Two-period duopolies with forward markets

Caleb Cox * & Arzé Karam † & Matthias Pelster ‡

Abstract We experimentally consider a dynamic multi-period Cournot duopoly with a simultaneous option to manage financial risk and a real option to delay supply. The first option allows players to manage risk before uncertainty is realized, while the second allows managing risk after realization. In our setting, firms face a strategic dilemma: They must weigh the advantages of dealing with risk exposure against the disadvantages of higher competition. In theory, firms make strategic use of the hedging component, enhancing competition. Our experimental results support this theory, suggesting that hedging increases competition and negates duopoly profits even in a simultaneous setting.

Keywords: Corporate hedging, duopoly, dynamic setting, game theory, laboratory experiments, strategic application.

JEL Classification: D21, D22, D43, D53.

*Virginia Commonwealth University, Snead Hall, 301 W. Main Street, Box 844000, Richmond, VA, USA 23284. Phone: +1 804 828 7101. Fax: +1 804 828 9103 E-mail: *cacox@vcu.edu*.

†Durham University, Mill Hill Lane, DH13LB, England. Phone: +44 191 33 45460. Fax: +44 191 3345201. E-mail: *arze.karam@durham.ac.uk*.

‡Paderborn University, Center for Risk Management. Warburger Str. 100, 33098 Paderborn, Germany. Phone: +49 5251 60-3766. Fax: +49 5251 60-4207. E-mail: matthias.pelster@upb.de

1 Introduction

Corporate hedging is of great interest to both practitioners and academics (e.g., Graham and Rogers, 2002; Haushalter, 2000; Mello and Parsons, 2000; Tufano, 1996; Smith and Stulz, 1985). Managing risks can reduce firms' expected bankruptcy costs, agency costs, information asymmetries, or expected taxes, and thus increase shareholder value (e.g., Bolton et al., 2011; Campello et al., 2011; Froot et al., 1993; Mackay and Moeller, 2007).[1] While several optimal strategies developed theoretically propose a full hedge by firms in forward markets (e.g., Broll and Wong, 2013; Holthausen, 1979), several empirical studies find underhedging: hedge ratios that are less than one (e.g., Adam et al., 2015; Brown et al., 2006; Carter et al., 2006; Haushalter, 2000; Tufano, 1996).

A "sequential" setting where firms first decide on their hedging and then set their production quantity provides a theoretical rationale for underhedging in imperfectly competitive markets (Broll et al., 2009). In such cases, firms account for the effect that their hedging decision may have on the market (Brandts et al., 2008; van Eijkel and Moraga-Gonzalez, 2010; Leautier and Rochet, 2014; Le Coq and Orzen, 2006). Ceteris paribus, a larger hedging position of one firm increases the optimal output of this firm and decreases the competitors' optimal output (Allaz, 1992; Allaz and Vila, 1993; Broll et al., 2011). In equilibrium, however, this increases competition: Output increases, and prices decrease. Thus, firms may decide to hedge less to avoid reducing their profits. It is clear that firms face a strategic dilemma: They must weigh the benefits of hedging their risk against the adverse effects of an increase in market competition. However, Broll et al. (2011) theoretically show that this strategic dilemma is non-existent in a simultaneous one-shot output market interaction setting where firms decide on their production and hedging decision at the same time.

In this paper, our main objective is to examine experimentally the extent to which strategic considerations explain underhedging behavior in a simultaneous hedging setting in a multi-period framework in imperfectly competitive markets. We use a simple Cournot duopoly model with a simultaneous hedging setting and repeated interaction to examine how hedging affects market equilibrium. Ex ante, we first allow firms to hedge their risk exposure toward demand uncertainty on a forward market. Second, we provide firms with the real option for storage that allows them to react to

[1] For literature discussing the goal of firms employing corporate hedging see, among others, Géczy et al. (1997); Kajüter (2012).

low demand realizations ex post. This latter feature introduces real dynamics into the multi-period model and ensures that our setting is not simply a repetition of the single-shot game.

In our experimental study, we conduct two treatments: one treatment with an additional production opportunity after the initial demand state is realized (Double Production), and one treatment without (Single Production). Subjects play repeatedly for 20 rounds to allow them to learn about the strategic setting, but they are randomly re-matched in each round to minimize any potential repeated game effects.

Our experimental results provide supportive evidence that subjects tend to account for the adverse effects of their own financial decisions on the market equilibrium. However, we do not find any evidence that the experimental decision makers consider the hedging decisions of their competitors – which are common knowledge – in subsequent decisions. As the game is closer to a simple repetition of the single-shot game in our second setting, subjects' level of supply prevents duopoly profits, on average. Our results underline that hedging creates a strategic dilemma for producing firms and significantly increases competition—even in a simultaneous setting.

2 Risk-sharing markets and competitiveness in duopoly markets

According to the principle of increasing uncertainty, the risk-averse firm will produce less under (demand) uncertainty than it would under certainty (Leland, 1972; Sandmo, 1971). However, with an access to risk-sharing markets such as forward markets, the decision to produce is not subject to risk considerations. The reason is that forward markets allow the firm to buy or sell contracts for future delivery and thus, hedge and manage its risk exposure. As a result, the production decision of the competitive firm is separated from the forward trading decision and should match the production amount under certainty (Feder et al., 1980). This result indicates that risk-sharing markets provide an important social benefit by offering the opportunity to reduce or even eliminate output fluctuations that are due to the variation in firms' subjective distributions of uncertainty. While risk-sharing markets increase the production and profits for a competitive firm, this does not necessarily apply to a duopolistic (oligopolistic) market.

Duopolistic markets are characterized by an inverse relationship between the cumulative production of the competing firms and the market price of the offered product. As a result, firms may generate higher revenues and profits by reducing their production in response to an increasing market price. The intuition here is that lower production eases competition in the market and allows firms to realize higher prices. Similar to the competitive firm under uncertainty, risk-averse firms in a duopoly also decrease their production in Nash Equilibrium (NE) when facing demand uncertainty. Lower production yields higher prices, and consequently firms may increase their revenues and profits under uncertainty, compared to the certainty case (Eldor and Zilcha, 1990).

In such a setting, forward markets may increase the competition between duopolistic firms via two channels. First, forward markets allow the firms to manage the risk exposure of their production decisions. Being able to manage their risk exposure not only by reducing their production, but also via the risk-sharing markets, firms may as a result increase their production. Second, a firm can credibly establish its intention to provide a large supply, which thereby (ceteris paribus) increases its own optimal output and decreases the competitors' optimal output (Broll et al., 2011). As noted by Wolak and McRae (2009), the larger is a supplier's fixed forward contract obligation, the larger is its best-reply output level. Forward sales reduce the residual demand that face the firm, and thus reduce the gain from restricting output to increase price (Wolak and McRae, 2009). Consequently, forward sales reduce the incentive to withhold output.

Both channels yield an increase in NE output. However, the firms are not necessarily better off. The introduction of risk-sharing markets have two opposing effects. First, the risk-averse firm improves its position by reducing riskiness via risk-sharing markets. Second, however, the increased production results in lower market prices. Eldor and Zilcha (1990) show that although firms are risk-averse, in some cases risk-sharing markets make all firms worse off in the NE. Firms must thus weigh the reduced risk of forward sales against the accompanying reduction in profitability.

3 Related literature

Following the seminal work of Allaz (1992) and Allaz and Vila (1993), several experimental studies investigate the strategic impact of a hedging device on market competition. Importantly, one has to distinguish two settings. First, in a simultaneous setting, hedging and output decisions are taken at the same point in time. According to Broll et al. (2011), in this setting, hedging is exclusively used for risk-managing reasons as it is not possible to use hedging strategically. Second, in a sequential setting, the hedging decision is made before the output decisions. In this setting, hedging is not only used to manage the risk exposure but also as a strategic device and increases competition (Allaz and Vila, 1993; Broll et al., 2009; Wolak and McRae, 2009).

The competition-enhancing effect of selling forward has been tested in experimental Cournot duopolies several times. Based on Allaz and Vila (1993), Le Coq and Orzen (2006) study a single forward and a spot market phase. First subjects sell their product in the forward period, before they compete on the residual demand in the subsequent spot period. These experimental results show that the introduction of forward markets does have competition-enhancing effects, which are, however, not as strong as theory predicts.

Motivated by the specific design of forward markets that occur in the electric power industry, Brandts et al. (2008) consider both quantity and supply function competition as strategic variables. For both types of competition, they find that the introduction of a forward market significantly increases competition, as is predicted by the model of Allaz and Vila and in line with the notion of Wolak and McRae (2009). Closely related, van Koten and Ortmann (2013) show that forward markets are a more effective remedy to increase competition compared to increasing the number of competitors.

Our study contributes to this literature by allowing players to utilize the risk management purpose of the hedging device; they thus face a dilemma between hedging their risk exposure and maintaining high market prices. The previous experimental studies discussed here exclusively focus on the strategic impact of the hedging device and abstract from risk management considerations, as their settings do not incorporate risk. Thus, our study is closer to the theoretical setting of Broll et al. (2011), which accounts for risk, than to the theoretical setting of Allaz and Vila (1993). Hence, our setting is cognitively more complex than the setting of Allaz and Vila, as decision makers have to account for the risk that is associated with their decisions.

In addition to experimental studies, some contributions use field data and provide empirical evidence of the topic. Wolak (2000) shows that, for the Australian power market, the effect is pro-competitive when firms use the forward market (see also Wolak and McRae, 2009). Similarly, van Eijkel and

Moraga-Gonzalez (2010) study the Dutch wholesale market for natural gas and show that strategic reasons play an important role in explaining the observed firms' hedge ratios. However, these studies are unable to separate the market views of managers from strategic applications of the hedging device. Our laboratory setting allows us to implement the desired variations with a high degree of control.

4 Hypotheses development

We experimentally study the strategic considerations of corporate hedging in a simultaneous setting. For this, we use a simple Cournot duopoly model with repeated interaction. We restrict ourselves to the Cournot setting, as Kreps and Scheinkman (1983) argue that quantity precommitment and Bertrand competition yield Cournot outcomes. In other words, in an oligopoly under mild assumptions about demand, the unique equilibrium outcome is the Cournot outcome.[2]

We consider two different settings, Single Production and Double Production.

4.1 Single Production setting

Our basic experimental setting considers a two-period model without discounting. The first period runs from time $t = 0$ to time $t = 1$; the second period stretches from $t = 1$ to $t = 2$. Two symmetric firms—firm A and firm B—decide to produce a homogeneous good, $q_t^A \geq 0$ in $t = 0$. Production takes place between $t = 0$ and $t = 1$ and gives rise to unit costs of 1 in $t = 1$. Each firm's production becomes common knowledge in $t = 1$.

In $t = 1$ and $t = 2$ firms have the opportunity to sell their production on the same market. The demand for the homogeneous good is uncertain. The price in time t is determined by the inverse demand function, $\tilde{p}_t = \tilde{\varepsilon}_t - (s_t^A + s_t^B)$, where $\tilde{\varepsilon}_t$ expresses the uncertainty of the realization of demand and s_t^A denotes the supply of firm A in time t. The initial random demand state ε_1 is drawn from $\{40, 60\}$ with equal probability. The subsequent random demand state ε_2 is drawn

[2]Even though the Cournot model has been criticized for its theoretical foundations, the model is simple and has pleasing comparative statics and has proved useful in the literature (see, e.g. Mas-Colell et al., 1995; Martin, 1994; Maggi, 1996; Larue and Yapo, 2000).

with equal probability from $\{50, 70\}$ conditional on the high initial demand state, or from $\{30, 50\}$ conditional on the low initial demand state. Figure 1 depicts the uncertainty of demand.

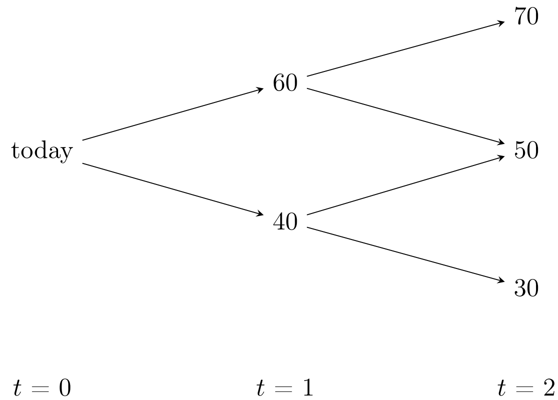


Figure 1: Evolution of random variables

As firms can sell their production in $t = 1$ and $t = 2$, they are endowed with the real option to distribute their production between periods. This allows firms to react to bad price realizations in $t = 1$ due to low demand and store their production (or parts of their production) to sell in $t = 2$. In $t = 1$, with knowledge of the actual realization of demand for this period, firms make their sales decision (s_1) and, thus, also their storage decision ($q_1 - s_1$). Sales and inventory have to add up to the production amount.

In addition, firms are able to ex ante manage their exposure to price risk via an unbiased forward market.[3] The forward market offers contracts with a maturity of one period.[4] Hence, firms can purchase or sell forward contracts on the good that they produce in time $t = 0$ with maturity in $t = 1$ and in $t = 1$ with maturity in $t = 2$.

Binding first-period hedging decisions (h_1) are made simultaneously with the production decision in $t = 0$; second-period hedging decisions (h_2) are made in $t = 1$ and manifest in $t = 2$. As the natural risk management decision for a producing firm is to sell its product on the forward market, $h > 0$ denotes a short position in our context. As firms that take a long position on the forward market are increasing their risk exposure, we do not allow $h < 0$.[5]

[3] The forward market is called unbiased if the forward price equals to the expected spot price.

[4] Since in reality forward contracts also have limited maturities, we do not include contracts with a maturity of two periods or longer in our model.

[5] Note that this is only relevant if decision makers are risk-neutral or even risk-seeking.

Similar to the spot price, the forward price is the result of expected demand and expected (equilibrium) decisions of the duopolists: the supply. Forward-market participants act rationally and have perfect knowledge.[6] As a result, they are aware of the optimal decisions of the duopoly and act accordingly.[7]

Consequently, the one-period forward price (which is agreed on in $t = 0$, and is executed in $t = 1$) is given by

$$f(0,1) = \mathrm{E}[\tilde{\varepsilon}_1] - (\hat{s}_1^A + \hat{s}_1^B) = 50 - (\hat{s}_1^A + \hat{s}_1^B), \tag{1}$$

where $\hat{s}_1 = s_{SP}(q_1^A, q_1^B, h_1^A, h_1^B)$ denotes the (anticipated) equilibrium choices of producing firms for a given subgame-path.[8] The forward rate for second-period contracts is uncertain in time $t = 0$; only the probability distribution of the forward rate is known. As the distribution of the random demand state ε_2 is conditional on the initial demand state, the second-period forward rate relates to the spot rate in $t = 1$.

As a result, the forward price for the second period fulfills

$$\begin{aligned}\tilde{f}(1,2) &= \mathrm{E}_1[\tilde{\varepsilon}_2 \mid \varepsilon_1] - \text{industry supply} \\ &= \tilde{\varepsilon}_1 - (\check{q}_1^A + \check{q}_1^B - s_1^A - s_1^B),\end{aligned}$$

where $\check{\cdot}$ denotes realized choices from previous interactions.

In $t = 1$, the demand uncertainty for the first period is resolved. Based on the demand state firms choose their supply for the spot market (s_1), which is sold immediately. The remainder of the production is stored and will be sold in $t = 2$. Warehouse charges are 0.25 per unit, for every unit that is produced in the first period and sold in the second period. Additionally, firms decide on their second-period hedging (h_2) in $t = 1$.[9]

[6] Besides demanders for the homogeneous good, speculators may have incentives to engage in forward trading and take offsetting positions of the firms.

[7] Cyert and DeGroot (1970) make a similar argument, that the counterpart's choices cannot be observed in a simultaneous-move game and, hence, subjective expectations have to be considered.

[8] We provide the first-period forward price that take the equilibrium choices into account in Equation (5) below.

[9] Note, that at this point we do not allow firms to enter production in time $t = 1$. Hence, firms cannot produce additional goods for the second period. Possible justifications for this limitation include the possibility to produce large lot sizes, high setup costs, or seasonal limitations in production.

In $t = 2$, the demand uncertainty for the second period is resolved and the remaining production is sold. As all goods have to be sold at this point, second-period sales are an immediate result of the firm's previous decisions ($s_2^A = q_1^A - s_1^A$). Therefore, second-period sales do not represent a decision variable. Figure 2 visualizes the timing of the decisions.

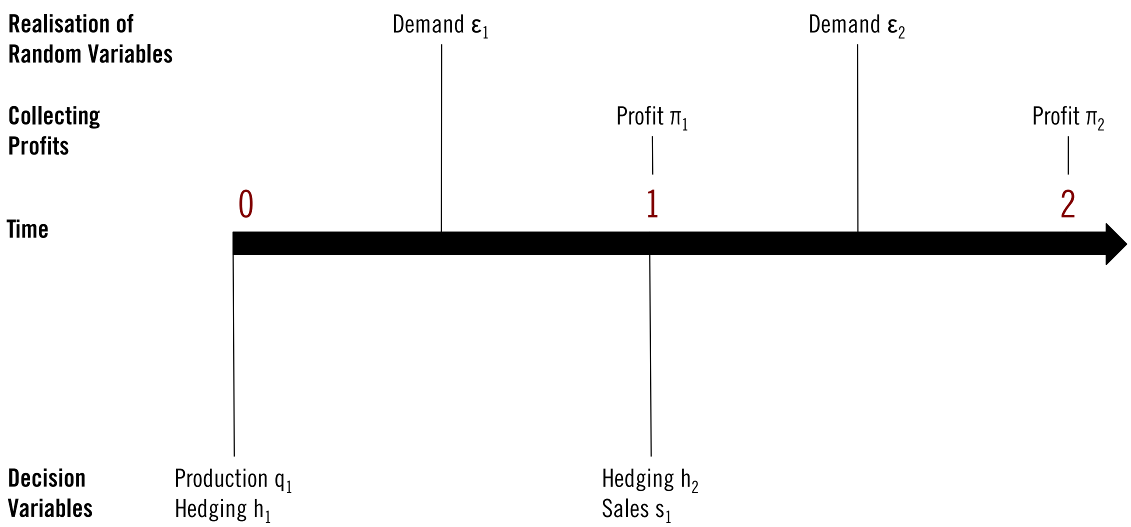


Figure 2: Single Production setting

The profits of the firm are the sum of period 1 and 2 profits, as given by

$$\begin{aligned} \text{profit period 1} = &\ \text{spot market price}_1 \cdot \text{supply}_1 - \text{production costs} \\ &+ \text{profits or losses from hedging decision}_1 - \text{storage costs} \end{aligned} \tag{2}$$

and

$$\text{profit period 2} \;=\; \text{spot market price}_2 \cdot \text{supply}_2 + \text{profits or losses from hedging decision}_2 \tag{3}$$

where *profits / losses from the hedging decision* are given by

$$\text{profits or losses from hedging decision} = \text{hedging amount} \cdot (\text{forward price} - \text{spot price}).$$

Mathematically, profits of firm A (B) are given by $\tilde{\pi}^A = \tilde{\pi}_1^A + \tilde{\pi}_2^A$ with

$$\tilde{\pi}_1^A = (\tilde{\varepsilon}_1 - (s_1^A + s_1^B))s_1^A - q_1^A + h_1^A(f(0,1) - \tilde{p}_1) - 0.25(q_1^A - s_1^A) \text{ and}$$
$$\tilde{\pi}_2^A = (\tilde{\varepsilon}_2 - (q_1^A + q_1^B - (s_1^A + s_1^B)))(q_1^A - s_1^A) + h_2^A(\tilde{f}(1,2) - \tilde{p}_2),$$

where $s_1^A = s_1^A(\check{q}_1^A, \check{q}_1^B, \check{h}_1^A, \check{h}_1^B)$. That is, the supply in $t = 1$ is a function of the decisions that were made in the previous stage. Additionally, $s_1^A \in [0, \check{q}_1^A]$. As the duopoly is symmetric, firm B has the same profit functions.

In order to determine forward prices and derive hypotheses about participants expected choices, we assume that both firms maximize (μ, σ)-preferences. Here, $\mu = \mathrm{E}[\tilde{\pi}^A]$ denotes the expected value and $\sigma^2 = \mathrm{var}(\tilde{\pi}^A)$ the variance of the stochastic profit of firm A. We rely on the (μ, σ)-approach as it provides a simple approach to complex problems and consequently a cost-efficient approach to information.[10] Thus, the decision rule of firm A (B) is given by

$$\Phi^A = \mu_1^A + \mu_2^A - \frac{\alpha^A}{2}((\sigma_1^A)^2 + (\sigma_2^A)^2).$$

The preference value of the firm increases in the expected profits across both periods and decreases in the variance of those profits. Parameter α^A denotes the degree of risk aversion of firm A and specifies the sensitivity of the firm reactions to the variance of its profits.[11] Note that $\alpha^A \equiv 0$ denotes risk neutrality—and thus the situation under certainty. (Since participants received all payments at a single point in time (the end of the session), time preferences play no role in the experiment.) Thus, we abstract away from discounting. All parameters are common knowledge.

We focus on subgame-perfect Nash equilibrium (Selten, 1965) in a Cournot setting. The strategy choice consists of the optimal production and hedging decisions as well as strategy sets for the supply that constitute a Cournot-Nash equilibrium for every possible production and forward decision. We first have to find the Cournot-Nash equilibrium in $t = 1$ for all possible production and forward decisions. Then, we go back to $t = 0$ and determine the optimal output and hedging decisions which consider the effects on the quantity sold in $t = 1$ as well as the subsequent hedging decision. A

[10] For more detailed justification of the (μ, σ)-approach see, e.g., Robison and Barry (1987).

[11] The preference function describes risk-averse behavior as long as utility increases in expected profits and decreases in risk and marginal utility in expected profits does not increase ($\partial\Phi/\partial\mu > 0$, $\partial\Phi/\partial\sigma < 0$, and $\partial^2\Phi/\partial\mu^2 \leq 0$).

detailed numerical example is provided in Appendix A.

In a subgame-perfect Nash equilibrium, the optimal supply decision in $t = 1$ fulfills (given the realization of demand uncertainty ε_1)

$$\varepsilon_1 - (2s_1^A + s_1^B) + \check{h}_1^A = \varepsilon_1 - (2\check{q}_1^A - 2s_1^A + \check{q}_1^B - s_1^B) - 0.25. \tag{4}$$

The first part of the left-hand side of the equation denotes the marginal revenues from the spot sales in $t = 1$, while the second part of the left-hand side ($\check{h}_1^A$) denotes the marginal revenues from the hedging decision that was made in $t = 0$ and is executed in $t = 1$. The right-hand side of the equation denotes the marginal revenues from spot sales in $t = 2$, adjusted for the costs that result from the shift of sales: the costs for storage 0.25. Thus, the intuition of Equation (4) is that decision makers seek to smooth their marginal revenues over the periods.

For the optimal decision, the marginal revenues that are realized in $t = 1$—the left-hand side of the equation equal the marginal revenues that are realized in $t = 2$: the right-hand side of the equation. Note, that the forward-market decision for the second period does not directly influence the sales decision in $t = 1$. However, the existence of a forward market enables firms to separate their sales decision in $t = 1$ from their risk preferences α, which do not appear in Equation (4).

In Equation (4), $\check{h}_1^A$ shows that the optimal sales decision is influenced by the hedging decision that is made in $t = 0$. This highlights the strategic impact of the hedging decision in a simultaneous setting. The reason is that hedging increases the quantities that are supplied and thus effectively increases the vigor of competition: The decision maker increases her supply on the spot market with her own forward position ($\partial \hat{s}_1^A / \partial h_1^A = 1/3$, see Equation (17) in Appendix A) and decreases her supply on the spot market with her competitors forward position ($\partial \hat{s}_1^A / \partial h_1^B = -1/6$, see Equation (17) in Appendix A). As the forward price is fixed and not subject to the quantity that is offered on the spot market, the decision maker is less sensitive towards price changes due to additional supply (see also Wolak and McRae, 2009). Hence, with a larger forward position the decision maker also increases supply in $t = 1$.

With respect to the equilibrium solution, the first-period forward price for the hedging decision that is made in $t = 0$ and executed in $t = 1$ reads

$$f(0,1) = 50 - \frac{1}{2}(q_1^A + q_1^B) - \frac{1}{6}(h_1^A + h_1^B) - \frac{1}{3} \cdot 0.25. \tag{5}$$

The forward price reflects that the market supply in $t = 1$ depends on the firms' production decisions and firms' initial hedging decisions. Hence, the forward price decreases in the firms' production decisions and in their hedging decisions. Finally, the forward price decreases in the costs that result from the shift of sales (costs for storage, 0.25) from $t = 1$ to $t = 2$, as the market supply in $t = 1$ increases in costs for the storage for goods that are not sold in $t = 1$.

Next, we consider the hedging decision that is made in $t = 1$ and executed in $t = 2$. In equilibrium, the producers will sell the entire production that is taken into storage on the forward market (see Equation (16) in Appendix A. This result is consistent with the observation that any risk-averse decision maker—independent of the degree of risk aversion—will always prefer the safe choice over the lottery as long as both have the same expected value. Thus, the profit that a firm realizes in $t = 2$ becomes deterministic in $t = 1$.

Given the equilibrium decisions in the second period, we turn to the equilibrium in $t = 0$. Here, we obtain several insights: First, decision makers cannot separate their production and their risk management decisions in $t = 0$. Their production decision depends on their risk preferences α and their expectations about the uncertainty. Therefore, production is reduced, as compared to the duopoly setting under certainty.

Second, firms account for the strategic impact of the hedging decision. The hedging decision depends on risk preferences, on the expected uncertainty, and on the effect of the hedging choice on the future sales decisions of the firm and of its competitor. As was shown above, the equilibrium sales decisions of firms are subject to the hedging decision that is made in $t = 0$. The equilibrium industry supply increases with every additional forward contract that decision makers engage in, which yields lower market prices. Thus, decision makers have to balance the reduced risk exposure that is due to a larger hedging position (the risk management aspect) against the revenue potential of their sales.

Decision makers that focus only on the risk management aspect will engage in large hedging positions while those who only focus on the potential revenue and not on the risk will take smaller hedging positions. Due to the balancing of these extreme behaviors, we expect that decision makers will choose an underhedge in time $t = 0$ (which follows from Equations (18) and (19) in Appendix A).

To summarize, we hypothesize that

1a. Firms will make their sales decision in an effort to equate marginal revenues over periods (see Equation (4)). They will attempt to equate the marginal revenues of the first period with the marginal revenues of the second period, adjusted for storage costs.

2a. Sales decisions are independent of degree of risk aversion. The existence of a forward market allows players to separate their sales decision in the first period from their risk preferences (see Equation (4)).

3a. Firms consider previous hedging choices when they make their sales decisions. Firms spot sales in $t = 1$ increase in their own first-period hedging choice with a marginal effect of $+1/3$, while spot sales in $t = 1$ decrease in the first-period hedging choice of the competitor with a marginal effect of $-1/6$ (see Equation (17) in Appendix A).

4a. In the second period, firms will sell the entire production that had been taken into storage on the forward market: Firms will take a full hedge. Their hedging decision is independent of their risk aversion.

5a. In the first period, firms will take a hedging position that increases in their risk aversion and is smaller than their expected sales: Firms will choose an underhedge.

4.2 Double Production setting

Next, we turn to the Double Production setting, which is similar to the Single Production setting—except for one crucial difference: Firms can make an additional production decision in $t = 1$ for production that will be available for sale in the second period: between $t = 1$ and $t = 2$. Again, decision makers have the opportunity to react to low demand realizations by storing their good and selling at a later time.

Due to the adjustment, the new decision sequence takes the following form: In $t = 0$, firms set their production for the first period as well as their forward position. Production takes place between

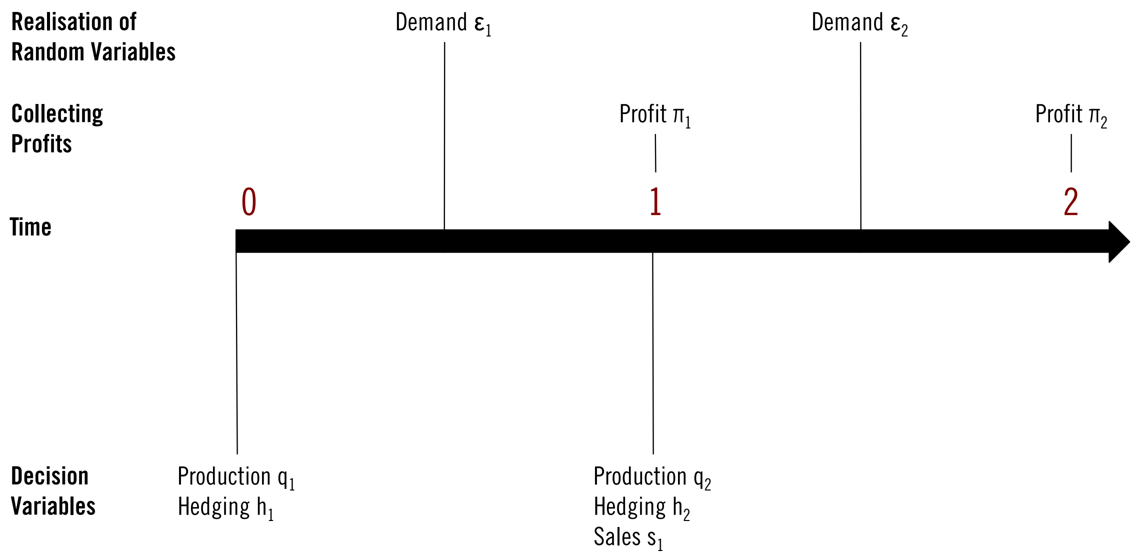


Figure 3: Double Production setting

$t = 0$ and $t = 1$. In $t = 1$, demand uncertainty for the first period is resolved. Firms choose their sales for $t = 1$. Excess production is taken into storage. Also, the forward position from the first period is closed. Moreover in $t = 1$, firms set their production for the second period and their forward position with maturity in $t = 2$ (which is agreed on in $t = 1$, and is executed in $t = 2$). The demand in $t = 2$ is still uncertain at this point. Again, production takes place between $t = 1$ and $t = 2$. At the final date ($t = 2$), firms sell their additional production and everything from storage. Figure 3 visualizes the setup of the model.

Consequently, the profit of firm A (B) in $t = 2$ is given by

$$\text{profit period 2} = \text{spot market price}_2 \cdot \text{supply}_2 - \text{production costs}_2 + \text{profits or losses from hedging decision}_2, \quad (6)$$

and, mathematically, by

$$\tilde{\pi}_2^A = \tilde{p}_2(Q_2)(q_1^A - s^A + q_2^A) - q_2^A + h_2^A(\tilde{f}(1,2) - \tilde{p}_2). \quad (7)$$

The first-period profit remains unchanged,

$$\tilde{\pi}_1^A = \tilde{p}_1(Q_1)s^A - q_1^A + h_1^A(f(0,1) - \tilde{p}_1) - 0.25(q_1^A - s^A). \tag{8}$$

The inverse demand function in time t is still given by $\tilde{p}_t(Q_t) = \tilde{\varepsilon}_t - Q_t$, where Q_t denotes the industry supply in time t. Specifically: $Q_1 = s_1^A + s_1^B$ and $Q_2 = q_1^A + q_1^B + q_2^A + q_2^B - (s_1^A + s_1^B)$, respectively. As in the Single Production setting, the forward prices are determined by (expected) demand and (anticipated) supply. For the second period

$$\begin{aligned} \tilde{f}(1,2) &= \mathrm{E}_1[\tilde{\varepsilon}_2 \mid \varepsilon_1] - \text{industry supply} \\ &= \tilde{\varepsilon}_1 - (\check{q}_1^A + \check{q}_1^B - \hat{s}_1^A - \hat{s}_1^B + \hat{q}_2^A + \hat{q}_2^B). \end{aligned}$$

Next, we determine the subgame-perfect Nash equilibrium. For time $t = 1$ decisions, the firm chooses its second-period production by taking into account the amount that remains in stock so that the marginal costs equal the marginal revenues. Its decision can be separated from its degree of risk aversion (α does not enter Equation (9)):

$$\mathrm{E}[\tilde{\varepsilon}_2] - 2(q_2^A + \check{q}_1^A - s_1^A) + (q_2^B + \check{q}_1^B - s^B) = 1. \tag{9}$$

Moreover, the amount in stock immediately relates to the amount to be sold on the spot market in $t = 1$. The firm chooses the amount to be sold on the spot market in $t = 1$ to smooth marginal revenues over time: The realized marginal revenues from period one equal the marginal revenues in the second period, corrected for storage costs and adjusted with respect to the risk management decision taken in $t = 0$:

$$\begin{aligned} \varepsilon_1 - (2s_1^A + s_1^B) + \check{h}_1^A &= \varepsilon_1 - 2(q_2^A + \check{q}_1^A - s_1^A) + (q_2^B + \check{q}_1^B - s_1^B) - 0.25 \\ &= 1 - 0.25 = 0.75. \end{aligned} \tag{10}$$

The first part of the left-hand side of the equation denotes the marginal revenues from the spot sales in $t = 1$, while the second part of the left-hand side ($\check{h}_1^A$) denotes the marginal revenues from the hedging decision that was made in $t = 0$ and is executed in $t = 1$. The right-hand side of the equation denotes marginal revenues from the sales in $t = 2$, adjusted for costs resulting from the shift of sales (costs for storage = 0.25). Due to the additional production opportunity and the hedging decision that is made in $t = 1$, the marginal revenues from sales in $t = 2$ equate to the marginal costs from production (see Equation (9)). As a result of the risk-sharing markets, the decision is independent of the degree of risk aversion of the firm, α. Additionally, Equation (10) indicates that the optimal sales decision is influenced by the hedging decision ($\check{h}_1^A$) that is made in $t = 0$, which highlights the strategic effect of the hedging opportunity.[12]

In $t = 1$, the uncertain demand from the first period is realized, which determines the current spot price. Also, the forward price for the second-period hedging choice—which firms make now and will be manifested in $t = 2$—is known. Hence, the firm can set its supply for both periods in a certainty-like situation. The optimal forward position in $t = 1$ can be determined in accordance with the full-hedge theorem: The firm sells its entire stock and additional production forward in $t = 1$:

$$h_2^{A*} = q_2^A + \check{q}_1^A - s_1^A \tag{11}$$

As a result, profits in $t = 2$ are deterministic.

The competition for both periods takes place at the same time and follows the basic rules known from Cournot duopoly: If the competitor increases its supply by one unit, the firm reacts by decreasing its own supply by 1/2. The equilibrium corresponds to the equilibrium from the one-shot Cournot duopoly under certainty.

The ability to take the realized spot price into account crucially depends on the ability to store the good. Due to the storage option, the produced quantity and the supplied quantity may differ. Thus, the decision for the sales on the spot market can be made when the spot price is known. Clearly, this is not possible without the possibility to store the production good.

The amount of additional production,

$$q_2^A(\check{q}_1^A, \check{h}_1^A, \check{h}_1^B) \quad = \quad \frac{\mathrm{E}[\varepsilon_2] - 1}{3} - (\check{q}_1^A - s_1^A) \tag{12}$$

[12]Note that Equation (10) is equivalent to Equation (4) from the Single Production setting in Section 4.1.

reflects the quantity that is known from the single-shot game corrected for stored goods. We obtain the well known example from game theory: In a repeated game the result of the final interaction corresponds to the result of the single-shot game (see, e.g., Vives, 1999).

Turning to the influence of the hedging decision on sales, we observe that hedging increases competition as it does in the Single Production setting: As firms increase their hedging position (= larger short position), the supply on the spot market increases due to the strategic impact of the hedging device. As a result, spot prices decrease.

The main decisions in $t = 1$ remain unchanged, as the firm smooths its marginal revenues over time—depending on its time preferences and storage costs. However, the firm can now adjust marginal revenues for the second period to marginal costs for the second period due to the ability to adjust production. This ability increases competition, as the second-period interaction effectively occurs under certainty.

Turning to the decision process in $t = 0$, we again observe that the firm cannot separate real and financial decisions. The firm chooses its initial production according to its intended sales. Intended sales are set in an effort to equate marginal revenue and marginal costs as the subsequent decision in $t = 1$ essentially takes place under certainty. Hence, firms do not use the option to take storage to be able to react to high demand realizations. However, ex post excess production can happen: If the realization of demand is not as expected but below the expected amount, firms react by putting current production into storage and decreasing their current supply.

With respect to the initial hedging decision, the strategic impact of the hedging component on competition in $t = 1$ again comes into play. Firms compete via their risk management decision, and thus account for the strategic impact of their hedging decision. The optimal hedging choice equals expected spot sales in $t = 1$ corrected for the impact on competition. The magnitude of correction depends on risk aversion and price risk. Thus, in $t = 0$, decision makers will choose an underhedge.

Hence, forward markets increase competition in oligopolistic markets in two ways: First, the decision maker is able to deal with uncertainty via forward markets which in itself increases the industry supply. The industry supply equals the industry supply under certainty. Second, the strategic impact and the fact that the first-period forward price is agreed on in $t = 0$ and does not react to the increased supply, reduces the gain from restricting the spot-market output and thus increases industry supply even further (see also Wolak and McRae, 2009).

Last, we compare the Double Production setting with the Single Production setting: The main difference between the settings is the firms' access to risk-sharing markets to manage the risk exposure for their supply in $t = 2$. In the Single Production setting firms' supply in $t = 2$ depends on their initial production decision, which they have to set in $t = 0$ without having access to risk-sharing markets for both periods. Firms can manage the risk exposure of sales made in $t = 1$; however, forward contracts with maturity in $t = 2$ become available only in $t = 1$. In the Double Production setting, however, firms can decide on their supply in $t = 2$ when setting their second-period production in $t = 1$, while having access to forward contracts to manage the risk exposure immediately. Hence, firms do not have to rely on initial production (from $t = 0$) to supply the market in $t = 2$. As a result, second-period supply will be larger in Double Production and the market will be more competitive. As firms equate marginal revenues in $t = 1$ with marginal revenues in $t = 0$ in both settings, the first-period spot market is more competitive in the Double Production setting as well, which is a result of the additional production decision's being detached from demand uncertainty.

To summarize, we hypothesize that

1b. Firms will make their sales decision in an effort to smooth marginal revenues over periods. They will aim for the marginal revenues of the first period to equal the marginal revenues of the second period, adjusted for storage costs.

2b. Sales decisions are independent of the degree of risk aversion. The existence of a forward market allows firms to separate their sales decision in the first period from their risk preferences.

3b. Firms consider previous hedging choices when making sales decisions. Firms' spot sales in $t = 1$ increase in their own first-period hedging choice with a marginal effect of $+2/3$, while spot sales in $t = 1$ decrease in the first-period hedging choice of the competitor with a marginal effect of $-1/3$ (see Appendix A, Equation (23)).

4b. In the second period, firms will sell their entire production that has been taken into storage and the additional production on the forward market: Firms will take a full hedge. Their hedging decision is independent from their risk aversion.

5b. In the first period, firms will take a hedging position that depends on their risk aversion and is smaller than their expected sales: Firms will choose an underhedge.

6. Spot sales in $t = 1$ in the Double Production setting will be larger than in the Single Production setting.

Table 1 summarizes the definitions of the decision variables and the other variables that are used in our study. Table 2 summarizes the treatments.

Table 1: Variable definitions

Variable	Variable name	Definition
q_1	quantity	quantity produced in the first period, decision in $t = 0$.
q_2	quantity2	quantity produced in the second period, decision in $t = 1$.
	otherquantity	quantity produced by the competitor in the first period, decision in $t = 0$.
s_1	spot sales1	quantity of sales in the first period, decision in $t = 1$.
s_2	spot sales2	quantity available for sale in the second period, immediately follows from decision in $t = 1$.
h_1	hedging1	quantity hedged in the first period, decision in $t = 0$.
h_2	hedging2	quantity hedged in the second period, decision in $t = 1$.
	otherhedging1	quantity hedged by the competitor in the first period, decision in $t = 0$.
	otherhedging2	quantity hedged by the competitor in the second period, decision in $t = 1$.
	highstate	indicator equal to one if the high demand realization occurs in the first period, zero otherwise.
	safechoices	number (from 0 to 10) of choices in the risk assessment where the subject chose the less risky option.
	round	number (from 0 to 20) of the current round of the experiment.
	riskconsist	indicator equal to one if choices in the risk assessment are consistent with transitivity, zero otherwise.
	gender	indicator equal to one if the player is a male, zero otherwise.
	major	indicator equal to one if the player field of study is Finance, Accounting or Economics, zero otherwise.

Table 2: Treatment Summary

Treatment	Sessions	Subjects	Production Opportunities	Demand States $t = 1$	Demand States $t = 2$ (Low)	Demand States $t = 2$ (High)	Unit Cost Parameters Production	Unit Cost Parameters Storage
Single Production	4	52	1	{40, 60}	{30, 50}	{50, 70}	1	0.25
Double Production	4	48	2	{40, 60}	{30, 50}	{50, 70}	1	0.25

Table 3 shows ex ante expected equilibrium choices by treatment. We derive expected equilibrium choices in Appendix A with the use of the average risk aversion that is elicited with the use of the Holt and Laury (2002) lottery choice procedure. Equilibrium choices within the experiment can differ from reported values due to the influence of the random demand variable and the subgame-path of the current game. We report equilibrium values for second-period choices given the subgame-path in squared brackets.

Table 3: Expected equilibrium values and summary statistics

The table presents expected equilibrium values in $t = 0$ and summary statistics. Expected equilibrium values are calculated using the average risk aversion of our participants elicited using a lottery choice procedure from Holt and Laury (2002). The median number of "safe" choices is six, which is consistent with $\alpha \approx 0.15$. Variable definitions can be found in Table 1. We present equilibrium values and summary statistics for Single Production and for Double Production, separately. Expected equilibrium values given participants' subgame-path are reported in squared brackets. In addition, we present equilibrium choices for the Single Production setting under risk neutrality/certainty. Standard deviations are reported in parentheses.

	Single Production				Double Production			
	Expected equilibrium		Summary statistics		Expected equilibrium		Summary statistics	
	($\alpha = 0.15$)	($\alpha = 0$)	(20 rounds)	(Rounds 15-20)	($\alpha = 0.15$)	($\alpha = 0$)	(20 rounds)	(Rounds 15-20)
quantity	6.47	32.58	34.742	34.178	23.89	16.33	25.755	24.086
			(0.835)	(0.921)			(0.852)	(1.024)
quantity2					16.33	16.33	15.744	13.162
					[9.20]	[9.20]	(0.919)	(1.164)
spot sales1	3.91	16.34	20.494	19.630	23.89	16.33	17.668	17.556
	[20.07]	[20.07]	(0.804)	(0.871)	[18.63]	[18.63]	(0.729)	(0.767)
spot sales2	2.56	16.24	14.25	14.55	16.33	16.33	23.83	19.69
	[14.67]	[14.67]	(0.256)	(0.408)	[16.33]	[16.33]	(0.466)	(0.736)
hedging1	3.80	0.05	15.932	15.069	22.42	0	18.263	17.546
			(0.916)	(1.136)			(1.295)	(1.584)
hedging2	2.56	-	16.808	15.599	16.33	-	17.294	16.180
	[14.67]	[-]	(0.897)	(0.985)	[16.33]	[-]	(1.010)	(1.118)
price1	42.18	17.32	10.497	11.681	2.22	17.34	15.640	15.043
			(0.588)	(0.898)			(0.532)	(0.763)
price2	44.88	17.52	22.071	22.122	17.34	17.34	11.237	14.853
			(0.748)	(1.061)			(0.425)	(0.959)
profit	272.71	530.89	347.731	354.717	295.98	533.66	347.308	386.088
			(8.763)	(19.801)			(19.689)	(34.413)

The equilibrium values emphasize our hypotheses of an underhedge in the first period (hedging1 < expected spot sales1) and a full hedge in the second period (Single Production: hedging2 = quantity - spot sales1; Double Production: hedging2 = quantity2). The impact of the hedging opportunity on competition is highlighted by the differences in quantities between the first and second period of Double Production. Finally, Double Production significantly increases competition, and we observe large expected sales in $t = 1$ and consequently a very low price, which is explained by the strategic aspect of the hedging opportunity: Firms compete via the forward and the spot market, thereby yielding low prices. For the second period, the additional production decision allows firms to decide on the market supply in $t = 2$ in a certainty-like situation—again increasing competition.

We also report equilibrium values for risk-neutral decision makers. The difference between risk-neutral and risk-averse decision makers is quite large in our setting due to the large variance of demand uncertainty. Note that the case of risk-neutral decision makers ($\alpha^A = 0$) is equivalent to the case under certainty. Thus, in this case the variance of demand uncertainty does not influence the equilibrium. We decided to use a large variance in our experimental setup in order to generate a noticeable effect on participants' payoffs.

Also note that in the Single Production model, in equilibrium firms also make use of the hedging device in the first period in the case of risk-neutral decision makers due to the strategic application of the hedging device. Absent a risk management motive, the hedging decision in this case only reflects the strategic signal to competitors. In the second period, the hedging device can be used only for risk management purposes; thus, risk-neutral decision makers are indifferent with respect to their hedging2 choice.

We show the risk-neutral case in the Double Production model only for completeness. In this setting, the decision problem collapses to a corner solution and yields the repeated single-shot duopoly.

5 Experimental Design

Both treatments—Single Production (Section 4.1) and Double Production (Section 4.2)—were implemented using z-Tree software (Fischbacher, 2007).[13] Treatments were varied between subjects.

[13] This study is registered in the AEA RCT Registry (unique identifying number: AEARCTR-0003940), and full experimental instructions are available at http://www.socialscienceregistry.org/trials/3940. The experimental data

Table 2 summarizes the treatments. All sessions were run at Durham University in Autumn 2015. Subjects were recruited using ORSEE (Greiner, 2015). Eight sessions were conducted in total, each with an even number of subjects (between 10 and 16), for a total of 100 subjects. On average, subjects earned approximately £14 each. Sessions lasted approximately 1 hour 45 minutes, on average.

In both treatments, subjects were randomly and anonymously matched into pairs of two at the start of each of 20 rounds (Strangers matching).[14] At the end of the experiment, two of these 20 rounds were randomly selected for payment. We use random, anonymous re-matching across rounds to allow subjects to learn about the decision environment while minimizing the possibility of collusive strategies or other repeated game effects, as is common practice in many laboratory experiments (see, e.g. Andreoni and Croson, 2008; Ferreira et al., 2016). While there is a positive probability of random re-matching with a previous rival, subjects do not see any identifiers of rivals on which to condition behavior. As our equilibrium benchmarks and hypotheses are based on one-shot interaction in each round, this feature is important for our design.[15]

Following the design of the decision problem, in the Single Production treatment, each round was divided into three stages. In the first stage, each subject chose a production quantity and a forward market position. In addition to their own choices, subject could make guesses about the choices of the other player. Since the game is complex, we provided a projection calculator tool to help subjects understand the game structure and incentives.[16] Projections of the calculator tool were based on own-production and the hedging choices of subjects and on guesses that the subjects made about the same decision variables that wouldbe chosen by the other player. Based on these choices and guesses, subjects were shown projections of expected spot and forward prices and profits and standard deviations of profits. Subjects could adjust their choices and guesses using sliders to see how projected prices, profits, and standard deviations changed. Figure 4 shows a screenshot of the decision screen and the calculator tool.

supporting this study are available from the corresponding author upon request.

[14] Due to a computer crash, one session had only 19 rounds.

[15] As will be discussed in our regression results in the next section, we find no significant correlation between current decisions and lagged feedback on the decisions of previous rival players.

[16] This approach has been used to aid subject understanding in many other experimental studies of complicated strategic environments (e.g. Durham et al., 2004; Healy, 2006; McIntosh et al., 2007; Gächter and Thöni, 2010; Van Essen, 2012; Van Essen et al., 2012).

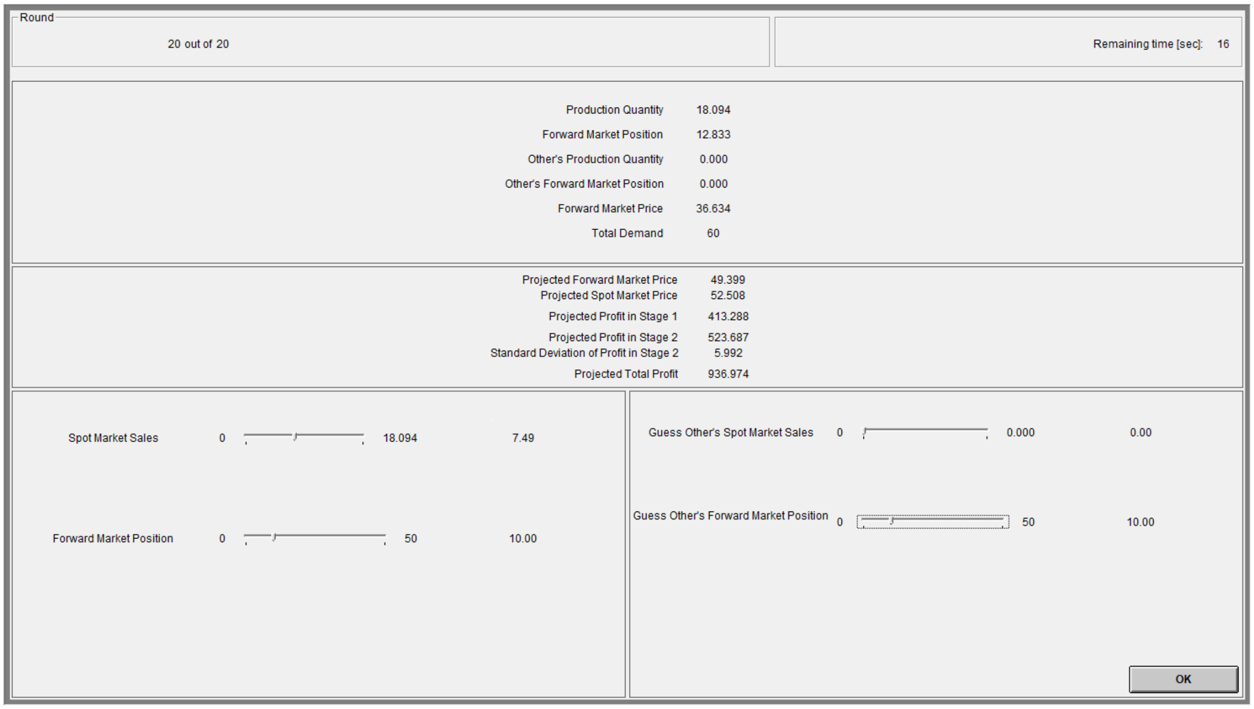


Figure 4: The screenshot shows the decision screen and calculator tool. Subjects can enter their choices and guesses about the choices of the other player and are shown projections of expected prices and profits, as well as standard deviations of profits.

In the second stage, each subject learned the outcome of the first stage, and then chose spot market sales and another forward market position. Subjects could again make guesses about the choices of the other player in the second stage and study projections of expected prices and profits, as well as standard deviations of profits, before finalizing their choices. In the third stage, subjects learned the final outcome of the round, including profits earned (denominated in pence) based on the decisions made and realized demand, as shown in Equations (2) and (3).

In the Double Production treatment, each round was also divided into three stages. The first stage was similar to the first stage of the Single Production treatment. However, in the second stage of the Double Production treatment, subjects chose an additional production quantity in addition to spot market sales and a forward market position. Subjects could also make guesses about the additional production, spot-market sales, and forward market position of the other player. As in the Single Production treatment, subjects had a calculator tool that showed projections of expected prices and profits and standard deviations of profits based on their choices and guesses about the other player in the first and second stages. In the third stage, similar to the Single Production treatment, subjects learned the final outcome of the round, including profits earned, as shown in Equations (2) and (6).

At the end of the experiment, subjects learned which two rounds were selected randomly for payment. Subjects' risk preferences were elicited using a lottery choice procedure from Holt and Laury (2002). Subjects also answered a brief demographic survey. At the end of the session, each subject was paid privately in cash their profits from the two randomly-selected rounds and the risk elicitation task.

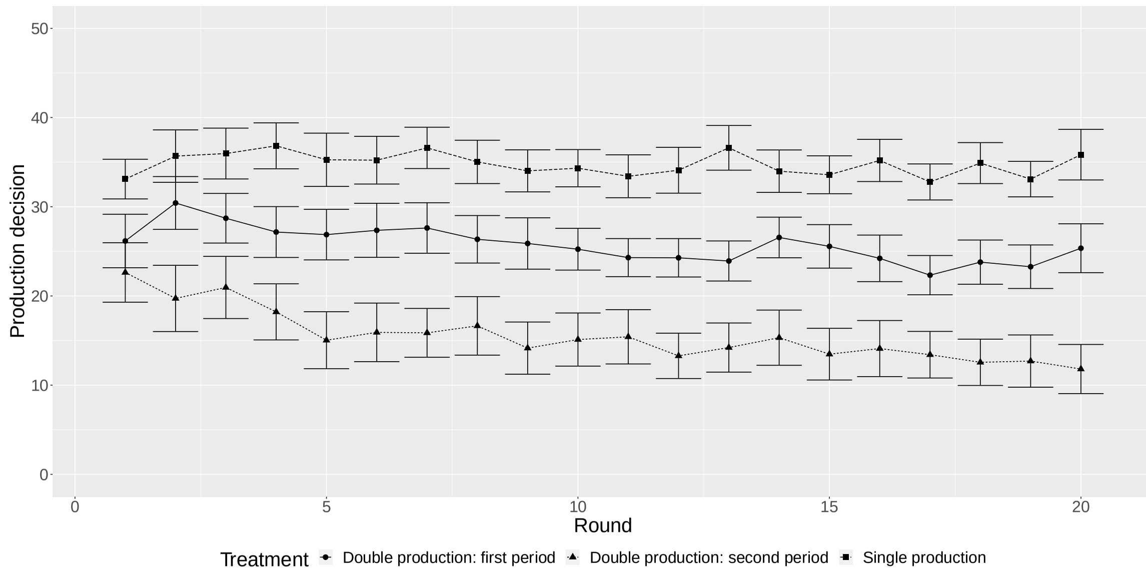
6 Experimental Results

To test our hypotheses, we run a number of paired block-bootstrap *t*-tests on sales, hedging, and production decisions in the low and high demand states.[17] Furthermore, we use a multilevel panel model to regress the variable of interest—spot sales1, first-period hedging, second-period hedging—on variables that should matter based on our predictions: risk aversion, the opportunity for additional production, and the state demand. We provide results for the data that were collected from the 20 rounds, and also the results from rounds 15-20 when subjects have gained some experience.

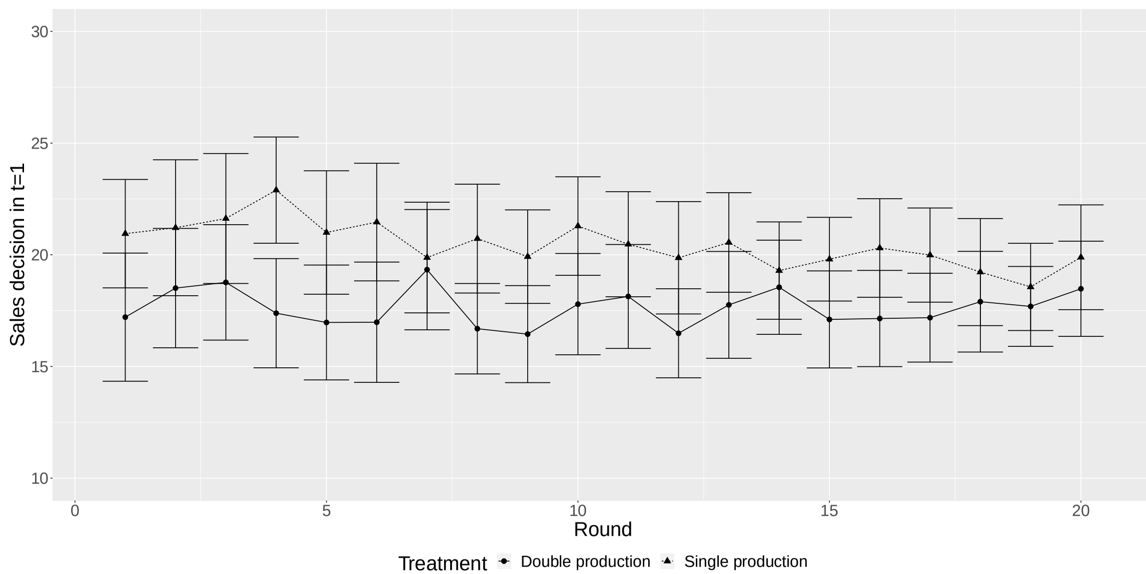
Figure 5 shows the path of average production and sales decisions while Figure 6 shows the path of average hedging decisions in the first and second period. Overall, average decisions appear to be fairly stable across rounds. Some decision variables show a trend in early rounds—such as second-period production in Double Production and first-period hedging in Single Production. However, these decisions appear to stabilize in later rounds. In particular, the generally stable path of average production is similar to the results that are found in Schubert (2015).

Finally, Figure 7 shows the path of average spot and forward prices across rounds. As intended by the model setup, forward and spot prices for the same period are largely consistent and statistically indistinguishable. Moreover, first-period spot and forward prices are below the standard Cournot level, which indicates stronger competition. Double Production prices are slightly higher than Single Production prices in the first period. Second-period spot and forward prices indicate some learning

[17]To account for correlation between observations within a session, we use block-bootstrap *t*-tests, re-sampling at the session level (Fréchette, 2012; Moffatt, 2016).

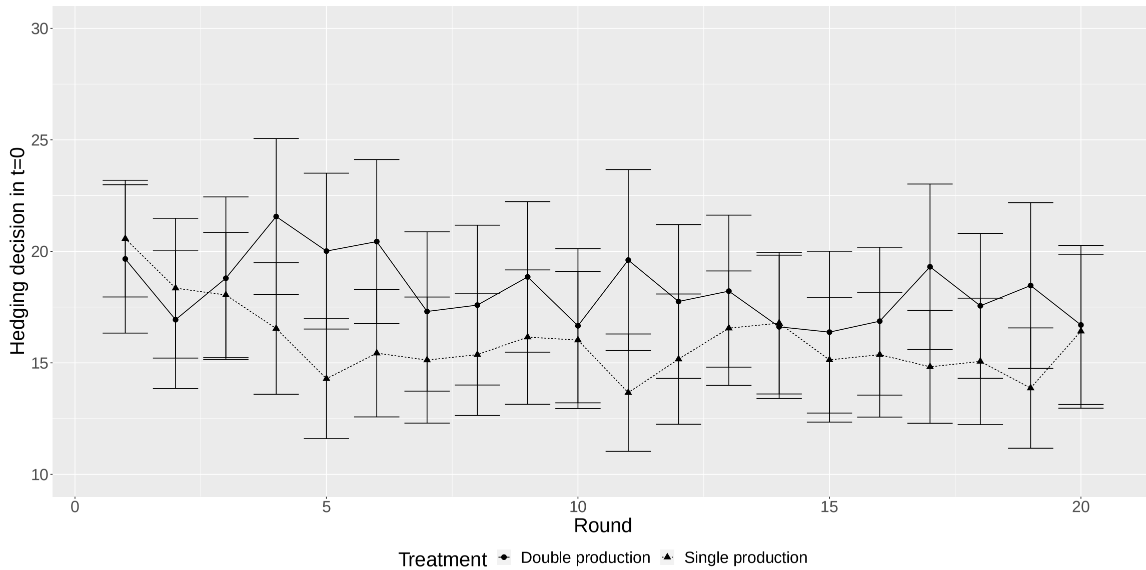


(a) Production decisions

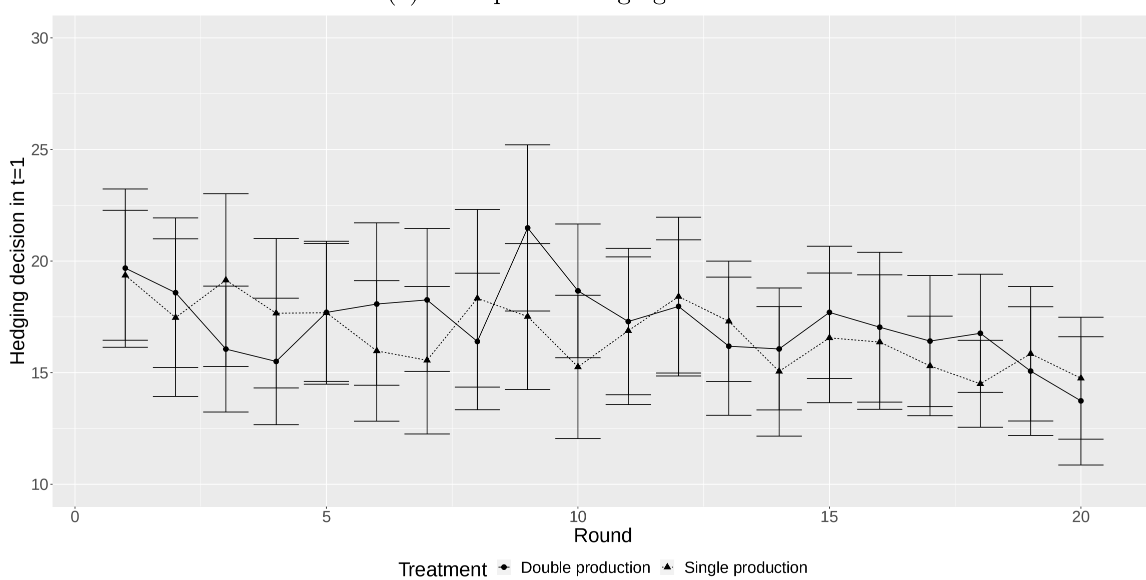


(b) First-period sales decisions

Figure 5: Evolution of production and first-period sales decision over rounds (with 95% confidence intervals).

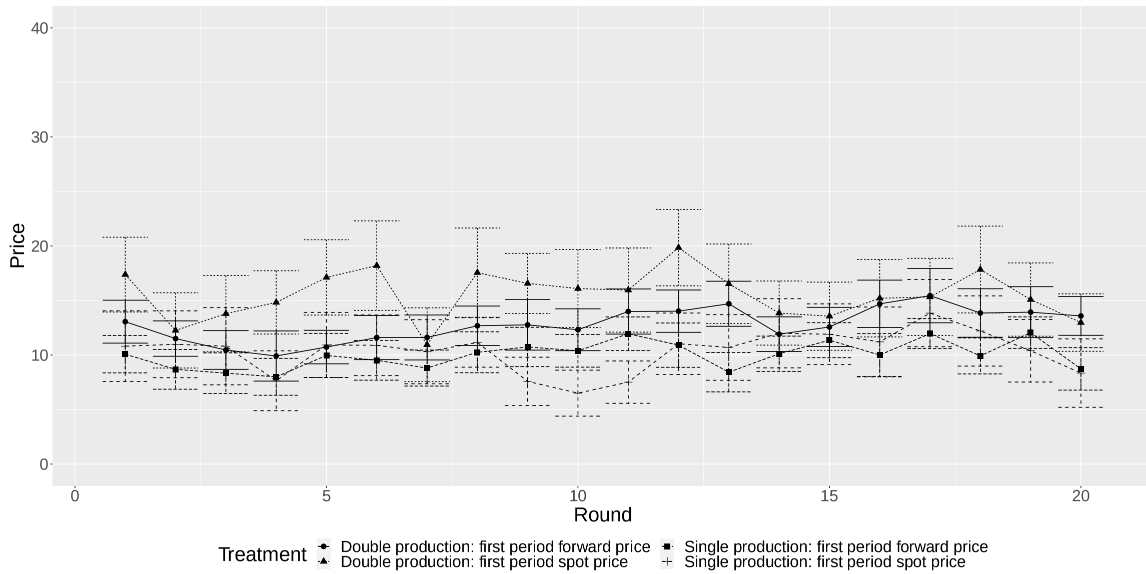


(a) First-period hedging decisions

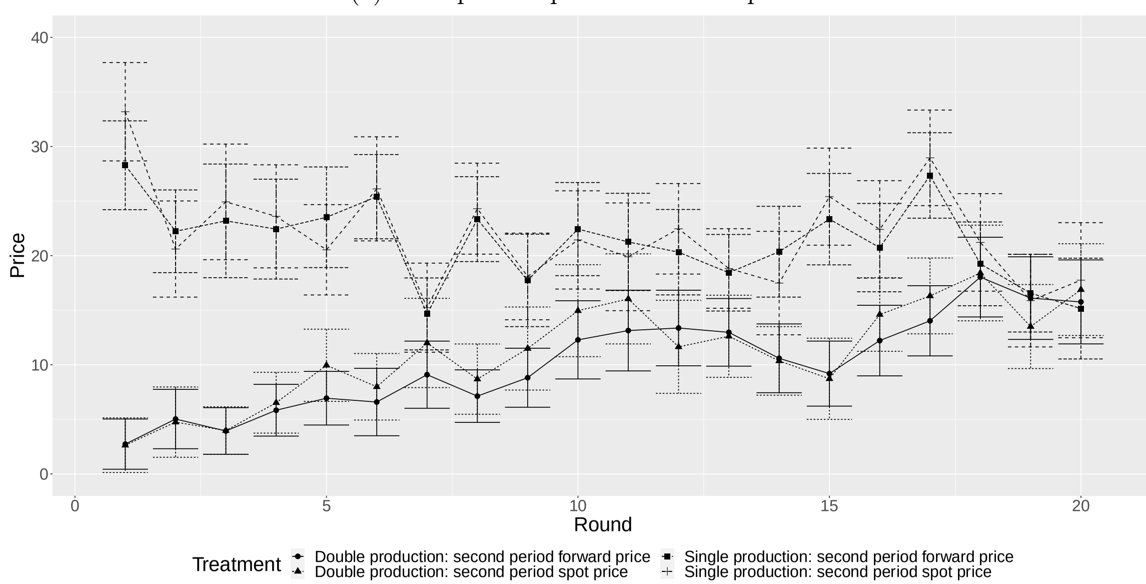


(b) Second-period hedging decisions

Figure 6: Evolution of hedging decision over rounds (with 95% confidence intervals).



(a) First-period spot and forward prices



(b) Second-period spot and forward prices

Figure 7: Evolution of prices over rounds (with 95% confidence intervals).

by participants—specifically for Double Production. Here, prices slowly increase over rounds and converge to the price levels of Single Production in later rounds.

Summary statistics are reported in Table 3. We capture the data for each player and each round, and then take the averages across players for Single Production and for Double Production, separately. Standard deviations of these averages within each round across player are low, which suggests that there is consistency in players' decisions. Almost 53% of players were in finance and economics, and 32% of players were male (demographic summary statistics are omitted from Table 3). We do not observe a significant difference in the behavior of players by gender or by course of study.

Comparing the summary statistics with equilibrium choices, we note that especially in the Single Production model, choices are much larger than anticipated. More precisely, average choices do not seem to be consistent with the risk aversion that is elicited from the Holt and Laury (2002) procedure. Instead, average choices correspond more with the risk-neutrality case (or, equivalently, the case under certainty). This may be explained by a combination of two effects: First, decision makers may weight the demand uncertainty less than appropriate for the given risk aversion or simply underestimate it. In line with this argument, we do not observe statistically significant correlations between subjects' degree of risk aversion and their hedging decisions (see Tables 4 and 5). Second, decision makers may pay less attention to the strategic implications of the hedging decision than is predicted by the model. The higher hedging choice also mitigates the impact of the demand uncertainty, and yields higher production. Given the participants' first-period choices, their spot sales1 decisions are in line with the equilibrium values for the given subgame-path.

Double Production averages are in the neighborhood of expected equilibrium choices for risk aversion. t-tests indicate that the average choices for production and second-period hedging decisions—given the hedging decisions that were made in $t = 1$—are not statistically different from the expected equilibrium choices. However, spot sales1 and first-period hedging decisions are statistically different from the expected equilibrium choices. Spot sales1 are again close to equilibrium values for the relevant subgame-path, given the first-period choices.

We first study decisions in time $t = 1$: We begin with the spot sales1 decision. According to our Hypotheses 1a and 1b, subjects decide on spot sales1 to smooth marginal revenues over periods. This reflects the risk-mitigating impact of hedging, as subjects should be less sensitive to price changes given that the forward price is fixed. To test this prediction, we compute the marginal revenues that are implied by the subjects' decisions in both periods. To reduce the likelihood that the results reflect the subjects' unfamiliarity with the strategic forces that they face, we provide results for all 20 rounds and also for rounds 15-20. We cannot reject the null hypothesis that the marginal revenues are equal in both periods in high demand realizations.

However, when demand is low, subjects choose to sell in a way such that the marginal revenues of the first period are significantly higher than the marginal revenues of the second period. The explanation is that production was too high for the low state demand. Therefore, subjects made their decisions such that the first-period marginal revenue was zero—which we cannot reject from a one tailed t-test ($p = 0.978$)—and then sold the remaining quantity in the second period at (possibly) negative marginal revenue.

Results from regressing spot sales1 on theoretically important variables are reported in Table 4.[18] We regress spot sales1 on the players' own quantity produced and own hedging in the first period as well as on the quantity produced and the hedging of their competitors. Consistent with Hypotheses 2a and 2b, "safechoices" is not significantly correlated with spot sales1, in either model.

To study Hypotheses 3a and 3b and the strategic impact of the hedging choice on sales, we examine whether spot sales1 increase with players' own hedging and decrease with their opponent's hedging. Own first-period hedging is significantly positive, but only in Single Production. Moreover, the coefficient is much smaller than the expected value (+1/3). Also, the results in Table 4 suggest that the coefficients on competitors' hedging are not significant. Finally, according to Hypothesis 6, sales decisions should be significantly larger for Double Production. Our results support this hypothesis.

With respect to the hedging decisions in $t = 1$: According to Hypotheses 4a and 4b, subjects should employ a full hedge in the second period to ensure deterministic profits in the final stage. To test this prediction, we examine the statistical significance of the difference between the second-period hedging (set in $t = 1$) and the quantity that is available to sell in the final stage. The results for the

[18] We use multilevel Tobit models to account for the bounds on the decision variables (between 0 and 50) with random effects at the individual and session levels to control for correlation within individuals and within sessions (Fréchette, 2012; Moffatt, 2016). To examine whether current decisions are correlated with previously observed feedback, we also ran models that are similar to Models (1) and (2) in Tables 4, 5, and 6 including controls for the lagged decisions of the other player in the previous round. We found no significant correlations, and chose to omit these results for brevity. We also tried alternative specifications using the log of round or round fixed effects, and we found very similar results to those presented in Tables 4, 5, and 6.

Table 4: Spot Sales1 Multilevel Tobit Regressions

Models 1-2 report the results from all 20 rounds, whereas Models 3-4 report the results from only rounds 15-20. Models 1 and 3 are restricted to the Single Production model, and Models 2 and 4 are restricted to the Double Production model. Variable definitions can be found in Table 1. All models include random effects at the individual and session levels.

	(1)	(2)	(3)	(4)
quantity	0.523***	0.547***	0.473***	0.559***
	(0.0287)	(0.0259)	(0.0526)	(0.0424)
otherquantity	-0.0530*	0.0128	0.0511	-0.00653
	(0.0230)	(0.0216)	(0.0394)	(0.0328)
hedging1	0.0799***	0.00666	0.0957*	0.0215
	(0.0241)	(0.0210)	(0.0408)	(0.0334)
otherhedging1	0.00958	0.0230	0.0217	0.0250
	(0.0198)	(0.0163)	(0.0315)	(0.0234)
highstate	2.616***	2.281***	1.663**	2.743***
	(0.409)	(0.392)	(0.633)	(0.582)
safechoices	-0.261	-0.0608	-0.673	-0.218
	(0.344)	(0.210)	(0.365)	(0.231)
round	-0.0707*	0.131***	-0.195	0.252
	(0.0354)	(0.0346)	(0.175)	(0.157)
riskconsist	1.229	-1.116	1.298	-0.742
	(1.430)	(1.184)	(1.511)	(1.312)
gender	-0.143	-0.395	0.440	0.309
	(1.152)	(1.111)	(1.222)	(1.219)
major	-1.160	0.912	0.235	0.741
	(1.118)	(0.993)	(1.173)	(1.105)
constant	3.311	0.808	5.364	-1.168
	(2.584)	(2.008)	(4.591)	(3.558)
Observations	1030	960	302	288

Standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Second-Period Hedging Multilevel Tobit Regressions

Models 1-2 report the results from all 20 rounds, whereas Models 3-4 report the results from only rounds 15-20. Models 1 and 3 are restricted to the Single Production model, and Models 2 and 4 are restricted to the Double Production model. Variable definitions can be found in Table 1. All models include random effects at the individual and session levels.

	(1)	(2)	(3)	(4)
quantity	0.232***	0.0434	0.156	-0.000503
	(0.0498)	(0.0436)	(0.0830)	(0.0777)
quantity2		0.147***		0.298***
		(0.0351)		(0.0686)
otherquantity	0.0816*	-0.00593	0.0942	0.0747
	(0.0406)	(0.0353)	(0.0634)	(0.0586)
otherhedging1	-0.0141	0.0217	-0.0982	0.160***
	(0.0348)	(0.0268)	(0.0507)	(0.0415)
highstate	-1.803*	-1.599*	-1.115	-2.587*
	(0.719)	(0.667)	(1.016)	(1.101)
safechoices	-0.750	0.493	-0.311	0.592
	(0.684)	(0.465)	(0.725)	(0.507)
round	-0.183**	-0.0688	-0.542	-0.573*
	(0.0617)	(0.0583)	(0.279)	(0.279)
riskconsist	0.0653	-2.572	-0.316	-3.387
	(2.839)	(2.617)	(2.849)	(2.839)
gender	-4.767*	1.533	-4.967*	-0.373
	(2.289)	(2.469)	(2.343)	(2.717)
major	-5.478*	4.575*	-4.953*	6.030*
	(2.231)	(2.196)	(2.266)	(2.403)
constant	16.14**	10.85**	23.48**	14.18*
	(4.930)	(4.093)	(7.733)	(6.795)
Observations	1030	960	302	288

Standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: First-Period Hedging Multilevel Tobit Regressions

Models 1-2 report the results from all 20 rounds, whereas Models 3-4 report the results from only rounds 15-20. Models 1 and 3 are restricted to the Single Production model, and Models 2 and 4 are restricted to the Double Production model. Variable definitions can be found in Table 1. All models include random effects at the individual and session levels.

	(1)	(2)	(3)	(4)
quantity	0.267***	-0.170***	0.438***	-0.336***
	(0.0412)	(0.0435)	(0.0791)	(0.0733)
safechoices	0.254	0.788	0.481	1.086
	(0.655)	(0.739)	(0.799)	(0.913)
round	-0.163**	-0.175**	-0.0933	0.154
	(0.0502)	(0.0562)	(0.251)	(0.239)
riskconsist	-3.795	-5.583	-4.569	-6.644
	(2.717)	(4.159)	(3.322)	(5.123)
gender	-6.338**	-0.338	-5.736*	0.106
	(2.186)	(3.923)	(2.677)	(4.848)
major	0.311	4.019	-0.133	5.090
	(2.127)	(3.489)	(2.592)	(4.307)
constant	11.47**	21.83***	3.996	18.56*
	(4.357)	(5.984)	(7.131)	(8.485)
Observations	1030	960	302	288

Standard errors in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

full sample suggest that there is an under hedge, as the difference is statistically negative. When we consider rounds 15-20, however, the results suggest that we cannot reject the null hypothesis: subjects tend to hedge fully for the Single Production setting (p-value is 0.486), but we still reject the null hypothesis for the Double Production setting.

In our regression analysis, we test whether the second-period hedging decision is independent of the risk aversion of the players. The results that are reported in Table 5 suggest that own-hedging in the second period is indeed independent of the risk aversion of subjects—as expected. Moreover, the table shows that, naturally, the hedging amount increases with the quantities that are produced in the two periods and decreases with the demand realization of the first period (since firms sell more of their first-period production on the spot market in this case). Our results also indicate that male decision makers hedge less in the Single production model.

Next, we turn to first-period hedging decisions: According to Hypotheses 5a and 5b, the initial hedging decision should be an underhedge. This means that we should observe an initial hedging decision that is smaller than expected sales. To test the hypotheses, we calculate the expected sales of participants that would result in equilibrium based on their production quantity and initial hedging choice as well as their guesses as to their competitors' choices. Then, we compare the expected sales with their hedging decision.

For Single Production, average first-period hedging (15.93, Table 3) is significantly smaller than expected spot sales1 (19.61; t-statistic of 9.73). Similarly, average first-period hedging in Double Production (18.26, Table 3) is significantly smaller than expected spot sales1 (19.42; t-statistic of 2.64). Thus, we observe a significant underhedge, which suggests that players do take into account the strategic impact of their first-period hedging decision.

Finally, we provide regression analyses on the own first-period hedging. Surprisingly, the results that are reported in Table 6 suggest that own-hedging in the first period is not correlated with the risk-aversion coefficients, even when we consider rounds 15-20 only. Similar to the second-period hedging choice, we observe a tendency of males to hedge less than females—though this difference is not always statistically significant. Lastly, we find that individuals reduce their first-period hedging decisions in later rounds, on average, as indicated by the negative coefficients on round in Models 1 and 2. This finding supports the notion of a small trend in early rounds observed in Figure 6.

7 Conclusion

In this paper, we experimentally investigate the influence of a simultaneous hedging opportunity on firm choices and competition in incomplete markets. In markets with imperfect competition, the risk management hedging opportunity introduces a strategic dilemma for competitors: Corporate hedging increases the competitiveness in the market; but the hedging opportunity also allows producers to deal with their risk exposure. Consequently, firms must weigh the advantages of being able to hedge their risk exposure against the disadvantages of more intense competition.

We consider a multi-period duopoly under demand uncertainty with a hedging opportunity and the possibility of storage in a simple framework with (μ, σ)-preferences. Our setting yields the following hypotheses: Duopoly firms consider the impact of their hedging choice on the market equilibrium and are thus willing to take a risky position to mitigate the adverse effect of the hedging actions on market prices. The simultaneous hedging opportunity should increase competition.

Our experimental results support the hypotheses: We find that subjects appear to be aware of the strategic effect of the hedging device, and thus reduce their own first-period hedging to an underhedge and adjust their spot sales in $t = 1$ according to their hedging choice. However, we do not find evidence that subjects account for their competitors' financial decisions when making their own quantity supply decisions. Moreover, as the game is closer to a simple repetition of the single-shot game in Double Production, competition increases to a level that completely negates duopoly profits. Hence, we find strong evidence that the hedging opportunity significantly increases competition—even in a simultaneous setting.

These results supplement the literature that provides evidence of a strategic dilemma that is introduced by a hedging opportunity in a sequential setting (Allaz, 1992; Allaz and Vila, 1993). We also supplement the findings by Brandts et al. (2008) who document that, in absence of risk and a strategic dilemma, the introduction of a forward market significantly increases competition in the market. Moreover, our results are related to the observations of Mueller (2006) who finds that the behavior of players in a Cournot duopoly with multiple production periods does not differ significantly from standard one-period markets—in contrast to theoretical predictions. In our Double Production treatment, first-period choices are significantly larger than in the one-period interaction—due to the strategic effect of the hedging opportunity.

Acknowledgements

This work was supported by the DUBS Seedcorn Fund from Durham University. We are grateful for comments from editor Lawrence J. White and two anonymous referees, as well as Udo Broll, Jack Wahl, Bernhard Ganglmair, and participants of the 2014 Cambridge Business & Economics Conference, the Experimental Finance North American Finance Meeting 2016, and the 2017 AEA Annual Meeting in Chicago. A previous version of this paper was circulated under the title "Strategic corporate hedging". We thank Minh-Lý Liêu and Sonja Warkulat for outstanding research support. Matthias Pelster gratefully acknowledges the warm hospitality of the Durham University Business School during his visits. Any errors, misrepresentations, and omissions are our own.

A Expected Equilibrium Values: Numerical Example

This appendix derives the equilibrium values that are shown in Table 3.

A.1 Single Production setting

We begin with the Single Production setting (see Section 4.1). First, we derive second-period choices. We present mathematical representations for firm A. As the duopoly is symmetric, similar representations apply for firm B. At this point in the model, all decisions from the first period, the realization of the demand uncertainty of the first period, and the forward rate for the second period are common knowledge. Thus, firms maximize

$$\Phi_L^A = \underbrace{(50-(s_1^A+s_1^B))s_1^A}_{\text{revenues from sales in } t=1} - \underbrace{q_1^A}_{\text{fixed production costs}} + \underbrace{\check{h}_1^A(f(0,1)-(50-(s_1^A+s_1^B)))}_{\text{profits from t=0 hedging position}} - \underbrace{0.25(\check{q}_1^A-s_1^A)}_{\text{storage costs}}$$
$$+\{\underbrace{(50-(\check{q}_1^A+\check{q}_1^B-s_1^A-s_1^B))(\check{q}_1^A-s_1^A)}_{\text{revenues from sales in } t=2} - \frac{\alpha^A}{2}\,200\,(\check{q}_1^A-s_1^A-h_2^A)^2\} \quad (13)$$

by choosing s_1^A and h_2^A. The first-order conditions are

$$50 - (2s_1^A + s_1^B) + \check{h}_1^A + 0.25 + \{-50 + (2\check{q}_1^A + \check{q}_1^B - 2s_1^A - s_1^B) + \alpha^A \ 200 \ (\check{q}_1^A - s_1^A - h_2^A)\} = 0 \quad (14)$$

and

$$\alpha^A \ 200 \ (\check{q}_1^A - s_1^A - h_2^A) = 0. \quad (15)$$

Subtracting these yields Equation (4). The optimal supply decision in $t = 1$ fulfills ($\mathrm{E}[\varepsilon_1] = 50$)

$$50 - (2s_1^A + s_1^B) + \check{h}_1^A = 50 - (2\check{q}_1^A - 2s_1^A + \check{q}_1^B - s_1^B) - 0.25. \quad \text{(4 revisited)}$$

For the second-period hedging decision, the full hedge immediately follows from Equation (15):

$$h_2^A = \check{q}_1^A - s_1^A. \quad (16)$$

Equation (4) yields a system of two equations (firm A and firm B) with six unknowns. Solving for spot-sale decisions, this leads to

$$s_1^A = \frac{1}{24} + \frac{1}{2}\check{q}_1^A + \frac{1}{3}h_1^A - \frac{1}{6}h_1^B. \quad (17)$$

Taking these *future* decisions into account, decision makers initially maximize

$$\Phi_L^A = \underbrace{(50 - \hat{s}_1^A - \hat{s}_1^B) \cdot \hat{s}_1^A}_{\text{revenues from sales in } t=1} - \underbrace{q_1^A}_{\text{production costs}} - \underbrace{0.25(q_1^A - \hat{s}_1^A)}_{\text{storage costs}} - \frac{\alpha^A}{2} 100(\hat{s}_1^A - h_1^A)^2$$
$$+ \{\underbrace{(50 - (q_1^A + q_1^B - \hat{s}_1^A - \hat{s}_1^B))(q_1^A - \hat{s}_1^A)}_{\text{revenues from sales in } t=2} - \frac{\alpha^A}{2}(200(\underbrace{q_1^A - \hat{s}_1^A - \hat{h}_2^A}_{=0,\text{ full hedge}})^2 + 100(\hat{h}_2^A)^2)\}.$$

based on the expectations in time $t = 0$.

Simplified first-order conditions that take second-period choices (that are made in $t = 1$) into account are

$$48.875 - q_1^A - \frac{q_1^B}{2} - 100 \cdot \alpha^A \cdot \left(\frac{3}{4}q_1^A - \frac{1}{48} - \frac{2}{3}h_1^A + \frac{h_1^B}{12}\right) = 0 \quad (18)$$

and

$$\frac{2 \cdot 100}{3} \cdot \alpha^A \cdot \left(\frac{1}{24} + \frac{q_1^A}{2} - \frac{2}{3} h_1^A - \frac{h_1^B}{6} \right) + \frac{1}{72} - \frac{2}{9} h_1^A - \frac{1}{18} h_1^B = 0. \tag{19}$$

This system of four equations (similar equations apply for firm B) with four unknowns (considering that risk aversion is a fixed parameter) yields expected equilibrium choices in $t = 0$.

For $\alpha^A = 0.15$, we obtain

$$q_1^A = q_1^B = 6.47$$

and

$$h_1^A = h_1^B = 3.80.$$

Equation (17) yields resulting spot sales1 in $t = 1$, $s_1^A = s_1^B = 3.91$. Based on the spot-sale decisions, the equilibrium forward price is

$$f(0,1) = 50 - \frac{1}{2}(q_1^A + q_1^B) - \frac{1}{6}(h_1^A + h_1^B) - \frac{1}{3} \cdot 0.25 = 42.18. \tag{5 revisited}$$

Expected prices are given by the inverse demand function,

$$p_1 = 50 - (s_1^A + s_1^B) = 42.18$$

and

$$p_2 = 50 - (q_1^A + q_1^B - s_1^A - s_1^B) = 44.88$$

Finally, expected profits read

$$\begin{aligned} \mathrm{E}[\tilde{\pi}_1^A] &= \mathrm{E}[\tilde{p}_1] s_1^A - q_1^A + h_1^A (f(0,1) - \mathrm{E}[\tilde{p}_1]) - 0.25(q_1^A - s_1^A) \\ &= 42.18 \cdot 3.91 - 6.47 + 0 - 0.25 \cdot (6.47 - 3.91) \text{ and} \\ \mathrm{E}[\tilde{\pi}_2^A] &= \mathrm{E}[p_2](q_1^A - s_1^A) + h_2^A (\tilde{f}(1,2) - \mathrm{E}[\tilde{p}_2]) \\ &= 44.88 \cdot (6.47 - 3.91) + 0 \end{aligned}$$

and consequently

$$\mathrm{E}[\tilde{\pi}^A] = \mathrm{E}[\tilde{\pi}_1^A] + \mathrm{E}[\tilde{\pi}_2^A] = 272.71.$$

For risk-neutral decision makers ($\alpha^A = 0$), the system of equations (18) and (19) simplifies to

$$q_1^A = 48.875 - \frac{q_1^B}{2}$$

and

$$h_1^A = \frac{1}{16} - \frac{1}{4} h_1^B,$$

which yields

$$q_1^A = \frac{2}{3} \cdot 48.875$$

and

$$h_1^A = \frac{3}{60}.$$

Second-period decisions, prices, and profits are obtained in the same manner as above.

A.2 Double Production setting

Next, we turn to the equilibrium values in the Double Production setting (see Section 4.2). We again start with the second-period decision problem. Firms maximize

$$\begin{aligned}\Phi^A = & \underbrace{p(Q_1)s_1^A}_{\text{revenues from sales in } t=1} - \underbrace{\check{q}_1^A}_{\text{first-period production costs}} + \underbrace{\check{h}_1^A(f(0,1) - (50 - (s_1^A + s_1^B)))}_{\text{profits from t=0 hedging decision}} - \underbrace{0.25(\check{q}_1^A - s_1^A)}_{\text{storage costs}} \\ & + \{\underbrace{\bar{p}(Q_2)(q_2^A + \check{q}_1^A - s_1^A)}_{\text{revenues from sales in } t=2} - \underbrace{q_2^A}_{\text{second-period production costs}} - \frac{\alpha^A}{2}\, 200\, (q_2^A + \check{q}_1^A - s_1^A - h_2^A)^2\},\end{aligned}$$

where Q_1 and Q_2 denote the industry supply in $t = 1$ and $t = 2$, respectively. To obtain the interior solution, we derive the first-order conditions ($\bar{\varepsilon}_1 = 50$):

$$\begin{aligned}50 - (2s_1^A + s_1^B) + \check{h}_1^A + 0.25 - (50 - (2q_2^A + q_2^B + 2\check{q}_1^A + \check{q}_1^B - 2s_1^A - s_1^B) \\ - \alpha^A\, 200\, (q_2^A + \check{q}_1^A - s_1^A - h_2^A)) = 0,\end{aligned} \tag{20}$$

$$50 - (2q_2^A + q_2^B + 2\check{q}_1^A + \check{q}_1^B - 2s_1^A - s_1^B) - 1 - \alpha^A\, 200\, (q_2^A + \check{q}_1^A - s_1^A - h_2^A) = 0 \tag{21}$$

and

$$\alpha^A\ 200\ (q_2^A + \check{q}_1^A - s_1^A - h_2^A) = 0. \tag{22}$$

The second-period hedging decision immediately follows from Equation (22). The addition of Equations (21) and (22) yields Equation (9): marginal costs = marginal revenues. Thus, firms sell 49/3 units (= standard Cournot quantity) in the second period and adjust their second-period production accordingly. Also, we obtain Equation (10):

$$50 - (2s_1^A + s_1^B) + \check{h}_1^A = 1 - 0.25 = 0.75. \tag{10 revisited}$$

Solving for the equilibrium, we obtain

$$s_1^A = \frac{50 - 0.75}{3} + \frac{2}{3}\check{h}_1^A - \frac{1}{3}\check{h}_1^B \leq q_1^A. \tag{23}$$

Then, decision makers initially maximize

$$\begin{aligned}\Phi^A = \ & \underbrace{(50 - (\hat{s}_1^A + \hat{s}_1^B))\hat{s}_1^A}_{\text{revenues from sales in } t=1} - \underbrace{q_1^A}_{\text{production costs}} - \underbrace{0.25(q_1^A - \hat{s}_1^A)}_{\text{storage costs}} - \frac{\alpha^A}{2}\ 100\ (\hat{s}_1^A - h_1^A)^2 \\ & + \underbrace{\text{prof}}_{\text{net revenues from sales in } t=2} + \underbrace{(q_1^A - \hat{s}_1^A)}_{\text{non-incurred second-period production costs}} - \frac{\alpha^A}{2}\ 100\ (q_1^A - \hat{s}_1^A)^2.\end{aligned}$$

Simplified first-order conditions to determine the interior solution, considering the second-period choices, are

$$q_1^A - \frac{49.25}{3} - \frac{2}{3}h_1^A + \frac{1}{3}h_1^B + \frac{0.25}{100\ \alpha^A} = 0$$

and

$$\alpha^A\ 100\ \left(\frac{2}{3}q_1^A - \frac{49.25}{9} - \frac{5}{9}h_1^A + \frac{1}{9}h_1^B\right) + \frac{49.25}{9} - \frac{4}{9}h_1^A - \frac{1}{9}h_1^B = 0.$$

This system of four equations with four unknowns (again considering that risk aversion is a fixed parameter) yields expected equilibrium choices in $t = 0$. For $\alpha^A = 0.15$, we obtain $q_1^A = q_1^B = 23.89$ and $h_1^A = h_1^B = 22.42$.

As a result, spot sales1 amount to $s_1^A = 23.89$ (see Equation (23)). With nothing in storage, the firms produce $q_2^A = q_2^B = 16.33$ and hedge the entire production on the second-period forward market $h_2^A = h_2^B = 16.33$. Prices and firm profits follow immediately from the inverse demand function and Equations 7 and 8.

For risk-neutral decision makers ($\alpha^A = 0$), the decision problem collapses to a repeated single-shot duopoly under certainty with a corner solution, which is consistent with the notion of Broll et al. (2011) that strategic considerations are absent in a setting where firms decide on their production and hedging decision at the same time.

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