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Asymmetric price adjustments: A supply side approach

Fabio Antoniou[*] Raffaele Fiocco[†] Dongyu Guo[‡]

Abstract

Using a model of dynamic price competition, we provide an explanation from the supply side for the well-established observation that output prices react faster in response to input cost increases than to decreases. When costs decline, the opportunity of profitable storing in anticipation of higher future costs allows competitive firms to coordinate on prices above current marginal costs. The initial price response is only partial and profitable storing relaxes competition. Conversely, when costs rise, storing is not beneficial in anticipation of lower future costs and firms immediately adjust their prices to current marginal costs, which entails the standard Bertrand outcome. Our results shed new light on the empirical evidence about asymmetric pricing and can stimulate further empirical investigation on this puzzle.

Keywords: Asymmetric price adjustments, Bertrand-Edgeworth competition, Storage, Gasoline market.

JEL Classification: D4, L1.

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1 Introduction

A common observation in several markets is that output prices react asymmetrically over time in response to changes in input costs. In particular, the price adjustment is faster when input costs increase than when they decrease. A well-known example that corroborates this phenomenon is the gasoline market.[1]

The economic literature provides systematic empirical support for the phenomenon of asymmetric price adjustments, which is also known as 'rockets and feathers' (e.g., Arbatskaya and Baye 2004; Asplund et al. 2000; Bacon 1991; Blair and Rezek 2008; Borenstein et al. 1997; Borenstein and Shepard 1996; Chen et al. 2008; Deltas 2008; Green et al. 2010; Hannan and Berger 1991; Peltzman 2000; Valadkhani 2013; Verlinda 2008). Peltzman (2000, p. 466) emphasizes that "output prices tend to respond faster to input increases than to decreases. This tendency is found in more than two of every three markets examined."

Asymmetric price adjustments have sometimes been associated with the firms' collusive behavior. However, as Peltzman (2000) points out, the pattern of rockets and feathers is equally likely to be found in concentrated and atomistic markets. As discussed below, a recent strand of the economic literature has focused on competitive environments, where consumers are imperfectly informed about market prices and incur search costs. Prices respond asymmetrically to cost changes since the firms' pass-through increases with the search intensity in the market.

In this paper we attempt to shed new light on the phenomenon of asymmetric price adjustments in a standard competitive environment where firms provide a homogeneous good and compete in prices, abstracting from market imperfections such as collusion and limited information. The traditional economic theory predicts that firms make zero profits and prices react symmetrically to cost shocks. Focusing on the supply side, we show that the nature of this result changes drastically if the storage of a non-perishable good is allowed.

We consider a repeated Bertrand-Edgeworth competition model where two firms set prices and then quantities. In the absence of a cost shock, the scope for price undercutting drives prices to marginal costs, and firms are trapped in the Bertrand paradox. When a cost shock occurs, firms revise their expectations about future costs. In our setting, costs evolve according to a Markov process that exhibits mean reversion, consistently with some empirical evidence from the crude oil and gasoline markets (e.g., Anderson et al. 2014; Bessembinder et al. 1995; Chesnes 2016; Deltas 2008). When costs decline, the unique prediction of our model is that the opportunity of profitable storing for the next period in anticipation of higher future costs allows competitive firms to coordinate on prices above current marginal costs. The first period equilibrium price reflects the second period expected marginal cost weighted by the discount factor. Since profitable storing induces each firm to fill its depository irrespective of what the rival does, a firm that prices at the discounted expected future input cost is indifferent between selling today or tomorrow, and it can store the quantity purchased (or produced) if the rival undercuts its price and serves the market

[1] Other examples can be found in the coffee, corn and banking industries.

today. Hence, the initial price response to a cost decrease is only partial and profitable storing relaxes competition.

When costs increase, storing is not beneficial in anticipation of lower future costs and firms immediately adjust their prices to current marginal costs. The firms' incentives for price undercutting restore the standard Bertrand outcome. Our results provide theoretical corroboration for the empirical evidence that the initial price response to a cost change is more significant when costs increase than when they fall.

To the best of our knowledge, this work is the first contribution which sheds some light on recent empirical findings about asymmetric price adjustments driven by the anticipation of future cost changes. Using US gasoline data from 1991 to 2010, Radchenko and Shapiro (2011) show that gasoline prices react asymmetrically to oil price changes and the response to an anticipated change is larger than the response to an unanticipated change. Our results suggest that a channel for asymmetric price adjustments to anticipated cost changes is the opportunity of profitable storing, which mitigates the initial price response to a cost decrease. Since Radchenko and Shapiro (2011) only capture the impact of anticipated current cost changes on current prices, we expect that the pattern of asymmetric pricing should be even more pronounced if the effect of anticipated future cost changes on current prices is also considered. As discussed in Section 4, our results lend themselves to an empirically testable validation and can stimulate further empirical investigation on this puzzle.

Notably, our analysis can also help to explain why inventories have often been advocated as a determinant of asymmetric pricing but the empirical literature (e.g., Borenstein and Shepard 2002; Peltzman 2000) generally finds no correlation between asymmetric pricing and inventory costs. Consistently with the empirical evidence, our results indicate that asymmetric price adjustments are not driven by inventory costs. The channel identified in our analysis, which relates inventories to asymmetric pricing, is indeed the opportunity of profitable storing in anticipation of higher future costs. As shown in Section 5, the mechanism for asymmetric pricing that our model generates is robust to changes in different assumptions and the driving force of our results persists in alternative scenarios.

Even though we do not aim at modeling explicitly the retail gasoline market, our setting reflects some relevant features of this market. As documented by the Retail Fuels Report of the Association for Convenience and Fuel Retailing (NACS 2015), an estimated 80% of gasoline in the US is currently sold by convenience stores, whose vast majority (about 95%) is owned by small independent companies. A station usually obtains gasoline either directly at a (publicly observable) terminal price known as the 'rack' price or through an intermediate supplier (a 'jobber'), which typically charges a competitive margin over the rack price. The market exhibits intense price competition, since the consumers' priority is to search for the lowest price. This limits the profits of a gasoline station, whose average margin ranges between 3 and 5 cents per gallon. Retail gasoline prices are publicly observable, and in some states (e.g., New Jersey and Wisconsin) consumer protection laws require that posted gasoline prices remain in effect at least for a given period, generally 24 hours. Moreover, a gasoline station usually receives multiple deliveries each week and adjusts the output to the consumer demand according to its storage capacity. Remarkably, the asymmetric price mechanism that our model generates — characterized by higher profit margins when costs decrease — provides theoretical support for the evidence that "[t]he pattern of retail profitability is the opposite of what most consumers think. Due to the volatility in the wholesale price of gasoline and the competitive structure of the market, fuel retailers typically see profitability decrease as prices rise, and increase when prices fall" (NACS 2015, p. 20).

Related literature The phenomenon of asymmetric pricing has been widely explored in the economic literature, which provides alternative explanations. A recent strand of literature considers competitive markets where consumers cannot perfectly observe prices and search is costly. The main contributions differ in the driving force of asymmetric price adjustments and in the empirical predictions. Tappata (2009) develops a non-sequential search model with symmetric learning, while Yang and Ye (2008) provide an explanation for asymmetric pricing based on asymmetric learning by consumers. Lewis (2011) assumes that consumers' price expectations are based on the prices observed during previous purchases. Cabral and Fishman (2012) investigate asymmetric price adjustments in a setting where agents are inattentive to new information most of the time and only update their information at pre-specified intervals. We feel that the supply side approach to asymmetric pricing provided in our paper nicely complements the results of search models that focus on consumer behavior.

Our analysis is also related to the literature on the role of inventories in the firms' decisions. Particular attention has been devoted to the importance of inventory adjustments as a means of smoothing the effects of shocks over time (e.g., Amihud and Mendelson 1983; Borenstein and Shepard 2002; Reagan 1982; Reagan and Weitzman 1982). Differently from these contributions, we unveil the role of inventories as a driver of asymmetric pricing.

The rest of the paper is organized as follows. Section 2 sets out the formal model. Section 3 derives the main results. Section 4 investigates the empirical implications of our results. Section 5 extends our model in different directions and explores the robustness of our results. Section 6 concludes. The main formal proofs are collected in the Appendix. Additional proofs are relegated to a Supplementary Appendix available online.

2 The model

2.1 Setting

We consider two symmetric firms, A and B, which provide a homogeneous good and engage in repeated Bertrand-Edgeworth competition by first setting prices and then quantities. This is known in the literature as 'production to order' (e.g., Chowdhury 2005; Dixon 1984; Maskin 1986).[2] As

[2] We also refer to Allen and Hellwig (1986), Dasgupta and Maskin (1986a, 1986b) and Osborne and Pitchik (1986) for an analysis of equilibrium existence in Bertrand-Edgeworth models. More recently, Chowdhury (2009) explores

documented by the Retail Fuels Report of the Association for Convenience and Fuel Retailing (NACS 2015), gasoline stations can choose prices and quantities sequentially. Our qualitative results go through when prices and quantities are set simultaneously, as discussed in Section 6. In each period $\tau \in \{1, 2\}$, firm $i \in \{A, B\}$ sets a price $p_{\tau i}$ for the good and then orders from its provider (or produces) a quantity $q_{\tau i}$. We denote by $s_{\tau i}$ the quantity that firm i places on the market in period τ (which corresponds to firm i's sales in equilibrium). Since we aim at analyzing short-term events, we assume that market demand is inelastic and in each period consumers purchase a quantity $d > 0$ irrespective of the price level.[3]

Following the relevant literature (e.g., Chowdhury 2005), the residual demand for firm i vis-à-vis firm j is given by

$$D_{\tau i}(p_{\tau i}, p_{\tau j}, s_{\tau j}) = \begin{cases} \max\{0, d - s_{\tau j}\} & \text{if } p_{\tau i} > p_{\tau j} \\ \max\left\{\frac{d}{2}, d - s_{\tau j}\right\} & \text{if } p_{\tau i} = p_{\tau j} \\ d & \text{if } p_{\tau i} < p_{\tau j}. \end{cases} \quad (1)$$

The residual demand in (1) is distributed according to the efficient rationing rule. As long as the demand is inelastic, this formulation captures any combined rationing rule, including the proportional rationing rule (e.g., Tasnádi 1999). The second line of equation (1) identifies the tie-breaking rule used, among others, in Kreps and Scheinkman (1983) and Davidson and Deneckere (1986). This formulation exhibits the attractive feature that it allows for the spillover of the uncovered residual demand from one firm to another.[4]

In each period firms set their prices and decide on the quantity ordered and placed in their depositories. Therefore, one period is identified by the firms' choice of prices and orders. This seems to reflect the practice in the retail gasoline market, where price changes are usually associated with new deliveries (NACS 2015). The quantity $q_{\tau i}$ that firm i orders in period τ cannot exceed d, which represents the firm's storage capacity.[5] This assumption is reasonable in markets where storing large quantities is unfeasible. For instance, gasoline evaporates quite quickly and the size of tanks in gasoline stations is limited by physical constraints. Notably, a storage capacity equal to d allows each firm to serve the whole market, and therefore the opportunity of price undercutting could drive prices to marginal costs. In Section 5.3 we show that our qualitative results carry over with alternative storage capacities.

The quantity $q_{\tau i}$ ordered by firm i in period τ can be either placed on the market or (partially) stored for the next period. Let $r_{\tau i}$ be the quantity that firm i stores in period τ for the period $\tau + 1$, namely, firm i's reserves.[6] Firms incur the same unit input cost c_τ in period τ, which evolves

a model of Bertrand competition in the presence of non-rigid capacity constraints. In Section 5.6 we investigate alternative market structures.

[3]The consumer demand for gasoline is largely unresponsive to price changes at least in the short run. In Section 5.4 we show that our qualitative results carry over under more general assumptions about the demand function.

[4]Our results hold with alternative tie-breaking rules, such as $D_{\tau i} = \frac{d}{2}$ or $D_{\tau i} = d\frac{s_{\tau i}}{s_{\tau i}+s_{\tau j}}$ (which reduces to $D_{\tau i} = \frac{d}{2}$ if $s_{\tau i} + s_{\tau j} = 0$).

[5]Storage is costless. Introducing a positive cost of storage does not alter our qualitative results.

[6]Without any loss of generality, we assume that firm i's reserves r_{2i} at the end of the second period can be

according to a Markov process whose state is given by the cost realization. With probability $\varphi \in (0,1)$, costs do not change across the two periods, i.e., $c_1 = c_2$, which captures the degree of cost persistence. With probability $1-\varphi$, a new cost c_2 is drawn in the second period from a distribution function with mean c.[7] The firms' expectation in the first period about the costs in the second period is given by $\mathbb{E}[c_2] = \varphi c_1 + (1-\varphi)c$.

Firms are risk neutral. The profits of firm $i \in \{A, B\}$ in period $\tau \in \{1, 2\}$ are

$$\Pi_{\tau i} = p_{\tau i} \min\{s_{\tau i}, D_{\tau i}(p_{\tau i}, p_{\tau j}, s_{\tau j})\} - c_\tau q_{\tau i},$$

which represents the difference between total revenues and total costs. The firm's total revenues depend on the quantity sold on the market. Since we allow for voluntary trading, this quantity is the minimum between the quantity $s_{\tau i}$ that the firm puts on the market and the firm's residual demand $D_{\tau i}(p_{\tau i}, p_{\tau j}, s_{\tau j})$ in (1).[8] The firm's total costs depend on the ordered quantity $q_{\tau i}$.

The aggregate profits of firm $i \in \{A, B\}$ can be written as

$$\Pi_i = \Pi_{1i} + \delta \Pi_{2i},$$

where $\delta \in (0, 1]$ is the discount factor on the second period.

2.2 Timing and equilibrium concept

Each period $\tau \in \{1, 2\}$ of the game includes the following three stages.
(I) Nature draws the unit input cost c_τ.
(II) Firm $i \in \{A, B\}$ sets the price $p_{\tau i}$.
(III) Firm $i \in \{A, B\}$ orders at the unit cost c_τ the quantity $q_{\tau i}$, which is either placed on the market, $s_{\tau i}$, or (partially) stored for the next period, $r_{\tau i}$.

The equilibrium concept we adopt is the Subgame Perfect Nash Equilibrium (SPNE). Moving backwards, we first derive the equilibrium prices and quantities in the second period. Afterwards, we determine the equilibrium prices and quantities in the first period. A SPNE is specified by the tuple $\{(p^*_{\tau i}, q^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})\}_{\tau \in \{1,2\},\, i \in \{A,B\}}$. Since the quantity $q^*_{\tau i}$ ordered by firm i in period τ corresponds to the sales $s^*_{\tau i}$ in period τ plus the difference $r^*_{\tau i} - r^*_{\tau-1i}$ between the reserves in periods τ and $\tau - 1$, we omit $q^*_{\tau i}$ when presenting our results.

2.3 Input cost shock

When input costs in the first period are above the mean, i.e., $c_1 > c$, firms anticipate that costs in the second period will decline, i.e., $\mathbb{E}[c_2] = \varphi c_1 + (1-\varphi)c < c_1$. Conversely, when input costs in the first period fall below the mean, i.e., $c_1 < c$, firms anticipate that costs in the second period will increase, i.e., $\mathbb{E}[c_2] = \varphi c_1 + (1-\varphi)c > c_1$. For instance, in the crude oil and gasoline markets

discarded or destroyed at no cost.

[7]This stochastic process is similar to the one adopted by Cabral and Fishman (2012), with the main difference that in our setting costs are common to both firms.

[8]Nothing substantial would change if firms must fully cover the consumer demand.

cost shocks can be driven by several reasons, such as extreme weather phenomena (that may lead to supply disruptions), changes in the political situation of oil-producing countries, or decisions of OPEC meetings (e.g., Wirl and Kujundzic 2004). In our setting, the second period input costs are expected to move in the opposite direction to the first period costs. In other terms, costs follow a mean reverting stochastic process, consistently with some empirical evidence from the crude oil and gasoline markets (e.g., Anderson et al. 2014; Bessembinder et al. 1995; Chesnes 2016; Deltas 2008). This reflects the idea that shocks are perceived as short-run and firms conjecture that input costs tend to revert to their fundamental (mean) value.

Other empirical investigations find that the statistical properties of crude oil prices vary according to the time periods and data frequencies used, and they can also exhibit a random walk pattern (e.g., Geman 2007; Tabak and Cajueiro 2007). In an attempt to reconcile these different results, in our model the parameter $\varphi \in (0,1)$ can be interpreted as the probability that each firm attaches to the fact that costs will return to the mean in the next period, namely, the speed of mean reversion. For $\varphi \to 0$ costs are expected to converge to the mean already in the next period, while for $\varphi \to 1$ costs are expected to remain stable, which resembles a random walk process.[9]

3 Main results

3.1 Second period equilibrium

The following lemma characterizes the equilibrium prices and quantities in the second period.

Lemma 1 *A. If $r_{1A} + r_{1B} \leq d$, any pure strategy equilibrium of the second period continuation game exhibits the following features: $p^*_{2i} = c_2$, $s^*_{2A} + s^*_{2B} \leq d$ and $r^*_{2i} = 0$, $i \in \{A, B\}$.*

B. If $r_{1A}+r_{1B} > d$, any equilibrium of the second period continuation game exhibits the following features: $\mathbb{E}\left[p^*_{2i} \middle| c_2\right] < c_2$, $s^*_{2A} + s^*_{2B} = d$ and $r^*_{2i} = r_{1i} - s^*_{2i}$, $i \in \{A, B\}$.

Lemma 1A indicates that, if the total amount of reserves from the first period does not exceed the demand d, the second period (pure strategy) equilibrium price reflects the second period marginal cost, i.e., $p^*_{2i} = c_2$, $i \in \{A, B\}$. This holds true even though the cost of reserves was incurred in the first period and therefore it is zero in the second period. A price above c_2 clearly drives a firm out of the market. No firm has an incentive to set a price below c_2, because it cannot undercut the rival's price and profitably sell more than its reserves. Moreover, since we allow for voluntary trading, in equilibrium a part of the market may remain uncovered, but the reserves are fully exhausted.[10]

[9] We refer to Section 5.2 for a further discussion on the statistical properties of input costs.

[10] If price randomization is allowed, there also exist mixed strategy equilibria under some particular conditions. One randomizing firm sets the price at c_2 with a relatively high probability and remains idle in the market (except possibly when its price is c_2), while the rival fixes the price at c_2 with probability 1 and serves the market. This can occur only when the randomizing firm does not carry any reserves from the first period (otherwise, it would prefer to be active and sell these reserves). Remaining idle in the market, the randomizing firm makes zero profits irrespective of the price realization, and therefore it does not have any incentive to deviate. The rival is not willing to set a price different from c_2, given a relatively high probability that the randomizing firm prices at c_2, which makes any (upward) price deviation unprofitable. These mixed strategy equilibria typically emerge in this class of games and

As Lemma 1B reveals, things differ when the aggregate reserves are greater than the demand. Since the market cannot absorb all the reserves and their cost is sunk, firms engage in a price war to sell off their reserves. Hence, in equilibrium the market is fully covered, and at least one firm cannot exhaust its reserves. It follows from Dasgupta and Maskin (1986a) that this subgame possesses a mixed strategy equilibrium. In the Supplementary Appendix available online we provide the proof of the existence of a mixed strategy equilibrium and derive its main features discussed below. For our purposes, it is relevant to note that, when aggregate reserves are greater than the demand, any equilibrium exhibits a price randomization within an interval bounded above by c_2, which yields expected prices such that $\mathbb{E}\left[p_{2i}^{*}\middle| c_2\right] < c_2$, $i \in \{A, B\}$. A price above c_2 cannot be set with positive probability, since the standard undercutting rationale applies. Contrary to Lemma 1A where the total amount of reserves does not exceed the demand, choosing with probability 1 a price equal to the marginal cost c_2 cannot be sustained as an equilibrium, since each firm has an incentive to undercut the rival's price and sell all its reserves. The lower bound of the price interval and the equilibrium expected price crucially depend on the amount of the reserves. In the symmetric case where each firm carries $r_1 > \frac{d}{2}$, in equilibrium firms randomize over prices within the interval $\left[\frac{c_2(d-r_1)}{r_1}, c_2\right]$ and the price distribution function is $\phi^*(p_2) = \frac{p_2 r_1 - c_2(d-r_1)}{p_2(2r_1-d)} \in [0,1]$. Intuitively, greater reserves make competition more severe and the equilibrium expected price declines ($\frac{\partial \phi^*}{\partial r_1} > 0$). At one extreme, for $r_1 \to \frac{d}{2}$, the equilibrium price converges to c_2 (the price interval degenerates to c_2), as in Lemma 1A. At the other extreme, when $r_1 = d$, each firm can undercut the rival's price and serve the whole market with its reserves, which drives the price to zero (the lower bound of the price interval becomes zero and $\phi^*(p_2) = 1$). In case of unequal reserves, similar results hold, with the main difference that the firm endowed with greater reserves charges a higher price in expectation.

An implication of Lemma 1, which is useful throughout the rest of the analysis, is that the second period equilibrium expected price can never exceed the second period marginal cost, i.e., $\mathbb{E}\left[p_{2i}^{*}\middle| c_2\right] \leq c_2$, $i \in \{A, B\}$, irrespective of what has occurred in the first period.

3.2 Benchmark case: No shock

For illustrative purposes, we first consider the benchmark case where no shock occurs in the first period, and therefore the realized cost reflects the mean value, i.e., $c_1 = c$. Firms do not expect any cost change in the second period since $\mathbb{E}[c_2] = \varphi c_1 + (1-\varphi)c = c$. This setting corresponds to a dynamic version of the one-period game described in Chowdhury (2005) where we introduce the opportunity of storing.

The following remark summarizes the equilibrium of the game in the absence of a shock.

Remark 1 *Suppose $c_1 = c$. Then, the outcome $(p_{\tau i}^*, s_{\tau i}^*, r_{\tau i}^*)$ constitutes a pure strategy SPNE if*

they do not provide any novel insight into our analysis, since the randomizing firm remains inactive and the rival sets the price at c_2, as in the pure strategy equilibrium. Moreover, these mixed strategy equilibria may exhibit some implausible features, since the firm with the higher price serves the market when the randomizing firm sets a price lower than c_2 and remains inactive. Therefore, throughout the analysis we focus solely on pure strategy equilibria (whenever they exist).

and only if $p^*_{\tau i} = c_\tau$ *and* $s^*_{\tau A} + s^*_{\tau B} \leq d$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. *If* $\delta < 1$, *then* $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. *If* $\delta = 1$, *then* $r^*_{1A} + r^*_{1B} \leq d$ *and* $r^*_{2i} = 0$, $i \in \{A, B\}$.

The opportunity of storing some quantity for the next period does not alter the outcome of the static game and standard undercutting incentives drive prices to marginal costs. If $\delta < 1$, storing is profit detrimental (in expectation), since the first period marginal cost $c_1 = c$ is higher than the second period discounted expected price, which is bounded above by $\delta\mathbb{E}[c_2] = \delta c$, as implied by Lemma 1. If $\delta = 1$, storing is not harmful and in equilibrium firms are indifferent between storing or not, provided that the total amount of reserves does not exceed the demand. Otherwise, the second period expected price would fall below the first period marginal cost and storing would result in losses.

3.3 Negative shock

We first investigate the case of a negative shock where input costs in the first period fall below the mean value, i.e., $c_1 < c$. Firms envisage higher costs in the following period, i.e., $\mathbb{E}[c_2] = \varphi c_1 + (1 - \varphi)c > c_1$, since costs are expected to converge to the mean. Intuitively, a negative shock creates an incentive to purchase at a cost c_1 a quantity higher than usual. We know from Lemma 1 that, if the aggregate stored quantity from the first period does not exceed the demand, the second period price will be equal to the new marginal cost c_2. Since $\mathbb{E}[c_2] > c_1$, firms have the opportunity to sell the quantity stored at a positive margin in the second period when the discount factor is high enough.

The following proposition describes the equilibrium of the game with a negative shock.

Proposition 1 *Suppose* $c_1 < c$.

A. If $\delta\mathbb{E}[c_2] \geq c_1$, *the outcome* $(p^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})$ *constitutes a pure strategy SPNE if and only if* $p^*_{1i} = \delta\mathbb{E}[c_2]$, $p^*_{2i} = c_2$, $s^*_{\tau A} + s^*_{\tau B} = d$, $r^*_{1i} = d - s^*_{1i}$ *and* $r^*_{2i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$.

B. If $\delta\mathbb{E}[c_2] < c_1$, *the outcome* $(p^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})$ *constitutes a pure strategy SPNE if and only if* $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$ *and* $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$.

Proposition 1A considers the case in which storing one unit of the good purchased at c_1 in the first period with the prospect of selling it at c_2 in the second period is profitable (in expected terms). When costs decline, the opportunity of profitable storing allows competitive firms to coordinate on prices above current marginal costs in anticipation of higher future costs. Specifically, we find that the first period equilibrium price reflects the second period discounted expected cost, i.e., $p^*_{1i} = \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$. Hence, after a negative shock, the initial price response is only partial and profitable storing relaxes competition.

In order to substantiate the intuition behind this result as provided in the introduction, it is important to realize that in equilibrium the demand is always covered in the first period,[11] and

[11] Otherwise, there would be (at least) one firm with aggregate demand lower than d, which would profitably deviate by setting a higher price to serve the residual demand. We refer to the proof of Proposition 1A (in the Appendix) for technical details.

therefore the aggregate reserves from the first period do not exceed the demand in the second period. It follows from Lemma 1A that in the second period the (pure strategy) equilibrium price reflects the current marginal cost, i.e., $p_{2i}^* = c_2$, which implies that $\mathbb{E}[p_{2i}^*] = \mathbb{E}[c_2]$, $i \in \{A, B\}$. As a consequence, for $\delta\mathbb{E}[c_2] \geq c_1$ each firm has an incentive to purchase a quantity d in the first period, which can be (partially) stored and profitably sold in the second period. A firm that sets its price at $\delta\mathbb{E}[c_2]$ is indifferent between serving the market today or tomorrow, and it can credibly commit to purchase d even if the rival undercuts its price. In particular, if the undercutting firm prefers to (partially) serve the market today, the non-deviating firm can store (a portion of) d and sell it tomorrow at c_2. Any deviation above $\delta\mathbb{E}[c_2]$ is unprofitable as long as the firm conjectures that the rival will cover the whole market.

We know from Section 3.2 that, in the absence of a shock, each firm cannot credibly commit not to be aggressive vis-à-vis the rival, and the standard Bertrand outcome applies. When input costs decrease, profitable storing acts as a commitment device to adjust prices above current marginal costs. As a result, competition is mitigated and firms earn expected profits equal to $(\delta\mathbb{E}[c_2] - c_1)\,d$. The equilibrium price and the associated profits increase with the discount factor δ. This is because more patient firms anticipate higher future input costs (and prices), which increases the scope for selling at higher current prices and generates higher profits.

Since firms can share the market in several manners, it is helpful to consider the symmetric equilibrium. In the first period each firm, which sets the price $\delta\mathbb{E}[c_2]$ and orders d, serves half of the market and stores the residual output, i.e., $s_{\tau i}^* = r_{\tau i}^* = \frac{d}{2}$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. In the second period the market is again shared equally between firms that sell their reserves at c_2. Naturally, the cost realized in the second period may differ from the expected one. If the second period discounted cost is higher (lower) than the first period cost, i.e., $\delta c_2 > (<)\, c_1$, firms make gains (losses). Since firms are risk neutral, their first period price choice clearly depends only on the expectation about future costs.

As we aim at analyzing short-term events, the discount factor should be relatively high and the outcome of Proposition 1A is the most relevant for our purposes. Proposition 1B describes what happens if the firms' future discounting is low enough, i.e., $\delta\mathbb{E}[c_2] < c_1$. Since storing is unprofitable and cannot be used as a commitment device to relax competition, firms are trapped in the Bertrand paradox and immediately adjust their prices to current marginal costs, which yield zero profits.

3.4 Positive shock

The following proposition summarizes the main results in case of a positive shock, where input costs are above the mean, i.e., $c_1 > c$.

Proposition 2 *Suppose $c_1 > c$. Then, the outcome $(p_{\tau i}^*, s_{\tau i}^*, r_{\tau i}^*)$ constitutes a pure strategy SPNE if and only if $p_{\tau i}^* = c_\tau$, $s_{\tau A}^* + s_{\tau B}^* \leq d$ and $r_{\tau i}^* = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$.*

Proposition 2 replicates the outcome of Proposition 1B. In response to a positive shock, firms adjust their prices to current marginal costs already in the first period. Since costs are expected to decline in the second period, i.e., $\mathbb{E}[c_2] = \varphi c_1 + (1-\varphi)c < c_1$, storing is not beneficial and price undercutting leads to the standard Bertrand outcome. Consistently with the empirical evidence, our model predicts that prices respond faster to cost increases than to decreases.

4 Empirical implications

4.1 Predictions of our model

We are now in a position to relate our results to the empirical predictions. In order to derive the price-cost pass-through rates over time, we introduce a pre-shock period, called period 0, where the marginal cost is equal to the mean c. It follows from Section 3.2 that the price in period 0 reflects the current marginal cost, i.e., $p_0 = c$. Using the results in Propositions 1 and 2, the price percentage variations after a cost shock in period 1 are

$$\beta_0^+ = \frac{c_1 - c}{c},\ \beta_1^+ = \frac{c_2 - c_1}{c_1},\ \beta_0^- = \frac{\delta\mathbb{E}[c_2] - c}{c},\ \beta_1^- = \frac{c_2 - \delta\mathbb{E}[c_2]}{\delta\mathbb{E}[c_2]},$$

where β_0^+ and β_1^+ respectively denote the price percentage variations between periods 1 and 0 and between periods 2 and 1 after a positive shock ($c_1 > c$). The interpretation of β_0^- and β_1^- follows similarly in case of a negative shock and profitable storing ($c_1 < \delta\mathbb{E}[c_2] < c$). A comparison between β_0^+ and β_0^- immediately reveals that $\beta_0^+ > |\beta_0^-|$, namely, prices react faster when input costs increase than when they fall if storing is profitable. While prices fully respond to cost increases in the first period, the initial price adjustment is less significant when costs decline, and some price stickiness emerges. A higher discount factor δ reduces $|\beta_0^-|$ and therefore exacerbates the initial price stickiness. The idea is that more patient firms anticipate higher input costs (and prices) in the second period and are less inclined to reduce immediately their prices. The degree of cost persistence φ plays a complementary role to the discount factor. A lower φ induces firms to expect higher future costs after a negative shock, which makes storing profitable for a larger range of the discount factor and mitigates the initial price response to a cost decrease. Therefore, a higher cost volatility, which is associated with a lower φ, exacerbates the price stickiness. As φ also measures the speed of mean reversion, our results show that the magnitude of asymmetric pricing is associated with that speed.

The intensity of later adjustment is captured by the terms β_1^+ and β_1^-, whose values depend on the cost realization in the second period. To identify the effect of a cost shock over time, the empirical literature (e.g., Borenstein et al. 1997; Chesnes 2016) typically estimates the price response to a one-time cost change, and therefore costs remain constant over the following periods. In our setting, this corresponds to $c_1 = c_2$, which implies $\beta_1^+ = 0$ and $\beta_1^- = \frac{c_1 - \delta\mathbb{E}[c_2]}{\delta\mathbb{E}[c_2]} < 0$. Since $|\beta_1^-| > \beta_1^+$, the magnitude of later adjustment is reversed, namely, it is more pronounced with a negative shock than with a positive shock.

Figure 1 illustrates the aggregate price change until period $\tau \in \{1, 2\}$ in response to a cost shock

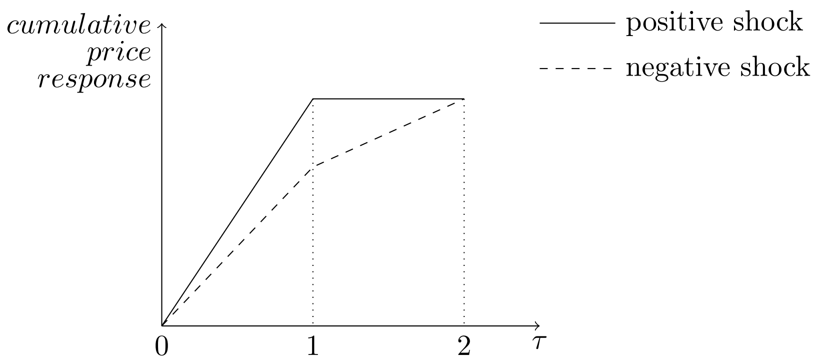

Figure 1: Asymmetric price adjustments

in period 1, according to the sign of the shock. In line with the empirical evidence, prices initially react faster to cost increases than to decreases but the opposite occurs when the total adjustment is near completion.

4.2 The econometric model

The predictions of our model suggest that the opportunity of profitable storing in anticipation of higher future costs is a crucial driver of the asymmetric price response to cost changes. To further appreciate the empirical implications of our results, we present the following dynamic econometric model that adopts the approach of Cochrane (1998) and Radchenko and Shapiro (2011)

$$\begin{aligned}\Delta p_\tau \;=\;& a^*(L)\left[\lambda^+\Delta c_\tau^+ + \left(1-\lambda^+\right)\left(\Delta c_\tau^+ - \mathbb{E}_{\tau-1}\left[\Delta c_\tau^+\right]\right)\right] + \sum\nolimits_{h=1}^{n}\gamma_h^+\mathbb{E}_\tau\left[\Delta c_{\tau+h}^+\right] \\ &+ b^*(L)\left[\lambda^-\Delta c_\tau^- + \left(1-\lambda^-\right)\left(\Delta c_\tau^- - \mathbb{E}_{\tau-1}\left[\Delta c_\tau^-\right]\right)\right] + \sum\nolimits_{h=1}^{n}\gamma_h^-\mathbb{E}_\tau\left[\Delta c_{\tau+h}^-\right] + \varepsilon_\tau. \quad (2)\end{aligned}$$

The structural lag polynomials $a^*(L)$ and $b^*(L)$ capture the impact of positive and negative cost changes Δc_τ^+ and Δc_τ^- on the price change Δp_τ between periods τ and $\tau-1$.[12] The cost changes are decomposed into unanticipated changes ($\Delta c_\tau^+ - \mathbb{E}_{\tau-1}[\Delta c_\tau^+]$ for positive changes and $\Delta c_\tau^- - \mathbb{E}_{\tau-1}[\Delta c_\tau^-]$ for negative changes) and anticipated changes ($\mathbb{E}_{\tau-1}[\Delta c_\tau^+]$ for positive changes and $\mathbb{E}_{\tau-1}[\Delta c_\tau^-]$ for negative changes). Ignoring for the time being the two summations, the econometric model in (2) reduces to the framework of Radchenko and Shapiro (2011), which focuses on the impact of anticipated and unanticipated current cost changes on current prices. The parameter $\lambda \in \{\lambda^+, \lambda^-\}$ allows for a different effect of anticipated and unanticipated shocks, according to the direction of the cost change. For $\lambda = 0$ only unanticipated shocks matter. For $\lambda = 1$ anticipated and unanticipated shocks have the same effect. Asymmetric price adjustments have often been investigated within this framework (e.g., Borenstein et al. 1997). For $\lambda \in (0,1)$ both shocks are relevant and their effects differ. In this framework, using US gasoline data from March 1991 to

[12]Clearly, ε_τ indicates the error term. The model may also accommodate for lagged price changes and an error correction term that measures deviations from the long-run equilibrium.

March 2010, Radchenko and Shapiro (2011) document evidence of asymmetric price adjustments and show that anticipated shocks have a larger effect than unanticipated shocks.

The two summations in (2) describe the impact of anticipated future cost changes on current prices. In particular, the terms γ_h^+ and γ_h^- measure the impact of the anticipation in period τ of a cost change in period $\tau + h$ on the price in period τ, according to the direction of the cost change. Put differently, γ_h^+ and γ_h^- capture the sensitivity of a price change Δp_τ to positive and negative anticipated future cost changes $\mathbb{E}_\tau \left[\Delta c_{\tau+h}^+\right]$ and $\mathbb{E}_\tau \left[\Delta c_{\tau+h}^-\right]$. Our results suggest that $\gamma_h^+ > \gamma_h^-$, which indicates asymmetric price response to anticipated future cost changes. Since in our model a decrease (increase) in current costs translates into higher (lower) anticipated future costs, the asymmetry of the impact of a cost change on prices in (2) is more pronounced than when the anticipation about future costs is neglected. Hence, the pattern of asymmetric pricing should be more significant than the one documented so far in the empirical studies.

Our results can stimulate further empirical investigation on the relationship between asymmetric pricing and inventories. For this purpose, it is recommendable to use daily or weekly data since inventories change frequently, as Peltzman (2000) points out. The empirical strategy should be able to identify the role of inventories that emerges from our analysis. Consistently with our results, the empirical literature (e.g., Borenstein and Shepard 2002; Peltzman 2000) generally finds no correlation between asymmetric pricing and inventory costs. Building on Cochrane (1998) and Radchenko and Shapiro (2011), a structural empirical approach can be implemented to explore the channel identified in our analysis through which inventories drive asymmetric price transmission. Our results indicate that inventories are endogenously determined by cost shocks and firms tend to store more than usual in anticipation of higher future costs.

Since in our model asymmetric pricing emerges with a relatively high discount factor, which is associated with low interest rates, some empirical investigation can be conducted on the relationship between asymmetric pricing and interest rates. Another result that deserves empirical corroboration concerns the impact of the speed of cost mean reversion on the magnitude of asymmetric pricing. In a similar vein, our prediction that higher cost volatility exacerbates price stickiness lends itself to an empirical validation.

5 Robustness

5.1 Endogenous input costs

In our model input supply is perfectly elastic, and each firm might order arbitrarily high quantities at the same current input cost. In reality, however, a change in the firms' demand can affect input costs. In order to examine this case, we assume that in the first period the (common) provider can obtain a quantity up to d (which is the 'historical' quantity, i.e., the quantity in the absence of a shock) at a cost c_1, for instance, due to long-term contracts. If the provider wants to acquire larger quantities to serve the firms' demand, it must resort to other sources (say, the futures market) and pay a cost equal to $\mathbb{E}[c_2]$ on the additional amount. The average input cost in the first period is given by

$$\widetilde{c}_1 = \begin{cases} \frac{c_1 \min\{d, q_{1A}+q_{1B}\} + \mathbb{E}[c_2] \max\{0, q_{1A}+q_{1B}-d\}}{q_{1A}+q_{1B}} & \text{if } q_{1A}+q_{1B} > 0 \\ c_1 & \text{if } q_{1A}+q_{1B} = 0. \end{cases} \tag{3}$$

The provider's average cost function exhibits a kink at d, and the price charged by the provider now depends on the firms' demand for the input. Endogenous input costs complicate the analysis, since they create an interdependence between the firms' costs. We assume that the provider sets an input price equal to the average cost in (3) plus a fixed markup (normalized to zero). This input price rule captures in a simple but effective manner the idea that the firms' demand affects the input price, abstracting from the particular features of the upstream market. When the firms' aggregate demand does not exceed d, the provider does not need to purchase any quantity from additional sources and therefore the first period input cost is c_1. If, however, the firms' aggregate demand is higher than d, the provider must acquire any additional quantity at $\mathbb{E}[c_2]$, which increases (decreases) the average cost in (3) if $\mathbb{E}[c_2] > (<) \, c_1$.

Negative shock

The following proposition considers the case of a negative shock.

Proposition 3 *Suppose* $c_1 < c$.

A. If $\delta \geq \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$*, the outcome* $(p^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})$ *constitutes a pure strategy SPNE if and only if* $p^*_{1i} = \delta \mathbb{E}[c_2]$, $p^*_{2i} = c_2$, $s^*_{\tau A} + s^*_{\tau B} = d$, $r^*_{1i} = d - s^*_{1i}$ *and* $r^*_{2i} = 0$, $\tau \in \{1,2\}$, $i \in \{A, B\}$.

B. If $\frac{c_1}{\mathbb{E}[c_2]} < \delta < \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$*, no equilibrium exists.*

C. If $\delta \leq \frac{c_1}{\mathbb{E}[c_2]}$*, the outcome* $(p^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})$ *constitutes a pure strategy SPNE if and only if* $p^*_{\tau i} = c_\tau$ *and* $s^*_{\tau A} + s^*_{\tau B} \leq d$, $\tau \in \{1,2\}$, $i \in \{A, B\}$. *If* $\delta < \frac{c_1}{\mathbb{E}[c_2]}$*, then* $r^*_{\tau i} = 0$, $\tau \in \{1,2\}$, $i \in \{A, B\}$. *If* $\delta = \frac{c_1}{\mathbb{E}[c_2]}$*, then* $s^*_{1A} + r^*_{1A} + s^*_{1B} + r^*_{1B} \leq d$ *and* $r^*_{2i} = 0$, $i \in \{A, B\}$.

Proposition 3A indicates that, if the discount factor is sufficiently high, i.e., $\delta \geq \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, the equilibrium price equals $\delta \mathbb{E}[c_2]$ in the first period and c_2 in the second period, which ensures that each firm is indifferent (in expectation) to selling in either period. The threshold $\frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$ corresponds to the value for the discount factor above which each firm orders d in the first period and the demand is fully covered in each period. The intuition for this result falls across the same lines as in Proposition 1A. It is worth noting that the threshold of the discount factor is higher than in the baseline model, i.e., $\frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right) > \frac{c_1}{\mathbb{E}[c_2]}$. The idea is that now storing increases the firms' unit costs already in the first period, which strengthens the condition under which each firm finds it optimal to order a quantity equal to d in the first period. Since the equilibrium average input cost increases to $\widetilde{c}_1 = \frac{c_1 + \mathbb{E}[c_2]}{2} > c_1$, price stickiness still emerges after a negative shock, but it is less pronounced than in the baseline model.

For intermediate values of the discount factor, i.e., $\frac{c_1}{\mathbb{E}[c_2]} < \delta < \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, no equilibrium exists (in pure or mixed strategies). To fix ideas, consider the equilibrium prices described in Proposition 3A. At these prices, storing is still profitable but to a lower extent than in the previous case, which results in orders below d in the first period. Hence, a firm can infinitely raise its price in the first period and serve the uncovered part of the market. Following a loose dynamic argument, if a firm sets an infinitely high price, the rival has an incentive to undercut marginally and an infinite loop emerges. This indeterminacy arises only because of the assumption of rigid demand, and an equilibrium (in mixed strategies) exists if a choke price is introduced above which the demand is zero (Dasgupta and Maskin 1986a).

Proposition 3C predicts that, if the discount factor is low enough, i.e., $\delta \leq \frac{c_1}{\mathbb{E}[c_2]}$, storing is not strictly profitable and firms adjust their prices to the current input costs as in Proposition 1B. If $\delta = \frac{c_1}{\mathbb{E}[c_2]}$, storing is not harmful and in equilibrium firms are indifferent between storing or not, provided that the total amount of the quantities ordered in the first period does not exceed the demand. Otherwise, the first period average input cost would be higher than the second period discounted expected price and firms would incur losses.

Positive shock

The following proposition describes what happens in case of a positive shock.

Proposition 4 *Suppose $c_1 > c$. Then, the outcome $(p^*_{\tau i}, s^*_{\tau i}, r^*_{\tau i})$ constitutes a SPNE if and only if $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$ and $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$.*

Proposition 4 replicates the outcome of Proposition 2. Storing is not desirable since the first period cost $\widetilde{c}_1$ in (3) is higher than the second period expected cost $\mathbb{E}[c_2]$, and the standard Bertrand outcome applies. Note that, if the firms' aggregate orders exceeded the demand, $\widetilde{c}_1$ would be lower than c_1, which might make price undercutting below c_1 profitable. However, the undercutting firm cannot benefit from this cost reduction since the rival would abstain from ordering, and the cost $\widetilde{c}_\tau$ is equal to c_τ in each period τ.

5.2 Statistical properties of costs

Input costs exhibit mean reversion and our model is flexible enough to allow for different intensities of this stochastic process. Interestingly, asymmetric pricing emerges in our framework even when firms have heterogeneous cost expectations, and only some of them believe that costs evolve according a mean reversion pattern (Ter Ellen and Zwinkels 2010). To fix ideas, suppose that firm A expects that input costs will revert to the mean after a cost shock, while firm B believes that costs follow a random walk. Applying the same rationale as in the baseline model, firm A still has an incentive to set a price above the marginal cost after a negative shock (for a sufficiently high discount factor), since it is willing to cover the market in the next period in response to the price undercutting of firm B, which does not expect any cost change. The first period equilibrium price reflects the discounted expected future cost, as in the baseline model. Notably, firm B is not willing to store and serves the market in the first period, while firm A stores its entire output and operates in the second period.

It is worth emphasizing that our results hold whenever firms anticipate a cost change, independently of the rationale behind it. Suppose that costs vary deterministically over time, similarly to what Dudine et al. (2006) assume for demand changes. As formally shown in a previous version of our paper (Antoniou et al. 2015), in anticipation of higher future costs, firms have an incentive to store and immediately adjust their prices to discounted future costs (for a sufficiently high discount factor), whereas prices react only after a cost change materializes if future costs decrease. In line with our current framework, the initial price response is more pronounced when costs increase than when they fall.

5.3 Storage capacity

Throughout the analysis the firm's storage capacity is equal to the market demand d in each period. We now define by K the firm's storage capacity. The case in which $K < d$ does not provide any novel insight into our analysis. Each firm is a monopolist on the residual demand, which induces a price randomization within an interval whose upper bound is above marginal costs even in the absence of a cost shock and depends on the choke price (Levitan and Shubik 1972). When future costs are expected to rise and the discount factor is high enough, firms have incentives to fill their depositories and can coordinate on higher prices, as in the baseline model.

More interesting is the case in which $K > d$. To fix ideas, suppose that as a result of a negative shock the first period marginal cost drops to zero, i.e., $c_1 = 0$, and the expected cost in the second period is $\mathbb{E}[c_2] > c_1$. In this setting, storing is always profitable since firms can costlessly fill their depositories. Intuitively, the equilibrium depends on the size of the storage capacity. In the extreme case where $K \geq 2d$, the equilibrium prices in the two periods reflect the first period marginal cost because each firm can fully cover the market in both periods, and the standard Bertrand outcome arises. If, however, $d < K < 2d$, things are different. Note that, given a price equal to the marginal cost in the first period, the undercutting incentives imply that the price in the second period still reflects the first period cost, and firms make zero profits. However, a firm that increases its price in the first period can cover the residual demand at a positive margin or, if the rival serves the whole market, it expects to sell some quantity in the second period at (almost) c_2. Therefore, the first period price is set above the first period marginal cost. Notably, this price is lower than $\delta\mathbb{E}[c_2]$. The reason is that, if the rival sets the price at $\delta\mathbb{E}[c_2]$, the undercutting firm can ensure profits (almost) equal to $\delta\mathbb{E}[c_2]\,d$ already in the first period, while the first period profits from setting $\delta\mathbb{E}[c_2]$ are $\frac{1}{2}\delta\mathbb{E}[c_2]\,d$ but the second period (discounted) profits fall below $\frac{1}{2}\delta\mathbb{E}[c_2]\,d$. This latter result follows from Lemma 1B since the aggregate reserves from the first period exceed the demand d and therefore a price randomization occurs within an interval whose upper bound is c_2. A larger capacity strengthens the undercutting incentives and reduces the initial price stickiness. We know from Dasgupta and Maskin (1986a) that an equilibrium (in mixed strategies) exists, and the first period equilibrium price must lie between c_1 and $\delta\mathbb{E}[c_2]$. Since with a positive shock storing is unprofitable and prices reflect marginal costs, asymmetric pricing still emerges.[13]

[13]Interestingly, the intuition for the impact of the storage capacity on asymmetric pricing can also apply to the

5.4 Demand function

In our model firms face a rigid demand d in each period. We now consider a downward sloping demand $D_\tau(p_\tau) = 1 - p_\tau$ in period $\tau \in \{1, 2\}$. As in Section 5.3, we assume that a negative shock yields $c_1 = 0$ and $\mathbb{E}[c_2] > c_1$. The firm's storage capacity is 1, which ensures that each firm can serve the whole market in every period. In this framework, firms have incentives to fill their depositories and, in line with the baseline model, the first period price is set above the current marginal cost. To see this, suppose that in equilibrium $p_1 = c_1 = 0$, which implies that $p_2 = 0$ since firms keep undercutting each other. Following the same rationale as in case of a capacity $d < K < 2d$, this cannot be sustained as an equilibrium, since a firm that increases its price in the first period can serve the residual demand at a positive margin or, if the rival covers the whole market, it expects to operate in the second period, which yields positive expected profits. Therefore, in anticipation of higher future costs, firms can coordinate on prices above current marginal costs, as in the baseline model. In line with the case of a capacity $d < K < 2d$, the equilibrium price in the first period is lower than $\delta\mathbb{E}[c_2]$. To understand why, note that, if the rival sets $\delta\mathbb{E}[c_2]$, the undercutting firm can obtain profits (almost) equal to $\delta\mathbb{E}[c_2](1 - \delta\mathbb{E}[c_2])$ already in the first period. These profits outweigh the aggregate profits from setting $\delta\mathbb{E}[c_2] \leq \frac{1}{2}$ (a price above the monopoly level is clearly suboptimal), which are given by $\frac{1}{2}\delta\mathbb{E}[c_2](1 - \delta\mathbb{E}[c_2]) + \frac{1}{2}\delta\mathbb{E}[p_2(1 - p_2)]$, where p_2 ranges within an interval whose upper bound is c_2 since the aggregate reserves are larger than 1 (Levitan and Shubik 1972). Downward price deviations are now more appealing than in the baseline model because the demand increases. It follows from Dasgupta and Maskin (1986a) that there exists an equilibrium (in mixed strategies), and the first period equilibrium price must lie between c_1 and $\delta\mathbb{E}[c_2]$. Since with a positive shock storing is not beneficial and prices follow marginal costs, asymmetric pricing still arises.[14]

5.5 Number of periods

Our results can be also generalized to a setting with more than two periods. If each firm can sell the quantity stored only in the next period (as is the case with slightly durable goods), the pricing dynamics in a game of $T > 2$ periods directly follow from the results in Propositions 1 and 2. The equilibrium price in period $\tau \in \{1, 2, \ldots, T-1\}$ is $p^*_\tau = \delta\mathbb{E}_\tau[c_{\tau+1}]$ for $\delta\mathbb{E}_\tau[c_{\tau+1}] \geq c_\tau$, and $p^*_\tau = c_\tau$ otherwise, while $p^*_T = c_T$.

When the quantity stored can be sold at any future point in time, asymmetric pricing still

analysis of competition in the storage market. A more competitive storage market (which better exploits the arbitrage opportunities) can reduce the spread between the current costs and the expected ones, which mitigates the price stickiness after a negative shock.

[14]It is worth mentioning what happens in our model when we consider demand uncertainty instead of stochastic costs. Given a firm's capacity equal to the expected demand, in case of a negative demand shock each firm can cover the market and therefore the equilibrium prices reflect the marginal costs. On the contrary, when a positive demand shock occurs, the firm's capacity is insufficient to drive prices to marginal costs. Introducing a choke price, a mixed strategy equilibrium exists, which implies prices above marginal costs. Therefore, asymmetric pricing appears even with stochastic demand, although the mechanism is different. Along these lines, we expect that similar results will hold in a more complicated setting that accommodates for both demand and cost uncertainty.

emerges. Extending to $T > 2$ periods the evolution of expected costs, we have $\mathbb{E}_\tau[c_{\tau+1}] = \varphi c_\tau + (1-\varphi)c$, for any $\tau \in \{1, 2, \ldots, T-1\}$. Then, the expectation in period τ about the cost in period $\tau + h$, with $h \geq 1$, is given by

$$\mathbb{E}_\tau[c_{\tau+h}] = c - \varphi^h (c - c_\tau).$$

Suppose that a negative shock occurs in period τ, i.e., $c_\tau < c$. Future costs are expected to increase at a decreasing rate over time, as $\frac{d\mathbb{E}_\tau[c_{\tau+h}]}{dh} > 0$ and $\frac{d^2\mathbb{E}_\tau[c_{\tau+h}]}{dh^2} < 0$. A firm anticipates that filling its depository in period τ and in any future period $\tau + h$ will be profitable if the (per period) discount factor is such that $\delta\mathbb{E}_\tau[c_{\tau+1}] \geq c_\tau$ and $\delta\mathbb{E}_\tau[c_{\tau+h+1}] \geq \mathbb{E}_\tau[c_{\tau+h}]$. In this case, the equilibrium price in period τ reflects the discounted expected marginal cost in period $\tau + 1$, i.e., $p^*_{\tau i} = \delta\mathbb{E}_\tau[c_{\tau+1}]$, as in the baseline model. To fix ideas, consider a setting with three periods. Since $\delta\mathbb{E}_1[c_3] \geq \mathbb{E}_1[c_2]$, one might conjecture that firms can set the first period price at $\delta^2\mathbb{E}_1[c_3]$ instead of $\delta\mathbb{E}_1[c_2]$. Given this price in the first period, each firm would expect to charge $\delta\mathbb{E}_1[c_3]$ in the second period since storing is profitable, and $\mathbb{E}_1[c_3]$ in the last period. To understand why this cannot be sustained as an equilibrium, note that firms can refill their depositories in each period. If the rival sets a price equal to $\delta^2\mathbb{E}_1[c_3]$ in the first period, a firm can undercut the rival's price, serve the whole market and refill its depository in the second period. This deviation is profitable since the gains from serving the whole market (instead of one half) in the first period, which are (almost) equal to $\frac{d}{2}\delta^2\mathbb{E}_1[c_3]$, outweigh the (discounted expected) losses from refilling the entire depository (instead of one half) in the second period, which amount to $\frac{d}{2}\delta\mathbb{E}_1[c_2]$. Moreover, the undercutting firm still expects to charge $\delta\mathbb{E}_1[c_3]$ in the second period, which ensures that its quantity can be sold in the second or in the third period. As in the baseline model, the first period equilibrium price is $\delta\mathbb{E}_1[c_2]$, which allows a firm to sell profitably in the second period if the rival undercuts its price and serves the market in the first period. Clearly, when a positive shock occurs in period τ, i.e., $c_\tau > c$, storing is unprofitable since costs are expected to decrease, and the equilibrium price in period τ reflects the current marginal cost, i.e., $p^*_{\tau i} = c_\tau$. Hence, the asymmetric price pattern that our model generates is robust to an extension of the time horizon.

5.6 Market structure

Asymmetric pricing emerges in market structures different from Bertrand-Edgeworth competition. In the Supplementary Appendix available online we provide a formal description of the monopoly setting. We expect that analogous results will hold, though with a higher degree of complexity, when firms compete à la Cournot. If the cost shock is positive, storing is unprofitable and in each period the monopolist sets the price at the static equilibrium level that equalizes current marginal revenues and current marginal costs. If the shock is negative and (discounted) costs are expected to increase, equilibrium prices crucially depend on the size of the firm's storage capacity. Particularly interesting is the situation in which the storage capacity is bounded so that the monopolist cannot store the desired quantity but it is large enough for storing to remain profitable, and therefore a trade-off appears between selling in the first period and storing for the second period. Within this range, if the firm's capacity is above a certain threshold, the firm does not expect to order (or produce) in the second period, and in equilibrium the marginal revenue of the output sold in the first period is equal to the discounted marginal revenue of the reserves. If the firm's capacity is below that threshold, the firm still stores for the next period but anticipates that it will order (or produce) even in the second period. This implies that discounted marginal revenues associated with the first period output and the second period expected output (which includes the reserves) are equalized in equilibrium. In both cases the first period price is set above the static monopoly level. Hence, the initial price adjustment is less significant after a negative shock and some price stickiness emerges, as in the baseline model. Anticipating higher future costs, the monopolist is willing to forgo some sales in the first period in order to store more output for the second period.

6 Concluding remarks

In this paper we provide a theoretical explanation from the supply side for the well-established phenomenon of asymmetric price adjustments. When costs decline, the opportunity of profitable storing in anticipation of higher future costs mitigates the price response to a cost change. As a result, firms are better off in an inflationary upstream market where input prices are expected to increase, since this allows them to have some market power and earn windfall profits. The pattern of firms' profits that our model generates is consistent with the evidence from the gasoline market where retailers make larger profits when input costs fall than when they rise (NACS 2015).

Our model exhibits some desirable features of the markets for durable goods. As discussed in the introduction, a leading example is the retail gasoline market, which seems to be adequately described by a Bertrand-Edgeworth model where firms choose prices and quantities. We focus on the situation in which prices are set prior to quantities. However, we cannot dismiss the case that in practice prices and quantities are determined simultaneously. The main technical problem identified in a static framework by Chowdhury (2005) is the nonexistence of pure strategy equilibria. However, Allen and Hellwig (1986), Dasgupta and Maskin (1986a, 1986b) and Maskin (1986) establish the general existence of a mixed strategy equilibrium. Since in our framework profitable storing does not crucially depend on the timing of actions and by the observability of the rivals' prices, we expect that our results will, by and large, carry over in this scenario. In particular, if firms envisage a cost increase in the following period(s), they have an incentive to store, anticipating that their output will be sold at some point in the near future. Hence, the problem reduces to a price decision that follows the same dynamics as in our model.

Another relevant issue that deserves some attention concerns the nature of the vertical relationship between input providers and downstream firms. Consistently with the evidence in the gasoline market, we assume that each firm pays a price per unit of quantity ordered. Remarkably, our results carry over with more sophisticated contractual relationships, such as two-part tariffs that consist of a unit wholesale price and a fixed fee. It is well known in the literature (O'Brien and Shaffer 1992; Rey and Vergé 2004) that under some conditions the upstream firm charges downstream Bertrand competitors a wholesale price equal to its marginal cost and the downstream firms set the Bertrand price. Asymmetric pricing still emerges in this framework, with the only difference that the upstream firm can extract the downstream firms' profits through a fixed fee.

The results of our paper can apply to different sectors characterized by storage opportunities. For instance, banks that issue deposits and employ these funds to provide loans generally adjust the amount of liquidity they possess and the rates on their loans in response to a change in the central bank's interest rate (e.g., Chiesa 2001).

Our analysis sheds new light on the empirical evidence about asymmetric pricing. The predictions of our model lend themselves to an empirical validation that disentangles the demand side effects already investigated in the literature from the supply side effects identified in our approach.

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Appendix

This Appendix collects the proofs.

Proof of Lemma 1. A. Suppose $r_{1A} + r_{1B} \leq d$. In the quantity setting game, for $i, j \in \{A, B\}$, $i \neq j$, the analysis proceeds through the following cases:
(i) $p_{2i} = p_{2j} > c_2 \Rightarrow s_{2i} = \frac{d}{2}$, $i \in \{A, B\}$.
(ii) $p_{2i} = p_{2j} = c_2 \Rightarrow s_{2A} + s_{2B} \leq d$.
(iii) $p_{2i} > p_{2j} > c_2 \Rightarrow s_{2i} = 0$; $s_{2j} = d$.
(iv) $p_{2i} > p_{2j} = c_2 \Rightarrow s_{2i} = d - s_{2j}$; $s_{2j} \in [r_{1j}, d]$.
(v) $p_{2i} > c_2 > p_{2j} \Rightarrow s_{2i} = d - s_{2j}$; $s_{2j} = r_{1j}$.
(vi) $p_{2i} = c_2 > p_{2j} \Rightarrow s_{2i} \in [\min\{r_{1i}, d - s_{2j}\}, d - s_{2j}]$; $s_{2j} = r_{1j}$.
(vii) $p_{2i} = p_{2j} < c_2 \Rightarrow s_{2i} = \min\{r_{1i}, \max\{\frac{d}{2}, d - s_{2j}\}\}$, $i \in \{A, B\}$.
(viii) $p_{2j} < p_{2i} < c_2 \Rightarrow s_{2i} = \min\{r_{1i}, d - s_{2j}\}$; $s_{2j} = r_{1j}$.

The candidate equilibria in the price setting game are the following: (a) $p_{2i} = p_{2j} = c_2$; (b) $p_{2i} = p_{2j} > c_2$; (c) $p_{2i} > p_{2j} \geq c_2$; (d) $p_{2i} \geq c_2 > p_{2j}$; (e) $p_{2i} < c_2$, $i \in \{A, B\}$. We first show that candidate (a) is an equilibrium. It follows from (ii) that in equilibrium firm i's quantity is $s_{2i} \in [r_{1i}, d]$, which yields profits equal to $\Pi_{2i} = c_2 r_{1i}$. Given (iv), when $s_{2j} = d$, no profitable upward price deviation exists. From (vi) it follows that there is no incentive to deviate downwards, either. Therefore, the candidate (a) is an equilibrium.

We now show that the price in (a) is the unique equilibrium of this subgame. Candidate (b) is not an equilibrium since if firm i sets a price $p'_{2i} = p_{2j} - \epsilon > c_2$, with $\epsilon > 0$ and small enough, it can get higher profits. Candidate (c) is not an equilibrium since firm j can set a price $p'_{2j} \in (p_{2j}, p_{2i})$ and get higher profits. Candidate (d) is not an equilibrium since firm j can set a price $p'_{2j} \in (p_{2j}, c_2)$ and gain by selling its reserves. If it does not have any reserves, firm i can gain by setting a higher price. Candidate (e) is not an equilibrium since both firms have an incentive to raise their prices. Therefore, any pure strategy equilibrium of this continuation game must be such that $p^*_{2i} = c_2$, $s^*_{2A} + s^*_{2B} \leq d$ and $r^*_{2i} = 0$, $i \in \{A, B\}$. Since we allow for voluntary trading, the market may not be fully covered, but all the reserves are sold.

B. Suppose $r_{1A} + r_{1B} > d$. In the Supplementary Appendix available online, we show that it follows from Dasgupta and Maskin (1986a) that this continuation game possesses a mixed strategy equilibrium and we discuss its main features. This game corresponds to a price competition game with (a)symmetric capacity constraints. In equilibrium, firms randomize over prices within an interval whose upper bound is c_2, which yields expected prices $\mathbb{E}\left[p^*_{2i} \middle| c_2\right] < c_2$, $i \in \{A, B\}$. Any price above c_2 cannot be chosen with positive probability, since price undercutting is profitable. Moreover, choosing with probability 1 a price equal to c_2 cannot be sustained as an equilibrium since each firm has an incentive to undercut the rival's price and sell off its reserves (this is the final period of the game). In equilibrium, the market is fully covered and no firm orders any additional quantities (that would be paid at c_2), which implies that a firm's reserves at the end of the second period correspond to the leftovers from the first period that the firm is not able to sell in the second period. Then, any equilibrium of this continuation game must be such that $\mathbb{E}\left[p^*_{2i} \middle| c_2\right] < c_2$, $s^*_{2A} + s^*_{2B} = d$ and $r^*_{2i} = r_{1i} - s^*_{2i}$, $i \in \{A, B\}$. ■

Proof of Remark 1. Since $\mathbb{E}[c_2] = c$, it follows from Lemma 1 that $\mathbb{E}[p^*_{2i}] \leq c$, $i \in \{A, B\}$. For $\delta < 1$, storing induces losses, since $\delta\mathbb{E}[p^*_{2i}] < c_1 = c$, $i \in \{A, B\}$. Hence, as in Chowdhury (2005), in the pure strategy SPNE we have $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$ and $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. For $\delta = 1$, storing is not harmful if $r_{1A} + r_{1B} \leq d$, since it follows from Lemma 1A that $\mathbb{E}[p^*_{2i}] = c_1$. Then, any outcome $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$, $r^*_{1A} + r^*_{1B} \leq d$ and $r^*_{2i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$, can be sustained in equilibrium. ■

Proof of Proposition 1. A. For $\delta\mathbb{E}[c_2] \geq c_1$, each firm finds it profitable (in expectation) to order one unit at c_1 in the first period and sell it in the second period. Note that any pure strategy SPNE must exhibit the second period price $p^*_{2i} = c_2$, $i \in \{A, B\}$. This is because in equilibrium the demand is fully covered in the first period, and therefore the aggregate reserves from the first period cannot exceed d, which implies from Lemma 1A that the second period (pure strategy) equilibrium price is $p^*_{2i} = c_2$, $i \in \{A, B\}$. To see this, suppose that in equilibrium the demand in the first period is not fully covered. Since in equilibrium the first period price cannot exceed $\delta\mathbb{E}[c_2]$ (otherwise the standard price undercutting rationale applies), there exists (at least) one firm with aggregate demand below d, whose aggregate expected profits are lower than $(\delta\mathbb{E}[c_2] - c_1)\, d$. This firm can profitably deviate by ordering d and setting a sufficiently high price in the first period. By doing so, it can cover the residual demand or, if the rival serves the whole market, it expects to cover the full demand in the second period at c_2 (from Lemma 1A), which yields aggregate expected profits (at least) equal to $(\delta\mathbb{E}[c_2] - c_1)\, d$. Since the demand must be fully covered in the first period, the aggregate reserves from the first period cannot exceed d, which implies from Lemma 1A that in the (pure strategy) equilibrium we must have $p^*_{2i} = c_2$, $i \in \{A, B\}$, and therefore $\mathbb{E}[p^*_{2i}] = \mathbb{E}[c_2]$. Now, we argue that no equilibrium exists which involves a first period price such that $c_1 \leq p_{1i} < \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$. Proceeding by contradiction, suppose that such an equilibrium exists. This candidate equilibrium must imply that each firm will order d in the first period, i.e., $q_{1i} = d$, $i \in \{A, B\}$, since this quantity can be sold profitably in either period. Note that the outcome $s_{1i} = 0$, $s_{2i} = d$ and $s_{1j} = d$, $s_{2j} = 0$ cannot be supported as an equilibrium in the quantity setting game for $c_1 \leq p_{1i} < \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$. To see this, consider a deviation of firm j which stores a quantity $r_{1j} > 0$ for the second period. It follows from Lemma 1B that a mixed strategy equilibrium in the second period continuation game exists. Firm j can choose a sufficiently small quantity $r_{1j} > 0$ such that the lower bound of the price interval is higher than p_{1j}/δ. Hence, firm j which stores r_{1j} for the next period gains from such a deviation. This result is crucial in order to show that there exists an incentive for an upward price deviation in the first period with prices $c_1 \leq p_{1i} < \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$. Let $L_i \equiv \{\mathbb{E}[\Pi_i] : \mathbb{E}[\Pi_i] = p_{1i}s_{1i} + \delta\mathbb{E}[c_2](d - s_{1i}) - c_1 d\}$ be the set of firm i's expected profits associated with the candidate $c_1 \leq p_{1i} < \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$, if an equilibrium in quantities exists. It follows from the previous discussion that $\sup(L_i) < (\delta\mathbb{E}[c_2] - c_1)\, d$. Now, we characterize the equilibrium in the first period quantity setting game following a deviation such that $p'_{1i} > \delta\mathbb{E}[c_2] > p_{1j}$. Let $S_i \equiv \left\{\mathbb{E}\left[\Pi'_i\right] : \mathbb{E}\left[\Pi'_i\right] = p'_{1i}s'_{1i} + \delta\mathbb{E}[c_2]\left(d - s'_{1i}\right) - c_1 d\right\}$ be the set of firm i's expected profits associated with $p'_{1i} > \delta\mathbb{E}[c_2] > p_{1j}$. Firm j strictly prefers to store some quantity for the second period and therefore firm i can sell something in the first period. This implies that $\inf(S_i) > (\delta\mathbb{E}[c_2] - c_1)\, d > \sup(L_i)$. Since an equilibrium in quantities with $p'_{1i} > \delta\mathbb{E}[c_2] > p_{1j}$ exists (e.g., $s_{1i} = d$, $s_{2i} = 0$, $s_{1j} = 0$, $s_{2j} = d$), it follows that firm i has an incentive to deviate and $c_1 \leq p_{1i} < \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$, cannot be an equilibrium.

It is straightforward to show that any other price configuration cannot be sustained as an equilibrium, except $p_{1i} = \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$. In particular, $p_{1i} > \delta\mathbb{E}[c_2] > p_{1j}$ is not an equilibrium, since firm j can set a price $p'_{1j} = p_{1i} - \epsilon > \delta\mathbb{E}[c_2]$, with $\epsilon > 0$ and small enough, and gain higher profits. Moreover, $p_{1i} = \delta\mathbb{E}[c_2] > p_{1j}$ cannot be an equilibrium, either. Firm j does not have any incentive to deviate only when $s_{1j} = 0$ and $s_{2j} = d$ in equilibrium. However, in this case firm i gets expected profits $(\delta\mathbb{E}[c_2] - c_1)\, d$ and we know from the previous discussion that it can set $p'_{1i} > \delta\mathbb{E}[c_2] > p_{1j}$ and gain. Any price $p_{1i} \geq \delta\mathbb{E}[c_2]$, with $p_{1i} > \delta\mathbb{E}[c_2]$ for at least one $i \in \{A, B\}$, cannot be sustained as an equilibrium, because the standard undercutting rationale applies. Clearly, any price $p_{1i} < c_1$ for at least one $i \in \{A, B\}$ cannot be an equilibrium, either.

The only equilibrium price candidate that we have not investigated yet is $p_{1i} = \delta\mathbb{E}[c_2]$, $i \in \{A, B\}$, which gives firm i expected profits equal to $(\delta\mathbb{E}[c_2] - c_1)\, d$. Note that, irrespective of the direction of price deviation by firm i, there exists an equilibrium in the quantity setting game where $s_{1i} = 0$, $s_{2i} = d$ and $s_{1j} = d$, $s_{2j} = 0$. In this case, no deviation is profitable. Since for a price $p_{1i} = \delta\mathbb{E}[c_2]$ firm i is indifferent between storing or not, the outcome of the game is a pure strategy SPNE if and only if $p^*_{1i} = \delta\mathbb{E}[c_2]$, $p^*_{2i} = c_2$, $s^*_{\tau A} + s^*_{\tau B} = d$, $r^*_{1i} = d - s^*_{1i}$ and $r^*_{2i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$.

B. For $\delta \mathbb{E}[c_2] < c_1$, storing is not profitable, since the first period marginal cost is higher the second period discounted expected price. Therefore, the standard Bertrand outcome arises and, as in Remark 1 for $\delta < 1$, the outcome of the game is a SPNE if and only if $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$ and $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. ■

Proof of Proposition 2. Since storing is not profitable, the same argument as in the proof of Proposition 1B applies. ■

Proof of Proposition 3. See the Supplementary Appendix. ■

Proof of Proposition 4. See the Supplementary Appendix. ■

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Asymmetric price adjustments: A supply side approach
Supplementary Appendix

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1 Introduction

This Supplementary Appendix complements the paper and proceeds as follows. Section 2 proves the existence of a mixed strategy equilibrium in Lemma 1B (Section 3.1 of the paper) and illustrates its main features. Section 3 provides a rigorous and detailed description of the monopoly setting (Section 5.6 of the paper). Section 4 collects the proofs of Propositions 3 and 4 (Section 4 of the paper).

2 Mixed strategy equilibrium in Lemma 1B

2.1 Existence of equilibrium

For our purposes, it is helpful to present the following theorem of Dasgupta and Maskin (1986a, p. 24).

Theorem 1 (mixed strategy equilibrium) *For all agents $i = 1, \ldots, N$, let $A_i \subseteq R^m$ $(m \geq 1)$ be agent i's non-empty, convex and compact strategy set, where a_i is a typical element of A_i and a_{ik} $(k = 1, \ldots, m)$ is the k-th component a_i. Moreover, let $U_i : A \rightarrow R^1$, where $A = \prod_{j=1}^{N} A_j$, be agent i's payoff function which is continuous except on a subset $A^{**}(i)$ of $A^*(i)$, where $A^*(i)$ is defined for each pair of agents $i, j \in \{1, \ldots, N\}$ by*

$$A^*(i) = \left\{ (a_1, \ldots, a_N) \in A | \, \exists j \neq i, \exists k \in Q \subseteq \{1, \ldots, m\}, \exists d, 1 \leq d \leq D(i) \text{ such that } a_{jk} = f_{ij}^d(a_{ik}) \right\},$$

with d and $D(i)$ positive integers and $f_{ij}^d = \left(f_{ij}^d\right)^{-1}$.

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Suppose $\sum_{i=1}^{N} U_i(\mathbf{a})$ *is upper semi-continuous, and* $U_i(a_i, \mathbf{a}_{-i})$ *is bounded and weakly lower semi-continuous in* a_i*, where* $\mathbf{a} = (a_i, \mathbf{a}_{-i})$ *and* $\mathbf{a}_{-i} = (a_1, a_2, \ldots, a_{i-1}, a_{i+1}, \ldots, a_N)$*. Then, the game* $[(A_i, U_i); i = 1, \ldots, N]$ *possesses a mixed strategy equilibrium.*

We check step by step that all the assumptions of Theorem 1 are satisfied in our setting. Note that we can restrict the strategy set from which firm $i = 1, 2$ may choose. Any price above c_2 cannot be chosen with positive probability, since price undercutting is profitable. Moreover, choosing with probability 1 a price equal to c_2 cannot be an equilibrium, since at least one firm would have an incentive to undercut the rival's price and sell off its reserves. Since firm $i = 1, 2$ places on the market all its reserves r_{1i} (whose cost was incurred in the first period) and does not order any additional quantity (which would be paid at c_2), the strategy set of firm i is $A_i = [0, c_2] \times \{r_{1i}\} \subseteq R^2$, which is a non-empty, convex and compact set. Since r_{1i} does not play any role, with a small abuse of notation we drop it hereafter, and firm i's strategy coincides with its price. This game corresponds to a Bertrand-Edgeworth price competition game with capacity constraints, and the following analysis is closely related to Dasgupta and Maskin (1986b, pp. 27-29), who show the existence of a mixed strategy equilibrium in a Bertrand-Edgeworth game with a monotonically decreasing demand function.

Now, we check whether firm i's payoff U_i is continuous in $a_i \in [0, c_2]$. It turns out that firm i's payoff is everywhere continuous except in the set $A^*(i)$ where the price strategies of the two firms coincide (f_{ij}^d in Theorem 1 is the identity function). In particular,

$$A^*(1) = A^*(2) = \left\{ (a_1, a_2) \in [0, c_2]^2 \middle| a_1 = a_2 \right\}.$$

Moreover, U_i is bounded, given that $a_i \in [0, c_2]$ and the demand d is clearly finite. To verify that U_i is weakly lower semi-continuous, we present the following definition provided by Dasgupta and Maskin (1986a, p. 13).

Definition 1 (weakly lower semi-continuity) $U_i(a_i, \mathbf{a}_{-i})$ *is weakly lower semi-continuous in* a_i *if* $\forall \overline{a}_i \in A^{**}(i)$*,* $\exists \lambda \in [0, 1]$ *such that* $\forall \mathbf{a}_{-i} \in A_{-i}^{**}(\overline{a}_i) = \{\mathbf{a}_{-i} \in A_{-i} | (\overline{a}_i, \mathbf{a}_{-i}) \in A^{**}(i)\}$ *we have*

$$\lambda \lim \inf_{a_i \to \overline{a}_i^-} U_i(a_i, \mathbf{a}_{-i}) + (1 - \lambda) \lim \inf_{a_i \to \overline{a}_i^+} U_i(a_i, \mathbf{a}_{-i}) \geq U_i(\overline{a}_i, \mathbf{a}_{-i}),$$

where '$a_i \to \overline{a}_i^-$*' ('*$a_i \to \overline{a}_i^+$*') indicates that* a_i *approaches* $\overline{a}_i$ *from the left (from the right).*

A price decrease from $\overline{a}_1 = \overline{a}_2 \in (0, c_2]$ yields firm i a discontinuous increase in U_i, namely, $\lim \inf_{a_i \to \overline{a}_i^-} U_i(a_i, \mathbf{a}_{-i}) \geq U_i(\overline{a}_i, \mathbf{a}_{-i})$ for any $\mathbf{a}_{-i} \in A_{-i}^{**}(\overline{a}_i)$. In other words, $U_i(a_i, \mathbf{a}_{-i})$ is left lower semi-continuous in a_i for any $\overline{a}_i \in (0, c_2]$. If $\overline{a}_1 = \overline{a}_2 = 0$ we have $U_i(\overline{a}_i, \mathbf{a}_{-i}) = 0$ and therefore $U_i(a_i, \mathbf{a}_{-i})$ is right lower semi-continuous in a_i at $\overline{a}_i = 0$. Then, $U_i(a_i, \mathbf{a}_{-i})$ is weakly lower semi-continuous in a_i for any $\overline{a}_i \in [0, c_2]$. Finally, the summation of the firms' payoffs $U_1 + U_2$ is continuous and, a fortiori, upper semi-continuous. Since all the assumptions in Theorem 1 are satisfied, the second period continuation game in Lemma 1B possesses a mixed strategy equilibrium.

2.2 Main features of equilibrium

We now characterize a mixed strategy equilibrium for some relevant cases in Lemma 1B and derive its main features. The analysis closely follows Levitan and Shubik (1972).

Symmetric case

Suppose $r_{1A} = r_{1B} \equiv r_1 > \frac{d}{2}$. The second period profits of firm $i \in \{A, B\}$ are given by

$$\Pi_{2i}(p_{2i}) = p_{2i}\left[(1-\phi_j(p_{2i}))\min\{r_1, d\} + \phi_j(p_{2i})\max\{0, \min\{r_1, d-r_1\}\}\right],$$

where $\phi_j(.)$ is the price distribution function for firm $j \neq i$, which indicates the probability that firm j's price is lower than firm i's price. This expression reduces to

$$\Pi_{2i}(p_{2i}) = p_{2i}\left[(1-\phi_j(p_{2i}))r_1 + \phi_j(p_{2i})(d-r_1)\right].$$

We first derive the bounds of the price range $[p_l, p_h]$. It is straightforward to see that $p_h = c_2$, since for any price above c_2 the rival has an incentive to undercut. Given that Π_{2i} is constant over $[p_l, p_h]$, the value for p_l is the solution to the following condition

$$\Pi_{2i}(c_2) = c_2(d-r_1) = \Pi_{2i}(p_l) = p_l r_1,$$

which gives $p_l = \frac{c_2(d-r_1)}{r_1}$. Then, we derive the price distribution function in equilibrium. Using the expression for $\Pi_{2i}(p_2)$ and exploiting symmetry, we have

$$\Pi_{2i}(p_2) = p_2\left[(1-\phi(p_2))r_1 + \phi(p_2)(d-r_1)\right] = \Pi_{2i}(c_2) = c_2(d-r_1),$$

which yields $\phi^*(p_2) = \frac{p_2 r_1 - c_2(d-r_1)}{p_2(2r_1-d)} \in [0,1]$. Standard comparative statics analysis delivers the following results:

(i) if the firm's reserves can cover the whole market ($r_1 = d$), the second period equilibrium price is driven to zero ($p_l = 0$ and $\phi^*(p_2) = 1$);

(ii) if the firm's reserves can cover (approximately) half of the market ($r_1 \to \frac{d}{2}$), the price range degenerates to c_2 ($p_l \to c_2$) and the second period equilibrium price converges to c_2;

(iii) higher reserves make competition tougher and the second period equilibrium expected price decreases ($\frac{\partial\phi^*}{\partial r_1} = \frac{d(c_2-p_2)}{p_2(2r_1-d)^2} > 0$ for $p_2 < p_h$).

Asymmetric case

Suppose $r_{1A} = d$ and $r_{1B} < d$. The profits of firms A and B are respectively

$$\Pi_{2A}(p_{2A}) = p_{2A}\left[d - \phi_B(p_{2A})r_{1B}\right]$$

$$\Pi_{2B}(p_{2B}) = p_{2B}r_{1B}\left[1-\phi_A(p_{2B})\right].$$

As before, the upper bound of the price range $[p_l, p_h]$ is $p_h = c_2$. Since Π_{2i} is constant over $[p_l, p_h]$, the lower bound of the price range is the solution to the following condition

$$\Pi_{2A}(c_2) = c_2(d - r_{1B}) = \Pi_{2A}(p_l) = p_l d,$$

which gives $p_l = \frac{c_2(d-r_{1B})}{d}$. Then, we compute the price distribution functions for the two firms in equilibrium. Using the expressions for $\Pi_{2A}(p_2)$ and $\Pi_{2B}(p_2)$, we have

$$\Pi_{2A}(p_2) = p_2[d - \phi_B(p_2) r_{1B}] = \Pi_{2A}(c_2) = c_2(d - r_{1B})$$

$$\Pi_{2B}(p_2) = p_2 r_{1B}[1 - \phi_A(p_2)] = \Pi_{2B}(p_l) = p_l r_{1B} = \frac{c_2(d - r_{1B})}{d} r_{1B},$$

which yields $\phi_A^*(p_2) = 1 - \frac{c_2(d-r_{1B})}{dp_2} \in [0,1]$ and $\phi_B^*(p_2) = \frac{d}{r_{1B}} - \frac{c_2(d-r_{1B})}{p_2 r_{1B}} \in [0,1]$. Standard comparative statics analysis delivers the following results:
(i) if firm B's reserves can cover (approximately) the whole market ($r_{1B} \to d$), the second period equilibrium price is driven to zero ($p_l \to 0$ and $\phi_i^*(p_2) \to 1$, $i \in \{A, B\}$);
(ii) if firm B's reserves tend to zero ($r_{1B} \to 0$), the price range degenerates to c_2 ($p_l \to c_2$) and the second period equilibrium price converges to c_2;
(iii) an increase in firm B's reserves makes competition tougher and the second period equilibrium expected prices decrease ($\frac{\partial \phi_A^*}{\partial r_{1B}} = \frac{c_2}{dp_2} > 0$ and $\frac{\partial \phi_B^*}{\partial r_{1B}} = \frac{d(c_2-p_2)}{p_2 r_{1B}^2} > 0$ for $p_2 < p_h$);
(iv) the expected price of firm A (endowed with larger reserves) is higher than the expected price of firm B ($\phi_A^*(p_2) < \phi_B^*(p_2)$ for $p_2 > p_l$).

3 Monopoly setting

Consider a monopolist that operates in two periods with (constant) marginal costs c_1 and c_2. The demand function is $D_\tau(p_\tau) = 1 - p_\tau$ in period $\tau \in \{1,2\}$. Define by K^m the monopolist's storage capacity. When a positive cost shock occurs, i.e., $c_1 > c$, storing is unprofitable and the monopolist sells in each period τ the quantity that corresponds to the static monopoly level, i.e., $s_\tau^m = \frac{1-c_\tau}{2}$. Hereafter, we consider the relevant case of a negative cost shock, i.e., $c_1 < c$, where the second period discounted expected marginal cost is higher than the first period marginal cost, i.e., $\delta \mathbb{E}[c_2] > c_1$.

The monopolist's first period profits are given by

$$\Pi_1^m = [p_1(s_1) - c_1] s_1 - c_1 r_1,$$

where s_1 is the quantity sold in the first period and r_1 is the quantity stored for the second period.

The monopolist's second period profits associated with the expected cost $\mathbb{E}[c_2]$ are given by

$$\Pi_2^m = p_2(\max\{s_2^e, r_1\}) r_1 + \{p_2(\max\{s_2^e, r_1\}) - \mathbb{E}[c_2]\} \max\{s_2^e - r_1, 0\},$$

where s_2^e is the static monopoly quantity associated with $\mathbb{E}[c_2]$. Note that the quantity that the monopolist expects to sell in the second period is $\max\{s_2^e, r_1\}$.

The monopolist's maximization program can be written as

$$\max_{s_1, r_1, s_2^e} \Pi_1^m(s_1, r_1) + \delta \Pi_2^m(s_2^e, r_1) \quad s.t. \quad s_1 + r_1 \leq K^m.$$

It follows from our demand specification that in equilibrium $s_2^e = \frac{1-\mathbb{E}[c_2]}{2}$. For the sake of convenience, we restrict our attention to the situation where storing some quantity for the next period is always profitable for the monopolist. This means that the storage capacity is sufficiently large that, even when the monopolist cannot store as much as it wishes (i.e., the capacity constraint is binding), a trade-off occurs between selling in the first period and storing for the second period. The analysis proceeds through the following three cases.

(a) $K^m \geq 1 - \frac{c_1}{2\delta}(1+\delta)$. We claim that in equilibrium $\max\{s_2^e, r_1\} = r_1$, i.e., $s_2^e = \frac{1-\mathbb{E}[c_2]}{2} \leq r_1$, which can be checked ex post. It follows from the demand function that $p_2(\max\{s_2^e, r_1\}) = 1 - r_1$. Ignoring the capacity constraint (which is slack in equilibrium) and taking the first-order conditions for s_1 and r_1 yields $s_1^a = s_1^m = \frac{1-c_1}{2}$ and $r_1^a = \frac{1-c_1/\delta}{2}$. Note that, since it does not expect to order (or produce) in the second period, the monopolist equalizes the discounted marginal revenues associated with s_1^a and r_1^a. As $s_1^a = s_1^m$, the magnitude of the initial price variation is the same as with a positive shock. In order to investigate the magnitude of later adjustment, we assume $c_1 = c_2$ (see Section 4 of the paper). Since the marginal revenue associated with the quantity stored for the second period is higher than the second period marginal cost, i.e., $c_1/\delta \geq c_2$, the firm prefers to purchase from its distributor (or produce) even in the second period, which yields $s_2^m = \frac{1-c_2}{2}$. It is straightforward to see the later price variation is also the same as with a positive shock. Therefore, when the firm does not have any binding capacity constraint, the price adjustment to costs is fully symmetric.

(b) $1 - \frac{\mathbb{E}[c_2]}{2}(1+\delta) < K^m < 1 - \frac{c_1}{2\delta}(1+\delta)$. We claim that in equilibrium $\max\{s_2^e, r_1\} = r_1$, i.e., $s_2^e = \frac{1-\mathbb{E}[c_2]}{2} \leq r_1$, which can be checked ex post. Using $p_2(\max\{s_2^e, r_1\}) = 1 - r_1$ and substituting the binding capacity constraint into the firm's maximization program, the first-order condition for s_1 yields $s_1^b = \frac{1-\delta+2\delta K^m}{2(1+\delta)}$ and $r_1^b = K^m - s_1^b = \frac{2K^m - 1 + \delta}{2(1+\delta)}$. Note that, as in the previous case, the monopolist does not expect to order (or produce) in the second period and therefore the marginal revenues associated with s_1^b and r_1^b are equalized (in discounted terms). Since $s_1^b < s_1^m$ (and $s_1^b > s_0^m$, where $s_0^m = \frac{1-c}{2}$ is the quantity sold in the pre-shock period), the initial price adjustment is less significant after a negative shock. The monopolist mitigates its price response after a negative shock since it expects higher costs in the second period and therefore prefers to forgo some current sales in order to store a greater amount of output for the next period. Since for $c_1 = c_2$ the marginal revenue associated with r_1^b is higher than the second period marginal cost, i.e., $\frac{2-2K^m}{1+\delta} \geq c_2$, the second period quantity is s_2^m. This implies that the magnitude of later adjustment is higher with a negative shock.

(c) $K^m \leq 1 - \frac{\mathbb{E}[c_2]}{2}(1+\delta)$. We claim that in equilibrium $\max\{s_2^e, r_1\} = s_2^e$, i.e., $s_2^e = \frac{1-\mathbb{E}[c_2]}{2} \geq r_1$, which can be checked ex post. Using $p_2(\max\{s_2^e, r_1\}) = \frac{1+\mathbb{E}[c_2]}{2}$ and substituting the binding capacity constraint into the firm's maximization program, the first-order condition for s_1 yields $s_1^c = \frac{1-\delta\mathbb{E}[c_2]}{2}$ and $r_1^c = K^m - s_1^c = \frac{2K^m-1+\delta\mathbb{E}[c_2]}{2}$. Note that now, since the monopolist expects to order (or produce) even in the second period, the marginal revenues associated with s_1^c and s_2^e are equalized (in discounted terms). Since $s_1^c < s_1^m$ (and $s_1^c > s_0^m$), the initial price adjustment is less significant after a negative shock. As before, the monopolist mitigates its price response after a negative shock. Moreover, since for $c_1 = c_2$ the marginal revenue associated with r_1^c is higher than the second period marginal cost, i.e., $2 - 2K^m - \delta\mathbb{E}[c_2] \geq c_2$, the second period quantity is s_2^m. Therefore, the magnitude of later adjustment is still more pronounced with a negative shock.

4 Proofs of Propositions 3 and 4

Proof of Proposition 3. Let $\delta\mathbb{E}[c_2] \geq c_1$. We first derive the equilibrium in the first period quantity setting game for $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$. Note that in equilibrium both firms order $q_{1A} + q_{1B} \geq d$, since the unit cost is $\widetilde{c}_1 = c_1$ for $q_{1A} + q_{1B} \leq d$. The quantity ordered by firm i in the first period can be written as $q_{1i} = \widetilde{q}_{1i}^e + q_{1i}^e$, where $\widetilde{q}_{1i}^e$ denotes the quantity ordered by firm i such that together with the quantity ordered by firm j we have $\widetilde{q}_{1A}^e + \widetilde{q}_{1B}^e = d$. For a given $\widetilde{q}_{1i}^e$, firm $i \in \{A, B\}$ chooses the quantity q_{1i}^e and faces the unit cost $\widetilde{c}_1 = \frac{c_1 d + \mathbb{E}[c_2]\left(q_{1A}^e + q_{1B}^e\right)}{d + q_{1A}^e + q_{1B}^e}$. Firm i's maximization problem is given by

$$\max_{q_{1i}^e \geq 0} \delta\mathbb{E}[c_2](\widetilde{q}_{1i}^e + q_{1i}^e) - \widetilde{c}_1(\widetilde{q}_{1i}^e + q_{1i}^e).$$

For $i, j \in \{A, B\}$, $i \neq j$, the first-order condition for an interior solution is

$$\frac{\delta\mathbb{E}[c_2](d + q_{1A}^e + q_{1B}^e)^2 - c_1 d\left(d + q_{1j}^e - \widetilde{q}_{1i}^e\right) - \mathbb{E}[c_2]\left[(q_{1A}^e + q_{1B}^e)^2 + d\left(2q_{1i}^e + q_{1j}^e + \widetilde{q}_{1i}^e\right)\right]}{\left(d + q_{1A}^e + q_{1B}^e\right)^2} = 0.$$

Combining terms yields the best response function for firm i

$$q_{1i}^e\left(q_{1j}^e\right) = -\left(d + q_{1j}^e\right) + \frac{(\mathbb{E}[c_2] - c_1)^{\frac{1}{2}}\left[d\mathbb{E}[c_2]\left(d + q_{1j}^e - \widetilde{q}_{1i}^e\right)(1-\delta)\right]^{\frac{1}{2}}}{\mathbb{E}[c_2](1-\delta)}. \tag{A.1}$$

Solving (A.1) implies that in the unique (symmetric) equilibrium the quantity ordered by firm i is

$$q_{1i}^* = \widetilde{q}_{1i}^{e*} + q_{1i}^{e*} = \frac{(\mathbb{E}[c_2] - c_1)\,d}{4\mathbb{E}[c_2](1-\delta)}. \tag{A.2}$$

Since $\widetilde{q}_{1A}^e + \widetilde{q}_{1B}^e = d$, (A.2) is a solution for firm i's maximization problem if $\frac{(\mathbb{E}[c_2]-c_1)d}{4\mathbb{E}[c_2](1-\delta)} - \frac{d}{2} \geq 0$, which implies $\delta \geq \frac{1}{2}\left(1 + \frac{c_1}{\mathbb{E}[c_2]}\right)$. In the sequel, we split the analysis according to the value of the discount factor δ.

A. Assume $\delta \geq \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$. For $\delta = \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, we obtain from (A.2) $q_{1i}^* = d$, $i \in \{A, B\}$. Since $\frac{\partial q_{1i}^*}{\partial \delta} > 0$, it follows that $q_{1i}^* = d$, $i \in \{A, B\}$, still holds for higher values of δ. The analysis of

Proposition 1A carries over, and therefore $p_{1i}^* = \delta\mathbb{E}[c_2]$ and $p_{2i}^* = c_2$ are the equilibrium prices.

B. Assume $\frac{c_1}{\mathbb{E}[c_2]} < \delta < \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$. We first demonstrate that the candidate $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, cannot be an equilibrium since a firm has an incentive to increase its price in the first period. Such a deviation would not be profitable if and only if the rival orders and sells d in the first period. We show that this cannot be an equilibrium in the quantity setting game after this deviation. Note that, since firm i's (marginal) revenue increases (or at least it does not decrease) after this deviation, firm i does not want to buy less than in the candidate equilibrium and, in response, the non-deviating firm j does not want to buy more. For $\delta \geq \frac{1}{2}\left(1 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, the equilibrium in the quantity setting game with $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, is still described by (A.2). Therefore, after an upward price deviation of firm i, the non-deviating firm j will not buy more than $\frac{(\mathbb{E}[c_2]-c_1)d}{4\mathbb{E}[c_2](1-\delta)} < d$. Since firm i can gain from a sufficiently high price by serving the uncovered part of the market and an equilibrium in the quantity setting game exists after this deviation ($s_{1i} = d$, $s_{2i} = 0$ and $s_{1j} = 0$, $s_{2j} = d$), the candidate $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, cannot be an equilibrium for $\frac{1}{2}\left(1 + \frac{c_1}{\mathbb{E}[c_2]}\right) \leq \delta < \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$. If $\delta < \frac{1}{2}\left(1 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, the solution in (A.2) is no longer valid. This implies that firm i's maximization problem yields $q_{1i}^e = 0$. Hence, for prices $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, the firms do not want to order in aggregate more than d. For our purposes, it is sufficient to show that an equilibrium in the quantity setting game with $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, cannot involve $q_{1i} = 0$ and $q_{1j} = d$. This is because, given that firm j buys d in the first period, firm i's marginal revenue is higher than the marginal cost at zero, i.e., $\delta\mathbb{E}[c_2] > c_1$, and therefore firm i has an incentive to order some quantity in the first period (and sell it in either period). This implies that the non-deviating firm j will buy less than d, and it will do so even after firm i's (upward) price deviation. Since firm i can gain from a sufficiently high price by serving the uncovered part of the market and an equilibrium in the quantity setting game exists after this deviation ($s_{1i} = d$, $s_{2i} = 0$ and $s_{1j} = 0$, $s_{2j} = d$), the candidate $p_{1i} = \delta\mathbb{E}[c_2]$ and $p_{2i} = c_2$, $i \in \{A, B\}$, cannot be an equilibrium also for $\frac{c_1}{\mathbb{E}[c_2]} < \delta < \frac{1}{2}\left(1 + \frac{c_1}{\mathbb{E}[c_2]}\right)$. When the first period prices are higher than $\delta\mathbb{E}[c_2]$, each firm has an incentive to undercut the rival's price to sell in the first period. Moreover, any price below $\delta\mathbb{E}[c_2]$ cannot be supported as an equilibrium, since the non-deviating firm prefers to sell some quantity in the next period and the rival could increase the price and sell profitably in the first period. Along these lines, it can be shown that any asymmetric price configuration (one firm sets the price above $\delta\mathbb{E}[c_2]$ and the rival below $\delta\mathbb{E}[c_2]$) cannot be an equilibrium, either. Therefore, for $\frac{c_1}{\mathbb{E}[c_2]} < \delta < \frac{1}{4}\left(3 + \frac{c_1}{\mathbb{E}[c_2]}\right)$, in the price setting game no equilibrium exists in pure strategies. Since rigid demand allows the deviating firm to set an infinite price and profits are unbounded, no equilibrium exists also in mixed strategies.

C. Assume $\delta \leq \frac{c_1}{\mathbb{E}[c_2]}$. For $\delta < \frac{c_1}{\mathbb{E}[c_2]}$, the proof of Proposition 1B is replicated. For $\delta = \frac{c_1}{\mathbb{E}[c_2]}$, storing is not harmful and firms are indifferent between storing or not if $s_{1A}^* + r_{1A}^* + s_{1B}^* + r_{1B}^* \leq d$, since $\widetilde{c}_1 = c_1$ and $\mathbb{E}[p_{2i}^*] = \mathbb{E}[c_2]$, $i \in \{A, B\}$, where the last equality follows from Lemma 1A. Then, the outcome of the game is a pure strategy SPNE if and only if $p_{\tau i}^* = c_\tau$, $s_{\tau A}^* + s_{\tau B}^* \leq d$, $s_{1A}^* + r_{1A}^* + s_{1B}^* + r_{1B}^* \leq d$ and $r_{2i}^* = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. ■

Proof of Proposition 4. Note first that $r_{1i} > 0$ is never optimal since $\widetilde{c}_1 > \mathbb{E}[c_2] \geq \mathbb{E}[p^*_{2i}]$, $i \in \{A, B\}$, where the second inequality follows from Lemma 1. This implies that the second period equilibrium price is $p^*_2 = c_2$. It is straightforward to show that any price configuration where $p_{1i} \geq p_{1j} > c_1$ or $p_1 > p_j = c_1$, for $i, j \in \{A, B\}$, $i \neq j$, cannot be sustained as an equilibrium since the standard price undercutting rationale applies. Moreover, in equilibrium no firm will set a price lower than the minimum average cost $\frac{c_1+\mathbb{E}[c_2]}{2}$, independently of what the rival does.

To proceed, it is useful to determine the outcome in the first period quantity setting game for some relevant cases:

(i) $p_{1i} > p_{1j} = c_1$. In equilibrium, firm i sets $s_{1i} = 0$ and firm j sets $s_{1j} = d$. Any $s_{1i} > 0$ cannot be an equilibrium, since firm j's best response would be $s_{1j} = d$ (which gives positive profits since $c_1 > \widetilde{c}_1$), and firm i would make losses.

(ii) $p_{1i} > c_1 > p_{1j} \geq \frac{c_1+\mathbb{E}[c_2]}{2}$. There does not exist any pure strategy equilibrium. This is because there is a threshold $\widetilde{q}_{1i} \in (0, d]$ for the quantity ordered by firm i at which firm j's profits when serving the entire market are zero, i.e., $\Pi_j = (p_{1j} - \widetilde{c}_1)\, d = 0$, and $\Pi_j > (<)\, 0$ if and only if $q_{1i} > (<)\, \widetilde{q}_{1i}$. Hence, the best response function of firm j is discontinuous and jumps from $q_{1j}(q_{1i}) = 0$ for $q_{1i} \leq \widetilde{q}_{1i}$ to $q_{1j}(q_{1i}) = d$ for $q_{1i} \geq \widetilde{q}_{1i}$. For our aims, it is sufficient to show that any mixed strategy equilibrium must be such that (a) the expected profit of firm i is strictly positive, and (b) the expected profit of firm j is zero. Afterward, we show the features of this equilibrium. The result (a) follows since there exists a quantity $q_{1i} < \widetilde{q}_{1i}$ such that firm i can serve the market profitably, i.e., $\Pi_i = (p_{1i} - \widetilde{c}_1)\, q_{1i} > 0$ for $p_{1i} > c_1 \geq \widetilde{c}_1$, and $\Pi_j = (p_{1j} - \widetilde{c}_1)\, d < 0$. To see the result (b), recall that any strategy $q_{1j} \in (0, d)$ is strictly dominated by 0 and d. The only strategy profile which is part of a mixed strategy equilibrium is the set $\{0, d\}$. Since any pure strategy which is part of a mixed strategy equilibrium must yield the same payoff given the strategy distribution of the opponent and $q_{1j} = 0$ yields zero payoff, then $q_{1j} = d$ must also yield zero, which implies that the profit of firm j is zero. A mixed strategy equilibrium in the quantity setting game prescribes that firm i sells with probability 1 the quantity $s_{1i} = \widetilde{q}_{1i}$, which makes firm j indifferent between its pure strategies played with positive probability, and firm j randomizes between zero and d with a probability such that $\arg\max_{s_{1i}} \Pi_i(s_{1i}) = \widetilde{q}_{1i}$.

(iii) $p_{1i} = c_1 > p_{1j} \geq \frac{c_1+\mathbb{E}[c_2]}{2}$. In equilibrium firm i sets $s_{1i} \in [0, \widetilde{q}_{1i}]$, where $\widetilde{q}_{1i}$ is defined in (ii), while firm j sets $s_{1j} = 0$.

(iv) $p_{1i} < c_1$. In equilibrium each firm sets $s_{1i} = 0$, $i \in \{A, B\}$.

It can be seen from (ii), (iii) and (iv) that $c_1 > p_{1i} \geq p_{1j}$ or $p_{1i} = c_1 > p_{1j}$ cannot be an equilibrium since firm i can increase the price above c_1 and gain.

It remains to show that $p_{1i} = c_1$, $i \in \{A, B\}$, is chosen in equilibrium. From (iii) it follows that no firm has an incentive to deviate downward. Similarly, the result in (i) indicates there is no upward profitable deviation. Hence, the outcome of the game is a pure strategy SPNE if and only if $p^*_{\tau i} = c_\tau$, $s^*_{\tau A} + s^*_{\tau B} \leq d$ and $r^*_{\tau i} = 0$, $\tau \in \{1, 2\}$, $i \in \{A, B\}$. ■