical and realised production. As such, we add another set of factors to Regression Equation 15, controlling for whether the output is realised or not. Table 10 presents the results of the associated regression.

The regression output shows that for Regression (1), in the absence of any further controls, hypothetical output is below actual output by about 1 unit overall. As the auction selects mostly participants with lower production cost, the fact that those producers who were not selected appear they would have produced less, were they selected, can be interpreted as a positive signal towards the efficiency-enhancing feature of the auction. Further, the indicator variables for the treatments remain roughly identical to what we find when analysing actual production only, as in Table 5.

When bringing in the bid and the marginal production cost $c_i$ and $c_i^2$ in Regression (2), the win-term turns insignificant from zero. This suggests that when controlling for these factors, hypothetical and actual production do not differ.

**Table 10:** Random effects model regressing individual production on treatment dummies, the win-term and controls.

| | (1) | (2) | (3) |
|---|---|---|---|
| | | **Production**$_{i,t}$ | |
| Win | 1.000*** | 0.253 | 2.027*** |
| | (0.20) | (0.21) | (0.43) |
| Multiple=1 | 2.415*** | 3.086*** | 3.554*** |
| | (0.47) | (0.45) | (0.48) |
| Obligation=1 | 5.298*** | 5.243*** | 6.254*** |
| | (0.55) | (0.52) | (0.55) |
| Multiple=1 × | −2.515*** | −2.723*** | −3.293*** |
| Obligation=1 | (0.67) | (0.63) | (0.67) |
| Bid | | 0.014** | 0.014** |
| | | (0.01) | (0.01) |
| $c_i$ | | −0.377** | −0.398** |
| | | (0.16) | (0.15) |
| $c_i^2$ | | −0.019** | −0.018** |
| | | (0.01) | (0.01) |
| Period | | | −0.066** |
| | | | (0.03) |
| Multiple=1 × | | | −1.246** |
| win | | | (0.51) |
| Obligation=1 | | | −2.975*** |
| × win | | | (0.59) |
| Multiple=1 × | | | 1.578** |
| Obligation=1 × win | | | (0.72) |
| Constant | 5.207*** | 9.791*** | 9.618*** |
| | (0.39) | (0.82) | (1.34) |
| Controls | *No* | *No* | *Yes* |
| Number of observations | 2,520 | 2,520 | 2,520 |
| Number of panels | 252 | 252 | 252 |
| Within-model R-squared | 0.011 | 0.275 | 0.291 |
| Between-model R-squared | 0.388 | 0.463 | 0.449 |
| Overall R-squared | 0.150 | 0.344 | 0.350 |

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Standard errors in parentheses.

Lastly, we check in Regression (3) whether the difference between hypothetical and actual production is different between the treatments. In contrast to Figure 20, we can now control for various factors, such as individual production cost, the bid and other control factors. We find a significant difference of about 2 units for the *Single Free* case between hypothetical and actual production. For the *Multiple Free* scenario, this difference is considerably smaller at about 0.8 units (Wald Test $\beta_{\text{win}} + \beta_{\text{Multiple=1}\times\text{win}} = 0,\ \chi^2(1) = 5.84,\ p = 0.016$) and even negative for the *Single Obligation* treatment at about -0.9 units (implying more hypothetical production than actual production in that treatment) (Wald Test $\beta_{\text{win}} + \beta_{\text{Obligation=1}\times\text{win}} = 0,\ \chi^2(1) = 4.86,\ p = 0.028$). Also for the *Multiple Obligation* treatment, hypothetical production appears to exceed actual production by about 0.6

units (Wald Test $\beta_{\text{win}} + \beta_{\text{Multiple=1}\times\text{win}} + \beta_{\text{Obligation=1}\times\text{win}} + \beta_{\text{Multiple=1}\times\text{Obligation=1}\times\text{win}} = 0,\ \chi^2(1) = 3.49,\ p = 0.062$).

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