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Abstract

It is shown that staggered and sticky price adjustment is possible without *ad hoc* frictions, and without suspending full price flexibility. I consider an oligopoly with n price-setting firms which can strategically choose the timing of price decisions and thus the stage in a n-stage Stackelberg oligopoly game. After a shock, firms can credibly signal to delay their price adjustment for some time to (re-)establish a leader-follower structure. From the calculus behind this decision, it is derived which firm will adjust at which time and henceforth stage of the game. The delays are in general asymmetric with respect to direction and size of the shock, and they depend on market power, making the model consistent with a variety of empirical observations. Strategically delayed adjustment of firm prices implies also inertia in aggregated price level adjustment which plays a key role in macroeconomics.

Keywords: oligopoly, leader-follower structures, price dispersion, delayed price adjustment, cost shock, aggregated price dynamics, inflation

JEL Classification: D21, D43, L11, L16, E31

1 Introduction

Price rigidities are at the heart of New Keynesian Macroeconomics. The established explanations of such rigidities rely on some sort of frictions such like cost of price changes (á la Rotemberg (1982), Golosov and Lucas (2007), Alvarez et al. (2022)) or temporary inabilities to change a price (á la Calvo (1983)), or informational frictions (e.g. Reis (2006), Mankiw and Reis (2002), Woodford (2009), tracing back to Lucas (1972) signal extraction problem). A recent comprehensive overview over price setting models with frictions can be found in Costain and Nakov (2025). The microeconomic rigor of all these models starts *after* having accepted assumptions about not directly observable price adjustment costs, or Poisson arrival rates, interpreted as the fraction of firms which are "able" to adjust the price at time t, or fractions of agents who are not able or willing to use new information. The narratives behind the frictions may be convincing to some degree, e.g. Poisson arrival rates might reflect that firms are making contracts which guarantee a fixed price for a certain time period, or rational inattention to new information might be based on information-processing constraints (Sims (2003)). The empirical implications of all these mechanisms are different and might lead to different forms of inflation dynamics (e.g. state-dependent versus time-dependent, see Devereux and Siu (2007)).

But there is one key element all these mechanisms share: the reference point is a frictionless Arrow-Debreu world where the economy is in an efficient equilibrium. The Keynesian departure from that world is based on frictions and imperfections, thereby enabling welfare improving policy interventions which would be pointless in a seamless and frictionless world. The point is to show the relevance of imperfections and distortions by providing a rigorous microeconomic foundation which, however, always starts once when some frictions or constraints have been accepted beforehand. Although some constraints might be non-controversial, by following this route of argumentation we implicitly keep and protect the idea that with rational behavior and full flexibility we would achieve an efficient equilibrium outcome. As Blanchard (2025) points out, many economists accept nominal rigidities as an essential element of modern macroeconomics, but also feel uneasy because of the *ad hoc* character of the frictions. They use e.g. the Calvo mechanism though knowing that it is "at odds with reality".

In the recent years, empirical macroeconomic analysis considers more often sector-level or firm-level data, and theoretical models more frequently use oligopolies rather than monopolistic competition. Hence, a closer look to the *strategic* pricing behavior of oligopolistic firms could provide another approach to explain inertia in price adjustment which is in line with the rich set of empirical observations we have from micro data. As Alvarez et al. (2022) point out, understanding firm's price setting behavior is central for the analysis of nominal shocks and the resulting features of price stickiness. In this paper I develop a model which shows that price adjustment delays can be an outcome of intentional strategic choices even in a *frictionless* world. So we can obtain price inertia without suspending the assumption of full price flexibility. In contrast, it is essential that firms are free to decide to adjust prices at *any* desirable time. The only requirement is to consider the "generic market form" of a heterogeneous oligopoly. Market forms commonly used in macroeconomics, such as perfect competition or monopolistic competition, are artificial edge cases of this generic market form. The key insight is that in absence of frictions, firms can not only decide about *how* to change the price but also *when*. This dynamic element allows for establishing endogenous leader-follower structures which will boost firm's markups. Consequently, the absence of frictions does not necessarily mean that the economy moves towards more efficiency but enable, in contrast, a more sophisticated dynamic consumer rent extraction.

The core idea is that in case of price-setting symmetric firms, all firms benefit from a leader-follower structure compared to a simultaneous Bertrand-Nash solution. Under certain conditions, the follower benefits even more than the leader, thus creating an incentive to adjust the price "later" than the rivals. This is a quite simple insight which is well established in IO literature but not yet made fruitful for macroeconomics. As a side effect, such a strategic delay of price adjustment turns out to have features such as asymmetric responses to small and large shocks as well as asymmetries regarding positive and negative shocks, making the approach promising to explain a variety of empirical stylized facts. As we consider a dispersion of shocks across firms and industries, we obtain cumulated probabilities of delay times which can be interpreted like the Poisson arrival rates in the Calvo approach. Hence, the model enables a description of aggregate price level dynamics.

The paper is organized as follows: chapter 2 reviews some related literature on price stickiness from the field of macroeconomics and industrial organization, two different areas which usually do not have the same readership. Chapter 3 develops the core model. The first section shows the joint interest of n firms in a market to establish a n-stage Stackelberg leader-follower equilibrium. This is mainly based on Hamilton and Slutsky (1990). The strategic calculus for delayed price adjustment is developed in the subsequent section. Afterwards, the calculus is applied to the case of duopoly and a linear demand scheme for sake of simplicity. It is shown how price inertia depends on size and direction of the shock, the uncertainty about its idiosyncratic component, but also on substitution elasticity and the discount rate. Afterwards, it is shown that the results are qualitatively the same for the case of an iso-elastic demand scheme. Next, I explore the case of $n > 2$ firms to get an idea how the number of firms influences the aggregated delay time. Finally, chapter 4 shows that the pattern of price adjustment in time can be described by a Gamma distribution of adjustment rates across industries which result in an impulse response dynamic for the inflation rate. Chapter 5 concludes.

2 Related literature

The existing literature on price setting behavior based on frictions is reviewed already in Costain and Nakov (2025), among others. I concentrate on literature which explores the role of strategic firm behavior in macroeconomics, and its impact on price rigidity, as well as on industrial organization literature on endogenous leader-follower structures.

Wang and Werning (2024) explore oligopolies in a macro model: each firm is exposed to nominal rigidities á la Calvo. Henceforth, when being able to optimally adjust to an idiosyncratic shock, the adjustment is also best response to the rival's prices which have partially not yet adjusted to the shock. Each adjustment is then an adjustment according to the shock *and* also an adjustment to the changed rival's prices. This creates additional inertia to the aggregated price movement. A simple expression for the degree of strategic complementary guides the aggregate price dynamics. From that the authors can draw conclusions how market concentration (number of firms) affects price inertia and thus the slope of the Phillips Curve. However, their framework is based on exogenously given Poisson arrival rates to model nominal frictions, and they refer to simultaneous Nash equilibria instead of leader-follower structures.

While the Calvo model assumes a given fraction θ of firms which are "not able" to reset the price, Gasteiger and Grimaud (2023) modify this model by assuming that firms endogenously decide about the price setting frequency. They change prices in a frequency which is optimal in a certain sense, thereby endogenizing the decision about θ. As a result, they obtain a non-linear Phillips Curve. A decision about the frequency of price adjustment and a decision about a delay of price adjustment can be seen as equivalent. The model of Gasteiger and Grimaud (2023) has the advantage to be quite close to standard New Keynesian models, and they leave the basic Calvo idea intact. The model presented in this paper, instead, puts the focus on the role of strategic interaction.

Alvarez et al. (2011) consider costly state observation (whether a firm is exposed to a shock) which might lead to price reviews, and they also consider menu costs. They explicitly model optimal timing decisions for price adjustments. However, these timing decisions are not based on strategic considerations and are therefore applicable only in context of monopolistic competition. While costly state verification leads to time-dependent rules, menu cost lead to state-dependent rules. This approach combines both. However, both, costly state verification and menu costs are ad hoc frictions.

Devereux and Siu (2007) analyze a calibrated DSGE model with mixed time- and state-dependent pricing. They find significant evidence for asymmetric responses to positive and negative cost shocks which are rooted in strategic behavior of the firms. The incentive to respond to positive shocks faster is more pronounced than for negative shocks. Similar to the present model, firms do not just set prices but also decide about contract duration. This can be seen as a commitment to keep the price constant for a certain period. But firms can also "opt out" and revise the price earlier at some menu cost. However, the authors do not model the "strategic" element explicitly, and the approach is still based on an exogenous friction, the menu costs. But the approach it is very insightful regarding the implications for asymmetric and nonlinear responses to monetary policies shocks. Also Ascari and Rossi (2012) point out that state-dependent models (using Rotemberg pricing) and time-dependent models (using Calvo pricing) have very different implications regarding output and inflation as a response to shocks and trend inflation.

From an IO perspective, Hamilton and Slutsky (1990) prove that in case of strategic complementary, i.e. using the price as the strategic variable, both firms in a duopoly are better off in a leader-follower structure. If firms can decide about the timing/stage, the only subgame perfect solution is the Stackelberg outcome. However, the authors do not consider physical time like in Robson (1990). Robson arrives at similar conclusions regarding the Stackelberg outcome as a subgame perfect solution if firms can decide about the physical point in time when to fix the price. However, the model is based on a quite artificial ad hoc assumption of "timing cost". As a result, it is also possible that one or both firms may be better off in the leader rather than the follower position.

Pastine and Pastine (2004) explore oligopolies with price setting where firms can randomize over the timing of price announcements. The main goal of the paper is to explain why the price leader position empirically changes quite often. However, with mixed strategies, firms achieve the more favorable follower position only with a certain probability. In case of successive price changes, the positions in the leader-follower structure will change with a certain probability. The probabilities depend on the "cost of delay" which reflects the disadvantages of sticking into the unfavorable waiting position at a non-optimal price. This idea will be picked up in the present paper later on. When oligopolists are engaged in quantity competition, the leader position is more favorable. As van Damme and Hurkens (2004) point out, only firms with low cost have an incentive to commit to the leader position which is then determined by the heterogeneity of the cost structure among firms.

Also Kima et al. (2021) develop a model with n oligopolistic firms which arrange in a

n-stage Stackelberg leader-follower structure, following Hamilton and Slutsky (1990). They assume "delay cost", following Pastine and Pastine (2004), and firm-specific loyalty of consumers as expressed by their willingness to switch to other suppliers. They show that the degree of consumer loyalty together with the delay cost decide about the stage in a Stackelberg game (with $n = 3$). Firms with high degree of consumer loyalty tend to be leader.

Zhu et al. (2014) develop a model of duopoly with homogeneous goods with potentially mixed price and quantity competition. They consider discrete time, and firms make simultaneous announcements when to make a decision. After they made their choice, they decide in which type of competition (price, quantity, both) they engage. However, the model crucially depends on "time costs" which are, again, an ad hoc element. As the periods can be read as stages, and as the time costs decide about the endogenous sequence, we do not obtain results about the absolute delay in physical time.

The idea of "strategic delay" can also be found in bargaining (Admati and Perry (1987)), global games (Larson (2016)), market entry decisions (Gunay (2008)), or for the case of less informed consumers (L'Huillier and Zame (2022)). In all these sources strategic delay has to do with information asymmetry and thereby uncertainty. In bargaining, for example, the value of the outcome declines in time, so that the more patient player is able to delay decisions and thus "force" other (less patient) player to accept his proposal. Delays can serve as a signal which helps to coordinate beliefs, and delays could enable "later" players to learn from the experience of "earlier" players. Although idiosyncratic shocks also create information asymmetry and hence uncertainty about how strongly a shock affects rival's position, the reason for strategic delay in this paper is not rooted in information asymmetry. It would also work when we have common shocks and complete information. The ability to delay decides about the arrangement of the n-stage Stackelberg equilibrium, their primary function in this framework is not to coordinate beliefs.

The establishment of a leader-follower structure can also be coordinated by *price announcements* which could reveal private information (see Harrington and Ye (2019) and Harrington (2022)). Price announcements could have some credibility when deviations from them incur some deviation cost. Janssen and Karamychev (2025) show that in case these deviation cost are substantial, a unique equilibrium consists of asymmetric prices above the competitive level. Lower deviation cost lead to symmetry but even higher price levels. However, all these price announcements are collusive behavior and thus subject to cartel regulations. In this paper, it is argued that also *timing signals* could facilitate such leader-follower pricing which then comes with some delay. Early studies of the US automotive sector also confirm the empirical relevance of leader-follower pricing rather than Bertrand-Nash (Roy et al. (1994)). As Kauffman and Wood (2007) point out, there is empirical evidence for tacit collusion (prices above the Bertrand-Nash level) even in markets where transparency and flexibility are quite high. The authors claim that *timing* of pricing seems to play a role, not just as a response to shocks but also to timing of rival's price decisions. This is what the present paper aims to explain.

This paper contributes to the literature as it picks up insights on endogenous leader-follower structures from the IO literature with a focus on price-setting oligopolies with heterogeneous goods. In contrast to existing models, no exogenously given frictions are assumed, all delays are an outcome of *strategic* decisions, based on (expected) net present values of profit flows. Thereby it contributes to the recent macroeconomic literature which considers the role of strategic complementary for aggregate price dynamics. It changes the view of the nature of price stickiness in the sense, that with full price flexibility and absence of frictions we would *not* necessarily end up in a Walrasian New Classical (RBC) setting where "Keynesian features" vanish. This is mainly because delays help to establish leader-follower structures, thereby leveraging markups, and is thus a consequence of market power rather than frictions.

3 Strategic delay of price adjustment

3.1 Equilibrium leader-follower structures

First, we need to show that firms have a genuine interest in price setting in a sequential leader-follower structure. Consider an industry with n symmetric firms with constant marginal costs c, supplying a heterogeneous good, and using the price as the strategic variable. Throughout the paper we consider pure strategies only. Note that the strategy space is compact and convex. We do not consider capacity constraints or other additional strategic variables – except for the *timing* of the price decision. Hence, we have a n-firm oligopoly with strategic complementary in prices. We assume downwards sloped demand curves and thus concavity of the profit function in order to guarantee the existence of an economically meaningful Bertrand-Nash equilibrium. In such an equilibrium we have $p_i = BR(p_{-i})\ \forall i = 1, ..., n$ with p_{-i} as the price vector of all firms except for i, and BR as the best response function, derived from the first order condition of maximizing profits.

It is well known for Bertrand duopolies that sequential price setting in a leader-follower structure is beneficial for both, where the follower is relatively even better off than the leader in case of symmetric firms (Amir and Stepanova (2006)). The leader i maximizes $\max_{p_i} \pi_i(p_i, p_j = BR(p_i))$ with the solution p^L. The follower then sets

$p^F = BR(p^L)$. These leader-follower structures (or Stackelberg games) require a *logical* sequence of decision making, called *stages*. The term *follower* doesn't necessarily imply the she makes the decision "later" in physical time. If firms could decide about the stage (as a part of their strategy), both will clearly prefer to make decisions on different rather than on the same stage. This is a well established result by Hamilton and Slutsky (1990) (Theorem IV, Theorem VI) and Robson (1990), see also Deneckere (1992). Hamilton and Slutsky (1990) investigate various cases of downwards and upwards sloped best response functions. For the case of strategic complementary, they prove that a sequential play is the unique subgame perfect outcome when players can decide about the stages. The graphical proof is straightforward (see figure 1). In the Bertrand-Nash solution both iso-profit curves form a lens (price combinations which lead to a Pareto improvement), and both best response functions are within this lens, so any of both Bertrand-Stackelberg solutions must be in this area, and are thus superior. As we consider symmetric firms, also the prices in the Bertrand-Nash solution, p^N, are identical. Given the slopes of the best response functions, we then obtain $p^L > p^F > p^N$. As the price elasticity of demand in case of an equilibrium with price-setting firms is larger than one, the leader will have a lower market share and lower profits though having the higher markup over the marginal cost. Henceforth, it is then more attractive to achieve the follower position (see also Pastine and Pastine (2004)).

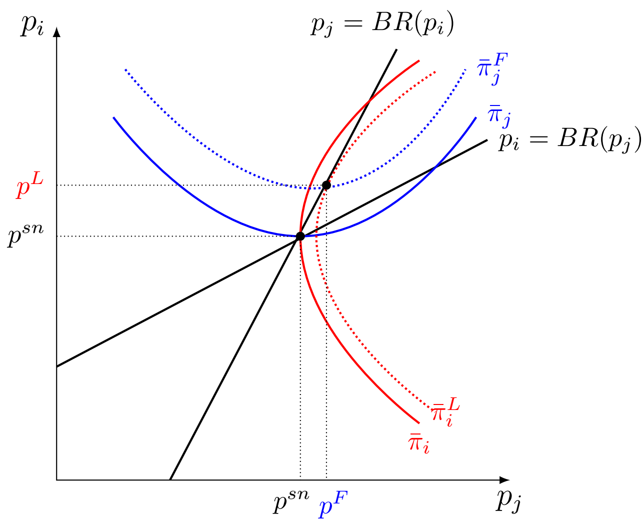

Figure 1: Incentive for endogenous leader-follower structure

Hamilton and Slutsky (1990) refer to their result as *endogenous timing*. Although stages are just a logical sequence, they argue that practically firms *react* to *observed* actions of their rivals. Henceforth, they interpret the endogenous formation of a sequence as an outcome of (a kind of) conjectural variation. However, in their paper they do not explicitly model what happens "in between" two price decisions. If we would start from $t = 0$ where the market comes into existence, is there market exchange *before* the follower has set his price? And how long does it take before setting (or adjusting) a price? Does this have an impact on the timing decision? This is the focus of the present paper as we are interested in *measurable* delay times.

The first step is to generalize the Hamilton and Slutsky (1990) result to the case of n firms. In general, these firms can engage in a m-stage Stackelberg game with $m \in \{1, 2, ..., n\}$ which means that they can set all prices simultaneously ($m = 1$), or each firm sets the price on an own stage ($m = n$), or any combination of sequential price decision of some firms, and simultaneous pricing of others ($1 < m < n$). Intuition suggests that no tuple of any firms i and j will be interested in making a simultaneous choice, henceforth a n-stage Stackelberg game is the unique equilibrium. Consider that i and j would make their price decision simultaneously at a certain stage s but could also decide to make a sequential arrangement so that prices are set at stages s and $s + 1$. In this situation some players have adjusted their price already at the stages prior to s, while some other players will adjust "later" as best responses to p_i and p_j. The prices set prior to p_i, p_j are such that p_i, p_j will be best responses to them, implying that they will be higher if i and j decide for different stages, due to strategic complementary. Henceforth, the profit functions can be written as $\pi_i(p_i, p_j, \cdot)$ where the dot indicates that the function is parameterized by the given prices of the rivals or anticipated best responses to p_i, p_j. But this can be seen as a kind of *parameterized Bertrand duopoly*. Given that the entire n-firm game has a Bertrand-Nash solution, also this parameterized game must have a Bertrand-Nash solution as $p_i = BR(p_j, \cdot)$ must have the properties which guarantees the existence of an intersection point with the rival's best response function. Henceforth the subgame proof leader-follower result applies for this parameterized duopoly game. As this is the case for any i and j out of $\{1, 2, ..., n\}$, each firm has an incentive *not* to make a simultaneous decision with any other firm, as simultaneous decisions lead to lower prices which then also reduces rival's prices. So the unique equilibrium must be a n-stage Stackelberg game. This implies that some firms are price leaders to one group of firms but followers of others as empirically supported by Kima et al. (2021).

From a macroeconomic perspective, the endogenous leader-follower structure is already an interesting result: price (and thus markup) *dispersion* though having symmetric firms is not due to frictions but an outcome of market power. Price dispersion is not transitory but can be seen as an equilibrium phenomenon which also fits to empirical observations (De Loecker et al. (2020), Peters (2020), Kaplan and Menzio (2015), Sheremirov (2020)). It is a leverage of markups compared to the Bertrand-Nash solution and hence an additional source of consumer welfare loss. As higher market power comes with higher markups, leader-follower structures could increase markup dispersion and amplify average markups which could have macroeconomic consequences such like decline of the labor share (De Loecker et al. (2020), Autor et al. (2020)), resource misallocation (Peters (2020)), and higher price stickiness (Wang and Werning (2024))).

The result we obtained so far is that any equilibrium will be an n-stage Bertrand-Stackelberg solution. While Hamilton and Slutsky (1990) consider conjectural behavior and "delay" of price decisions, it is not clear yet, how long these delays are in physical time, how to decide about them, how the sequence of decisions lead to a specific delay structure, and which implications for the dynamic of the aggregated price index in response to shocks are to be expected. In addition, it has to be pointed out that these results are derived from the assumption of symmetry of firms. Later on, when we consider shocks which may contain an idiosyncratic component, costs are no longer identical. If they differ substantially, it is no longer guaranteed that the follower position is more attractive than the leader position.

A key idea is that we do not consider a fictitious situation where "a market comes into existence". Instead, we start already with a market in a Stackelberg equilibrium and analyse how prices adjust to a (cost) shock. In particular, we are interested how firms are able to re-establish a leader-follower structure with reset prices though having limited knowledge about the rival's shocks. It turns out that the ability to delay adjustment provides a mechanism not only to signal the idiosyncratic shock, but in particular to establish a leader-follower structure. Henceforth, the suppliers have a mutual interest to establish such a mechanism as a coordination device. Firms have to consider several effects: how strong does the shock hit the firm (positively or negatively), how large are the benefits from being in a late (follower) stage of the game relative to the leader position, how large are the losses when being attacked by rival's best response while keeping the old price? From that we will derive the maximum delay time, beyond which the benefit from delaying price adjustment turns negative. This leads to a sequence of delay times and thus enables a new leader-follower structure. Given that after a shock the costs might substantially differ, it is also no longer guaranteed that the follower position is preferable. There might be cases where there is no rivalry for the follower position or rivalry for the leader position. In these cases, the proposed mechanism does not necessarily imply price stickiness.

In a later section where the influence of the number of firms on expected delay of adjustment is investigated, it is pointed out that with increasing n, all Stackelberg profits shrink and converge to the Bertrand-Nash profits. This happens quite quickly even for not very large n. A simple and empirically relevant alternative market structure, proposed in the literature, is that there are many firms, but only few firms dominate the market by having a huge market share, while the majority of firms are very small. Evidence for such structures can be found in De Loecker et al. (2020), Autor et al. (2020), and Chen (2006). The small firms have negligible influence on the market outcome and thus behave like under monopolistic competition. They can be modeled as a "fringe" firm while the few dominating firms are engaged in a Stackelberg game, taking the given behavior of the fringe into account (see Cherry (2000), Tasnádi (2000), Tasnádi (2004) for oligopoly analysis with a fringe). As we do not have any frictions, the fringe firms would immediately respond to the shock, while the few dominant firms delay their response strategically. I pick up this idea in the last section of this chapter.

3.2 The incentive to delay adjustment

How could firms arrange a leader-follower structure? I develop a mechanism where firms can produce credible signals to delay price adjustment after a shock, depending on how much worth it is to get into a late stage of the Stackelberg game. Again, consider an oligopoly with n symmetric firms $i = 1, ..., n$, providing a heterogeneous good, using the price as the strategic variable, and facing constant marginal cost c. The profit functions are concave, guaranteeing the existence of a Bertrand-Nash solution. As shown before, we know that firms have an interest to establish a leader-follower structure so that we initially start in a n-stage Stackelberg equilibrium. Now consider a cost shock $dc_i = \bar{dc} + dc_i$ where $dc_i \sim \mathcal{N}(0, \sigma^2)$ and $Cov[dc_i, dc_j] = 0$ for any $i \neq j$. This means that every firm is exposed to a shock which has a common component $\bar{dc}$ and an idiosyncratic component dc_i where the latter is private knowledge. This also allows for an analysis of pure common or pure idiosyncratic shocks.

Two major issues arise from this shock structure: first, as the idiosyncratic shock component is private knowledge, firms cannot perfectly know the best response function of their rival – and thus also not calculate an exact leader price, or the exact profits when keeping the old price while being attacked by the best response play of their rival. Strategic delay decisions thus have to be made with *expected* behavior of their rivals. Once when a firm optimally adjusts its price, the underlying idiosyncratic shock is revealed. This might eventually induce a change of the delay behavior of the rivals. Second, idiosyncratic shocks make the firms asymmetric. For the case of asymmetry is is no longer guaranteed that the follower position is preferred to the leader position. In case of significant cost differences we may have $\pi_i^L > \pi_i^F$ for at least one firm i. If it turns out that a firm prefers the leader position, there is no case for a strategic delay of this firm. Henceforth, delayed price adjustment, also in aggregate, requires that at least some firms have "sufficiently similar" costs after the shock so that they are in rivalry for a late Stackelberg position. The following approach of strategic delay addresses these two problems.

To illustrate the general setup with low notation effort, consider the case of a duopoly. As we start with symmetric firms, and as the common shock component $\bar{dc}$ doesn't affect symmetry, we define $\mathcal{F}$ as the set of all (dc_1, dc_2)-combinations such that for both firms, after idiosyncratic shocks are revealed, it is $\pi_i^F > \pi_i^L$ which implies rivalry for the attractive follower position. The problem is that each firm does not have information about rival's idiosyncratic shock, hence it is unknown (yet) whether there is rivalry for the follower position. As it is known that rival's idiosyncratic shock has zero mean and a given variance, the expected profits in each situation can be approximated by a second-order Taylor approximation around the mean:

$$E[\pi_i] \approx \pi_i(E[dc_j] = 0) + \frac{1}{2}\frac{\partial^2 \pi_i}{\partial dc_j^2}\tilde{\sigma}_j^2 \tag{1}$$

The shocks hit the different firms differently, not only because of their different idiosyncratic size but also because firms have been in a different Stackelberg position prior to the shock. The idea is that the firm which is more "patient" or able to delay price adjustment longer than the rival will get the follower position. Therefore they will calculate and signal a (preliminary) maximum delay time t_i^* when being in rivalry for the follower position. These signals will usually differ. Consider $t_i^* > t_j^*$: as j knows that she will not get the follower position, it is rational to immediately start with best response play until the delay time of the rival, and then to switch to the leader price, as the rival will then respond with the follower price. Consequently, the calculus for determining the longest possible delay time has to take into account that, when being successfully pushing the rival into the leader position, she will attack the non-adjusting firm by best-response play. The non-adjusting firm then earns profits which we call "waiting profits" $\pi_i^W(p_i = p_i(0), p_j = BR(p_i(0)))$. These are typically quite low as firm i is clearly in an uncomfortable situation of keeping a non-optimal price. As these signals t_i^*, t_j^* are based on the own idiosyncratic shock but not knowing the rival's shock, these signals are preliminary. As there can be different shocks leading to the same signal t_i^*, a signal does not yet reveal the shock. In case that idiosyncratic shocks do not play a role, we do not need the expectation operator, and all firms could mutually anticipate the delay times. Hence, it isn't necessary to signal them.

After sending the signals, the "weaker" firm j will immediately start to adapt the price in $t = 0$ as this is the best response against the non-adjusted old price of the rival. But the rival firm i will no longer stick to t_i^* as this is unnecessarily long in order to keep j in the leader position. Instead, it is rational to commit to wait until $t_i^{**} = t_j^* + \epsilon$ which means: just a little bit longer than the maximum delay time of firm j. This is what j can anticipate. Therefore j will switch from best response play to the leader price p_j^L in t_i^{**}, and i adjusts to the desired follower position. Hence we arrived at a new Stackelberg equilibrium after some time t_i^{**}. The details of the calculation of t_i^* will be discussed below. One might ask why firms do not have an incentive to signal extremely high t_i^* in order to intimidate potential rivals. First, a signal $t_i^*(dc_i, \bar{d}c)$ as an outcome of the calculus below has a maximum value. Any extreme signal above this threshold is *non-credible* as such a long delay time would lead to inferior profit flows. And if signals are not credible, they lose their function as a coordination device for establishing a leader-follower structure. Second, both firms would anticipate the incentive to produce exaggerated signals, so that t_i^{**} will lead to a "winner's curse" situation. Again, signaling and strategic delay would lose its function as a mutually beneficial coordination device, both firms are interested in.

What is the alternative if a re-arrangement of stages is not possible via strategic delay? When deriving a "maximum" delay time, we need an alternative what would happen if firms are not able to determine a sequence intentionally. One possibility is a kind of mutual best response dynamic which converges to the Bertrand-Nash equilibrium such like in Wang and Werning (2024), except for that we do not have a Calvo mechanism so that firms would immediately switch to an adjusted Bertrand-Nash solution. However, there is always an interest of the firms to decide in a sequential order. Any of these firms could stop the best response dynamic by playing the leader price p^L instead, and the other answers with the follower price p^F. But which of the firms is doing so is unclear. Therefore, we model this as a "random assignment scenario" where the Stackelberg stages are assigned randomly with the expected profits $\pi_i^{rand} = 0.5(\pi_i^F + \pi_i^L)$, for sake of simplicity, although the chances for achieving a particular stage might be asymmetric (see van Damme and Hurkens (2004)). Strategic delay, instead, should be such that the net present value of profits from delaying price adjustment are at least as high as the expected profits from such a random assignment scenario. Henceforth, the maximum delay time t_i^* is such that it solves the following comparison of NPVs of expected profits flows (using (1)):

$$\int_0^{t_i^*} \beta^t E\pi_i^W dt + \int_{t_i^*}^{\infty} \beta^t E\pi_i^F dt = \int_0^{\infty} \beta^t E\pi_i^{rand} dt$$

$$\Rightarrow \quad \frac{1-\beta^{t_i^*}}{-\ln(\beta)} E\pi_i^W + \frac{\beta^{t_i^*}}{-\ln(\beta)} E\pi_i^F = \frac{1}{-\ln(\beta)} E\pi_i^{rand} \tag{2}$$

$$\Rightarrow \quad t_i^* = \max\left\{0, \frac{\ln\left(\frac{E\pi_i^W - E\pi_i^{rand}}{E\pi_i^W - E\pi_i^F}\right)}{\ln(\beta)}\right\} \tag{3}$$

One can use $\beta = \exp(-\rho)$ instead which might be more common for continuous-time models. In this case we would have $\ln(\beta) = -\rho$ in the denominator of eq. (3). The l.h.s. of (2) is the NPV of delaying price adjustment while being attacked by rival's best response but then achieving the follower position in t_i^*. The r.h.s. is the alternative scenario of random assignment of stages. The condition is for a single experienced shock, not for expected future shocks. As prices are fully flexible, a firm is always able to set a reset price (or to delay this adjustment) *after* a shock has been perceived. The resulting maximum delay time (3) is thus a function of the known shock components: $t_i^*(\bar{dc}, dc_i)$. In case that the agent faces an extreme idiosyncratic shock so that she does not expect that the follower position is superior: $E\pi^F < E\pi^{rand}$, the absolute value of the bracket term in the numerator is larger than one, while β in the numerator is less than one, and hence we would obtain a negative delay time. But in such a case, the firm would not signal any delay time as the leader position is expected to be more attractive. Therefore, t_i^* is bounded to zero. For the case $E\pi^{rand} < E\pi^W < E\pi^F$, the bracket term in (3) is negative, and hence we obtain an economically not meaningful complex number t_i^*. However, this case implies that the "waiting scenario" is not a threat. This might eventually happen in case of huge cost reduction shocks where the old prices are then in a "collusion area". If necessary, this firm could wait infinitely long. If this would be true for *both* firms, then the current old price vector is within the lens of iso-profit curves of any of the two new Stackelberg equilibria, which means that both firms behave in a collusive manner. We could extend the calculus (3) by also comparing the NPV of waiting and then getting into the follower position, with a scenario of voluntarily moving into the leader position, while the rival remains in the waiting position. In case of a "collusion area" this would be clearly superior (as the rival sticks at a too high price) and would thus break up the collusion. Henceforth such a scenario cannot be stable, and there is no case for strategic delay. In the following we will not consider such an extension of the calculus as such a scenario doesn't occur with the parameter sets explored in this paper.

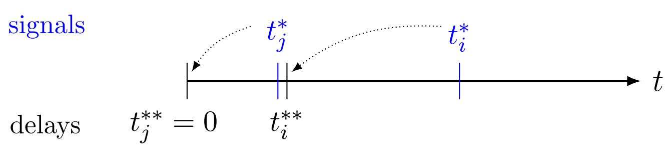

Figure 2: Signals and delay time structure

After sending the signals t_1^*, t_2^* (in case of duopoly), we can determine which firm is "weaker" or "stronger". Assume without loss of generality $t_j^* < t_i^*$. Then firm i will postpone price adjustment until $t_i^{**} = t_j^* + \epsilon$ (see figure 2), and j adjusts immediately. It is not rational to wait unnecessarily long, but it should be long enough to keep the rival in the leader position. By delaying until $t_i^{**} < t_i^*$ it is also guaranteed that the

NPV of profits is not only as good as a random assignment scenario but superior to it.

The first mover starts by playing best response: $p_j = BR(p_i(0))$. By doing do, j's idiosyncratic shock is revealed. If it now turns out that $(dc_i, dc_j) \in \mathcal{F}$, there is indeed rivalry for the follower position, and firm i has won this rivalry. Why isn't there an incentive to establish the Stackelberg solution *immediately*? This would require a premature adjustment of i before t_i^{**}. Beside the fact that for all $t < t_i^{**}$ also j could benefit from delaying adjustment, firm j still plays best response $p_j = BR(p_i(0))$ in $t < t_i^{**}$. If there would be an unexpected premature adjustment of i, how should this look like? And how would j respond to it? In fact, this would induce mutual best response play which can be stopped by any of the firms by setting p^L. But this is exactly the random assignment scenario which i doesn't prefer and could successfully avoid by sticking to t_i^{**}. Hence, t_i^{**} is *credible* for the case that i is really interested in the follower position. What happens in t_i^{**}? Recall that j doesn't know i's exact best response function yet. Therefore, firm j can just calculate a preliminary leader price, based on the expected best response. By optimally answering to the preliminary p_j^L, firm i reveals its idiosyncratic shock, too, which allows j to slightly re-adjust the leader price. We assume that this happens fast (instantaneously) within t_i^{**}. In practice, such small re-adjustments will probably not take place.

But it could also turn out, that by playing best response, the revealed shock dc_j is such that $(dc_i, dc_j) \notin \mathcal{F}$. Only firm i could know that at this moment. This means that although $E\pi_i^F > E\pi_i^L$ it turns out ex post that $\pi_i^L > \pi_i^F$. Firm i has the advantage of knowing rival j's best response function while his own idiosyncratic shock is not yet revealed. Nothing prevents firm i to ignore t_i^{**} and to immediately set the leader price p_i^L so that j is forced to play best response to it which is p^F. As this could happen quickly as we have fully flexible prices, we assume that such an adjustment happens instantaneously in $t = 0$. Hence, there is no case for credible delay with shocks $(dc_i, dc_j) \neq \mathcal{F}$. Thus, for any common shock $\bar{dc}$ we focus on the probability mass on all idiosyncratic shock combinations within $\mathcal{F}$ in order to calculate *expected delay*.

3.3 Linear demand scheme

We apply the model of delay signals to the case of an oligopoly market with a linear demand scheme. Linear demand functions are quite unusual in macroeconomics as it is inconsistent with CRRA household utility functions which are typically used in the literature (for a microeconomic foundation of linear demand schemes see Amir et al. (2017), and recently Pellegrino (2025) for the case of product differentiation).

But as it is possible to analytically derive best response functions and also the delay times t_i^*, t_i^{**}, we use the linear case to demonstrate how this approach works, and how the resulting delay times depend on size and direction of the shock but also on the discount factor β and the substitution elasticity. The more common case of an iso-elastic demand function will be discussed in the subsequent section. It will turn out that the qualitative results are nearly the same.

Consider a demand function $q_i = \frac{Y}{n} - b(p_i - \bar{p})$ with $\bar{p} = \frac{1}{n}\sum_i p_i$ as the average price (or price index in the linear case). It is Y a shifter, reflecting the market size, and parameter $b > 0$ determines the elasticity of substitution, i.e. how sensitive demand responds to differences between the price and the average price. In this section we consider $n = 2$. The profit functions are $\pi_i = (p_i - c_i)q_i$ where $c_i = c$ before the shock, and $c_i = c + \bar{dc} + dc_i$ after the shock as explained above. The best response functions and profits $\pi_i^F, \pi_i^L, \pi_i^{rand}$ are easy to calculate and omitted here. After the shock, the cost are no longer identical, and we have to compute the set $\mathcal{F}$ of (dc_i, dc_j)-combinations where $\pi_i^F \geq \pi_i^L$ and $\pi_j^F \geq \pi_j^L$ which means that there is rivalry for the follower position. Recall, that the common shock $\bar{dc}$ has no effect on symmetry. In case of a linear demand function this is a convex set between two lines which can be easily determined by equalizing $\pi_i^F = \pi_i^L$ and solving for dc_j, which gives $dc_j \in \left[(2^{3/2} - 1)\frac{y}{b} - dc_i, (2^{3/2} - 1)\frac{y}{b} + dc_i\right]$, see figure 3. In this figure also iso probability density lines of the joint shock distribution are depicted. Depending on the variance, usually a huge portion of the probability mass is within the set $\mathcal{F}$.

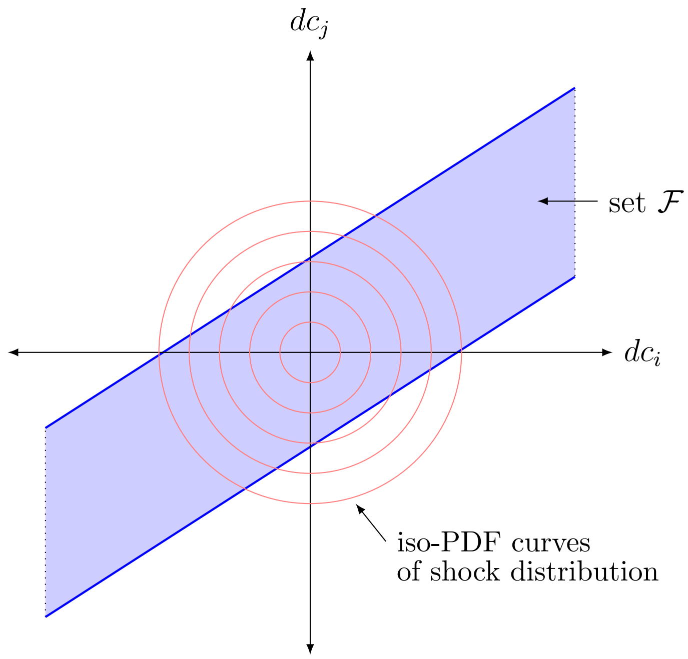

Figure 3: Set $\mathcal{F}$

Given the observed own idiosyncratic shock as well as the commonly known shock $\bar{d}c$, and given the initial position of firm i in the Stackelberg equilibrium, we can compute $E\pi_i^F, E\pi_i^L, E\pi_i^{rand}$ and $E\pi_i^W$ (see eq. (1)), and hence we obtain t_i^* from equation (2), see also the appendix. Doing the same for j, and selecting the lower value $t^{**} = \max\{t_i^*, t_j^*)$ (neglecting the $+\epsilon$), we obtain delay times t^{**} on the (dc_i, dc_j) plane as depicted in figure 4 for various values of common shocks $\bar{d}c$, and a given sample parameterization[1]. As $t_i^*(\bar{d}c, dc_i)$ with given $E_i[dc_j] = 0$ and therefore independent from the realized dc_j, and vice versa for the other firm, the contour lines for $t^{**} = \min(t_1^*, t_2^*)$ are "pyramid-shaped" (left panel, figure 4, where x-axis is dc_1 and y-axis is dc_2). The light yellow color indicates the highest delay, the more the color turns to dark blue, the lower is the delay. Observe that the maximum delay is *not* centered at the origin where we have the highest probability mass of the joint distribution of idiosyncratic shocks. With these parameterizations, all shock combinations with a non-negligible probability mass are within $\mathcal{F}$, while the black areas in the graphic denote $(dc_1, dc_2) \notin \mathcal{F}$ (no rivalry for the follower position, hence no strategic delay) Using the joint probability function for the idiosyncratic shocks, we can compute the probability density for each t^{**} (numerical PDF). On the right panel of figure 4 depicts the numerically derived CDFs (black curve). It turns out that they can be approximated quite well by a Γ distribution (red dashed curves). It allows to compute the expected delay time for each common shock.

The cost shocks hit the former leader and the former follower differently. We investigate how likely it is that the previous leader-follower position maintains or reverts. For the given parameterization and the given shocks from figure 4 we determine the combinations of idiosyncratic shocks where the announced delays are $t_1^* = t_2^*$. These are depicted in figure 5. In the area between the blue curves which represent all combinations with $t_1^* = t_2^*$, we have a switch of the positions, while in the areas left(right) of the left (right) blue curve the previous Stackelberg position prevail. The area inside the circle represents 95% of the probability mass as we have assumed a standard deviation $\sigma = 2$ of the idiosyncratic shock.

We now explore the determinants of expected delay times $E[t^{**}]$ after common shocks more systematically. In figure 6 we see the expected delay times as a function of the common shock $\bar{d}c$. Given the numerical parameterization, the displayed shocks are up to ±40% of the cost (x-axis). We obtain the following results which are robust against variations of the parameter set. These results are in line also for the case of zero idiosyncratic shocks where the corresponding features of the delay structure could be analyzed analytically (see appendix).

[1]The baseline parameterization for the graphic is $y = 100, b = 20, c = 20, \beta = 0.95, \sigma = 2$.

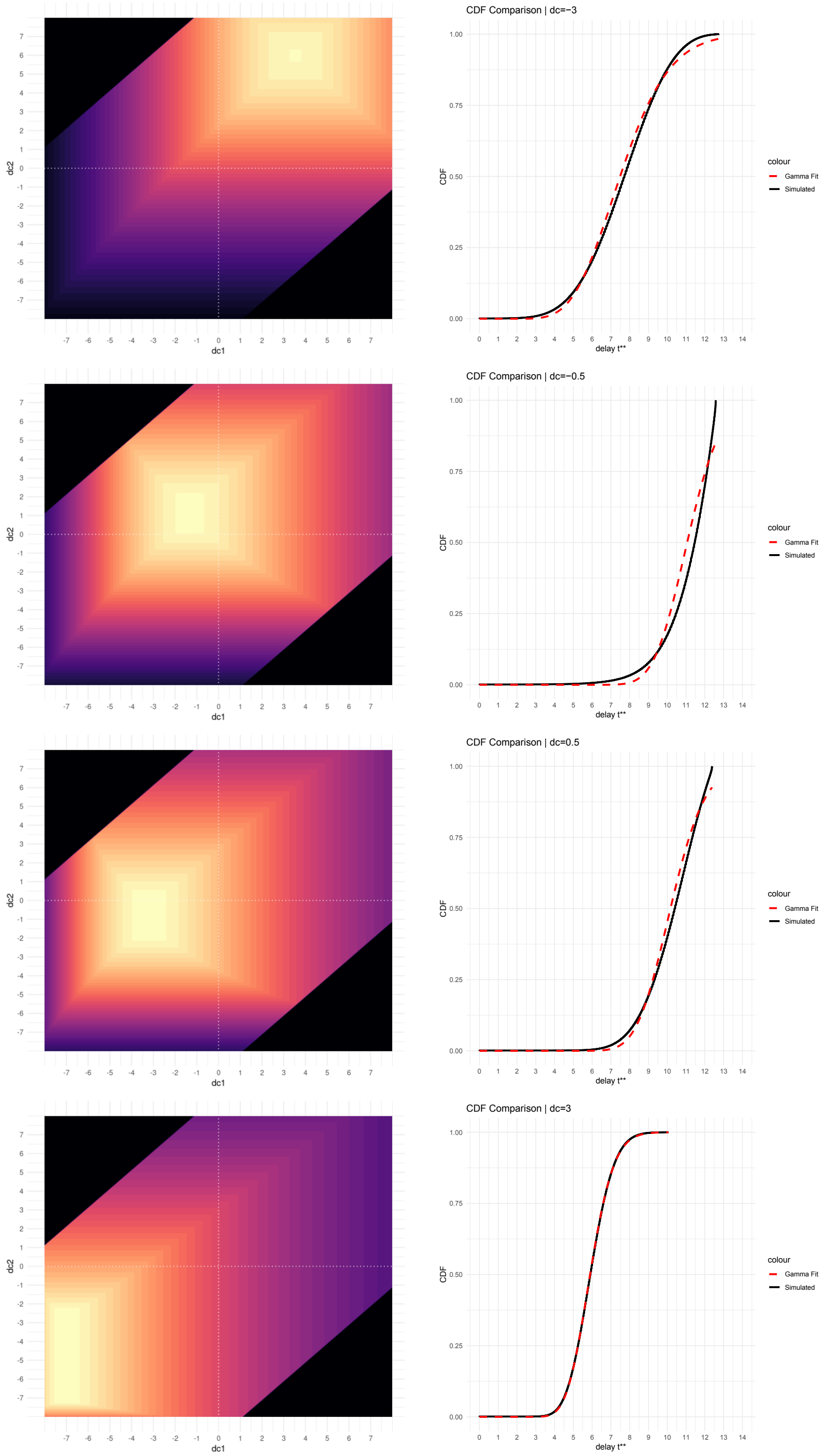

Figure 4: Delay times, depending on idiosyncratic shocks; common shocks $\bar{dc} = \{-15\%, -2.5\%, +2.5\%, +15\%\}$ (from top to bottom)

(a) There is an asymmetry regarding the shock size: small shocks lead to longer expected delays than large shocks. This is a quite intuitive result as large shocks

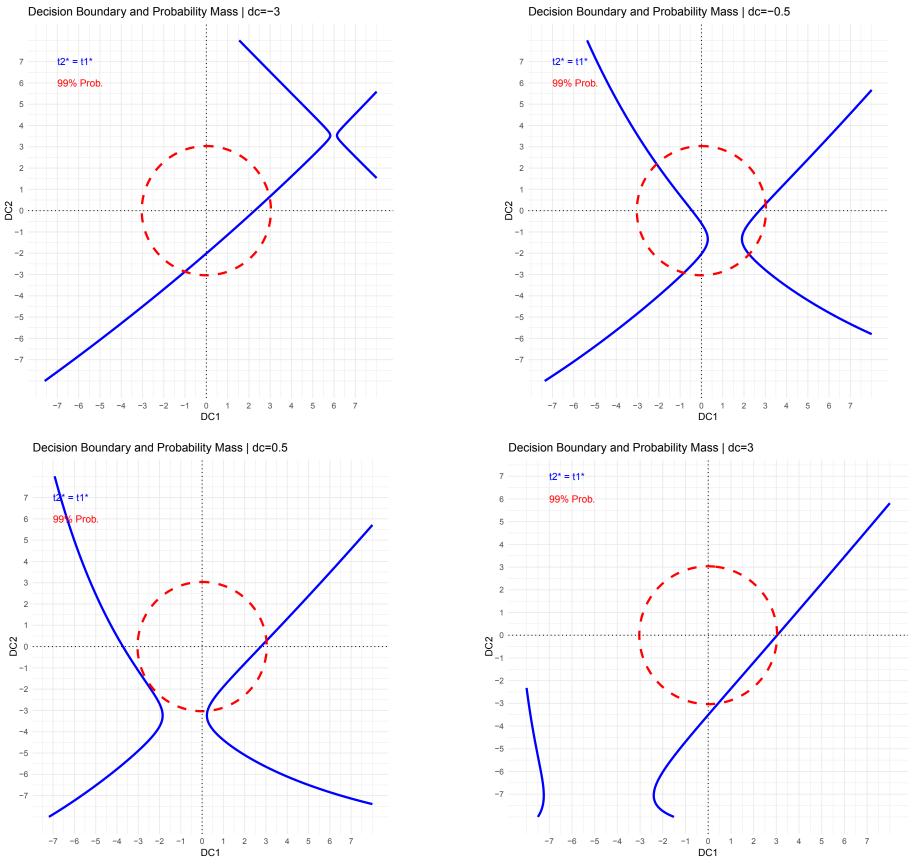

Figure 5: Preserving or reverting the leader-follower position due to a shock; common shocks $\bar{dc} = \{-3, -0.5, +0.5, +3\}$ (from left to right, from top to bottom)

makes it more painful to stay with a sub-optimal old price while being aggressively attacked by the rival's best-response play, thus implying lower delays. In the appendix it is shown that the functions $t_i^*(\bar{dc})$ are single-peaked, and the peak of $\min\{t_1^*, t_2^*\}$ is negative but close to zero. The result is in line with state-dependent inflation models which have a lot of empirical support (Luo and Villar (2025), Dedola et al. (2025)). As Cavallo et al. (2024) formulate: "Large shocks travel fast". While in case of small shocks, the differences between Calvo-type (time-dependent) and Rotemberg-type (state-dependent) friction-based models are small (Midrigan (2011)), this seems not to be the case for large shocks which lead to less inertia and thus being consistent with state-dependent models (Karadi and Reiff (2012)). The model result also fits to the empirical approach of estimated hazard functions: the higher the misalignment of the price after a shock, the higher is the probability of a price change (see Luo and Villar (2025)).

(b) There is an asymmetry regarding positive and negative shocks: for negative shocks (sudden decline of cost) the expected delays are larger than for cost increases of

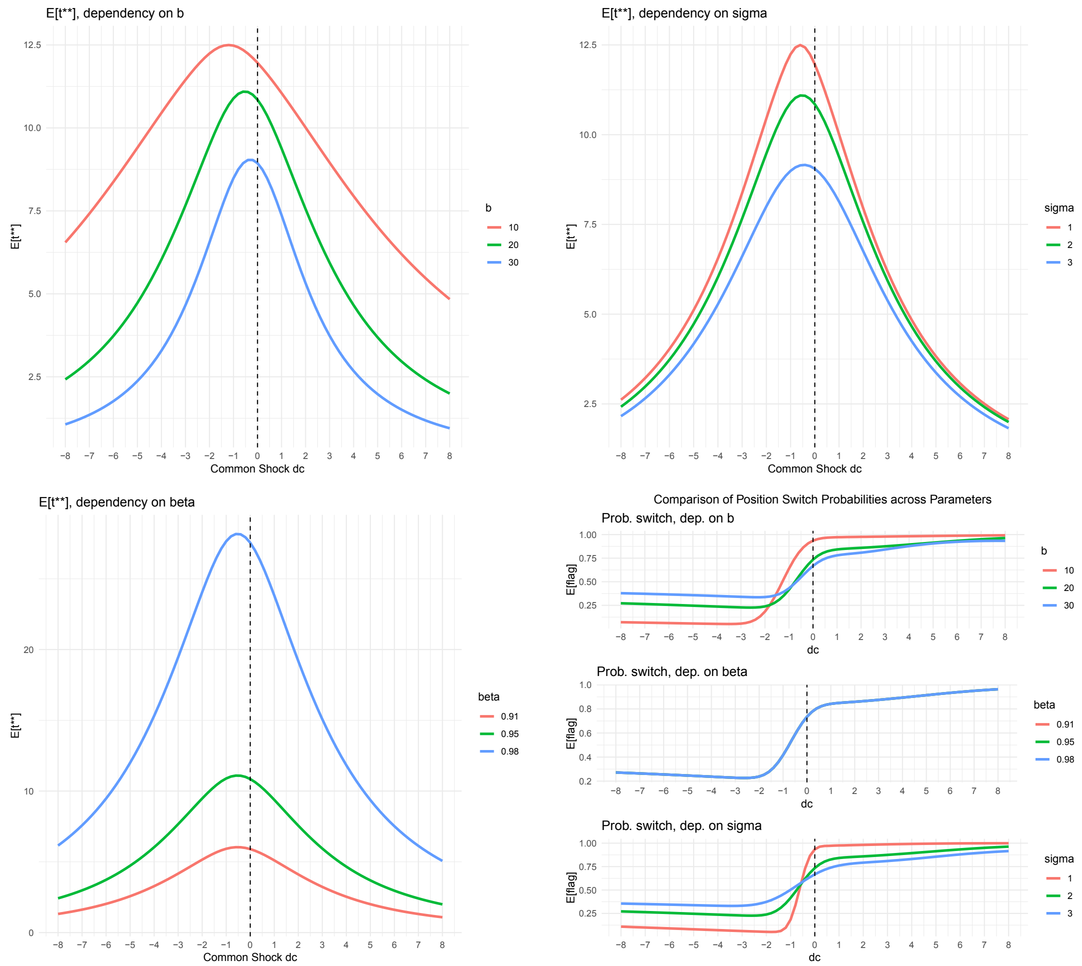

Figure 6: Expected delay times $E[t^{**}]$ and expected leadership switches

same size (the peak of the curves in fig 4 is always for $\bar{dc} < 0$), see also appendix. Also this confirms economic intuition and empirical observations (Dias et al. (2015), Gwin (2009)). It is also in line with asymmetries of estimated hazard functions which suggest that price increases are more likely than price declines (Luo and Villar (2021)). Cost declines improve profits even in the uncomfortable "waiting" position for both rivals, thus leading to willingness to delay adjustment. As we will see later, this asymmetry is even more pronounced for the case of iso-elastic demand.

(c) The larger the parameter b and thus the sensitivity to price differences (in other words: the closer substitutes the goods are), the lower are the expected delays. This implies different degrees of stickiness across industries which supply goods with different substitution elasticities, and might thus help to explain the substantial cross-industry variation in price adjustment dynamics (Dias et al. (2015), Gwin (2009), Klenow and Malin (2010)).

(d) The larger the discount factor β, the longer is the expected delay. Also this is according to intuition: larger β indicates more *patience* as beneficial future profits from the follower position are less discounted. To my knowledge, a direct empirical relationship between inflation inertia and the time preference or the natural interest rate – which should be tied to the time preference discount rate ρ – is not yet investigated. Falk et al. (2018) provide a comprehensive cross-country survey of patience data which could be associated with β values. With the heroic assumption that firm's pricing behavior is driven by the (time) preference of the firm owners, the model suggests a relationship between patience and inflation inertia. Instead, the time preference measures could be approximated by estimates of the natural interest rates r^* which should be a function of time preferences. According to the model, low natural rates would then imply a higher degree of inflation inertia.

(e) The expected delay times decline if the variance of the idiosyncratic shocks increases. This is mainly because a larger portion of the probability mass lies outside of $\mathcal{F}$ so that there is no rivalry for the follower position and hence no reason for strategic delay. But this also means that for the case of pure common shocks ($\sigma^2 = 0$) we have a quite large expected delay. This clearly shows that strategic delay, in this model, does not have anything to do with information asymmetry like in Admati and Perry (1987) or Larson (2016).

But there is a further interesting implication of the model: using figure 5, we define a flag which is one if the leader-follower positions switch after a shock, and zero if previous positions prevail. Integrating over all combinations of idiosyncratic shocks, we obtain the estimated probability of a switch, depending on the common shock $\bar{dc}$. The qualitative picture is the same for different parameterizations we considered in figure 6, therefore I plot the estimated probability of position switches for all parametrizations in figure 6, bottom right panel. The stylized model result (f) is that changes in the leadership position are much more likely in case of cost (and thus price) increases, while in case of price declines it is more likely that Stackelberg positions prevail. For very small shocks, the results are ambiguous. There are only few empirical studies on price leadership changes; the results from Seaton and Waterson (2013) point into the direction suggested by this model.

To sum up, the model of strategic delay is capable to explain a large variety of empirically relevant price adjustment asymmetries without relying on nominal frictions. As the profits in a particular Stackelberg position are the same for both (symmetric) firms, the results regarding delay signals t_i^* stem from the different impact of the shock on the profits in the waiting position. The latter depends on the prior Stackelberg stage. Henceforth, the strategic delay mechanism successfully propagates the dispersed price setting after each shock which enables higher markups than in the Bertrand-Nash solution.

3.4 Iso-elastic demand function

Although a Stackelberg duopoly with linear demand and constant marginal cost is a quite trivial model for undergraduates, the computation of $E[t^{**}]$ requires to integrate the probability-weighted delay times on the set $\mathcal{F}$ of all idiosyncratic shock configurations, separately for each common shock. Things become much more computationally expensive when considering an iso-elastic demand function of the form

$$q_i = \frac{Y}{P}\left(\frac{p_i}{P}\right)^{-\theta}, \qquad \text{with } P = \left(\sum_{j=1}^{n} p_j^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{4}$$

with $\theta > 1$. The FOC of maximizing $\pi_i = (p_i - c_i)q_i$ is nonlinear and not polynomial in the prices so that we do not have a closed form of the best response function $p_i = BR(p_{-i})$. Thus, we cannot analytically determine a Stackelberg equilibrium, even not for the case $n = 2$. Therefore, to my knowledge, all macroeconomic models which consider the case of a heterogeneous oligopoly with iso-elastic demand, are interested in the *symmetric* Bertrand-Nash solution which is easy to determine analytically (like in Wang and Werning (2024), Etro and Rossi (2015) and Etro and Colciago (2010), for example). In our model, however, this is not an option.

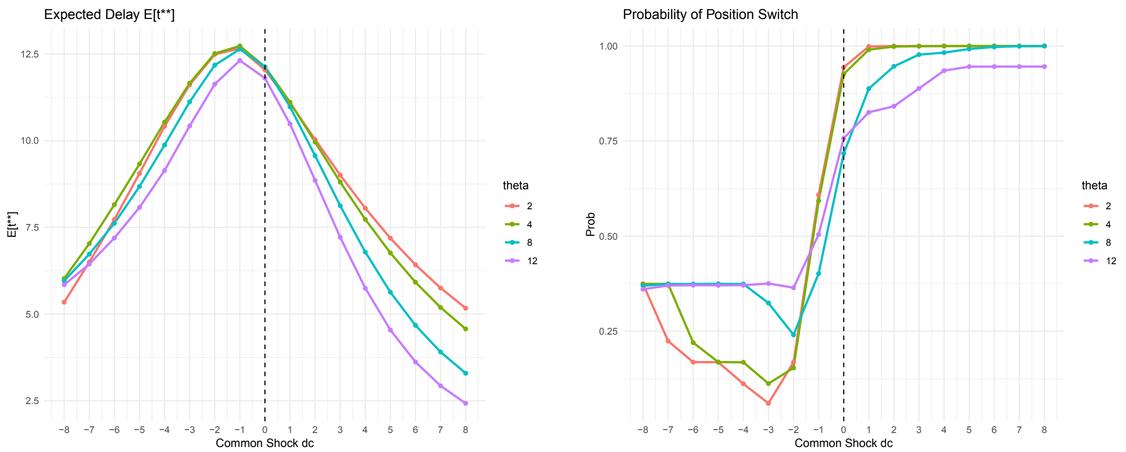

Figure 7: Expected delays and leadership switches in case of iso-elastic demand function

For the case of iso-elastic demand, we calculate a second order Taylor approximation of the (numerically specified) profit function at the symmetric Bertrand-Nash solution in order to obtain linearized best response functions. This allows then for an approximate Stackelberg solution. Afterwards, we repeat the procedure by approximating the profit function at the proxy Stackelberg solution and so on. For a good approximation of the Stackelberg solution the slope of the rival's best response function and the slope of the firm's iso-profit curve should be nearly identical. After some iterations of the approximation procedure described above, we obtain the Stackelberg solution with quite high precision. This needs to be done for each set of idiosyncratic shocks (dc_1, dc_2) for each given common shock $\bar{dc}$, separately for both firms which have to form *expected* profits for the cases of being in the leader or in the follower position. It turns out that the expected delay times $E[t^{**}]$ qualitatively show a similar pattern than in the linear case, and they respond in a similar manner to parameter changes. Figure 7 shows the dependency on the elasticity θ. Compared to the linear demand function, the asymmetry regarding positive and negative shocks is even more pronounced[2]. For small and large positive shocks, a higher θ reduces the expected delay time, similar to the case of a linear demand function. For small and negative shocks the result is ambiguous: the effect of θ on the delay time is negligible and non-monotonous. Also the result that switches in the leader-follower position are likely for positive shocks but unlikely for negative ones, prevails for the case of iso-elastic curves (right panel of fig. 7). However, for negative shocks the (low) probability of position switches seems to be U-shaped.

3.5 The case of $n > 2$ firms

With a linear demand scheme one can easily see that the Bertrand-Nash price converges to the competitive solution where price equals marginal cost for $n \to \infty$. In case of the iso-elastic demand scheme it converges to the monopolistic competitive solution. Stackelberg prices are above but tied to Bertrand-Nash prices. The higher n, the lower the slope of the best response function: the strategic complementarity declines. For the linear demand case this is straightforward. For the iso-elastic demand scheme, denote the price index $P = (p_i^{1-\theta} + (n-1)\tilde{p}^{1-\theta})^{\frac{1}{1-\theta}}$ with $\tilde{p}$ as an *average* of all rival prices. Given the iso-elastic demand scheme, let $p_i = g(\tilde{p})$ denote the best response to the average rival's price. The response to an individual rival's price is thus

$$\frac{\partial p_i}{\partial p_j} = \frac{1}{n-1}\frac{dg(\tilde{p})}{d\tilde{p}} \quad \text{which is} \quad \left.\frac{\partial p_i}{\partial p_j}\right|_{\text{Nash}} = \frac{\theta - 1}{n(n-1)\theta} = B \tag{5}$$

when all firms set Bertrand-Nash prices. As mentioned before, we cannot analytically derive a best response function $g(\tilde{p})$ from the FOC, but we can compute eq. (5) from the total derivative of the FOC in the Bertrand-Nash solution. Expression B indicates that with increasing n, the strategic complementarity declines (also the key element in Wang and Werning (2024)). The flatter the best response functions, the closer the tangential point with rival's iso-profit curve must be to the Bertrand-Nash solution. Henceforth, the dispersion of Stackelberg prices declines and the average Stackelberg price gets closer to the Bertrand-Nash price with increasing n, while the

[2] Same parameterization than in the linear baseline model, except for replacing b by θ, and $\sigma = 1$.

latter converges to the monopolistic-competitive price. Doing the same exercise with a linear demand scheme where the price index is $P = \frac{p_i+(n+1)\tilde{p}}{n}$, we obtain

$$\left.\frac{\partial p_i}{\partial p_j}\right|_{\text{Nash}} = \frac{1}{2(n-1)} = \tilde{B}$$

which also shows a negative dependency on n.

This has consequences for the delay times. The maximum delay time t_i^* according to eq. (3) is based on the relation of $(E\pi_i^W - E\pi_i^{rand})/(E\pi_i^W - E\pi_i^F)$. Henceforth, as $E\pi_i^{rand}$ is the expected average of Stackelberg prices, this relation converges to one for large n, and as we take the log of it, the maximum delay time converges to zero. This perfectly makes sense, as for large n, the follower position is no longer so much better than the leader position. It is less worth to fight for it. This allows us to directly use the relation $E\pi^{rand}/E\pi^F$ to study the impact of n on delay times. It is not necessary to compute $E[t^{**}]$ with a lot of computational effort as we are interested only in the systematic influence of n on $E[t^{**}]$. In the following, for further simplification, we neglect idiosyncratic shocks. As common shocks are common knowledge, we can drop the expectation operator. The delay times t^* (given symmetry of the firms) then do not need to be signalled as they can be mutually anticipated.

With increasing n, all Stackelberg prices converge to the Nash equilibrium, making leader and follower profits more similar. Hence, we can directly conclude that the delay time t_i^{**} which is necessary to push one firm into the first leader position (stage 1) will decline with n. But then we still have a rivalry among the remaining firms for the follower position (last stage). So we have another delay t_2^{**} which is necessary to push the next firm into the second stage and so forth until t_{n-1}^{**}. The calculus of the maximum delay time t_i^* does not base on the varying number of rivals which have adjusted so far. It assumes the worst case that *all* other rivals engage in a Stackelberg game, given the own old price $p_i(0)$, meaning that all other rivals play a kind of best response against i. Hence, the sequence $\{t_1^*, t_2^*, ..., t_n^*\}$ doesn't need to be computed again each time when another rival starts to adjust the price. Consequently, we will arrive at the full reset price distribution of Stackelberg prices at t_{n-1}^{**}. This is different for the case of idiosyncratic shocks because here the first mover plays best response and thus reveals his own idiosyncratic shocks. This requires to update the beliefs of the rivals. As we neglect idiosyncratic shocks here, we can omit this step. As a result, the total time until we have a full reset Stackelberg prices is t_{n-1}^{**}. We know that with increasing n delay times t_i^{**} declines. Whether this also holds true for the cumulated delays until t_{n-1}^{**}, we need to explore numerically.

Figure 8 (left panel) shows the profit relation π^{rand}/π^F for increasing n. If this relation is 1, then for any value of waiting profits π^W the delay time t^* becomes zero.

We used the parameterization of the baseline model in the previous sections except for the value $\beta = 0.99$. On the right panel we see the total delays t^{**}_{n-1} for a range of common shocks for an increasing number of firms. The delay times until some price adjustments *and* full price adjustments take place, will decline significantly with increasing n – proportionally to the gap of follower and leader prices and profits.

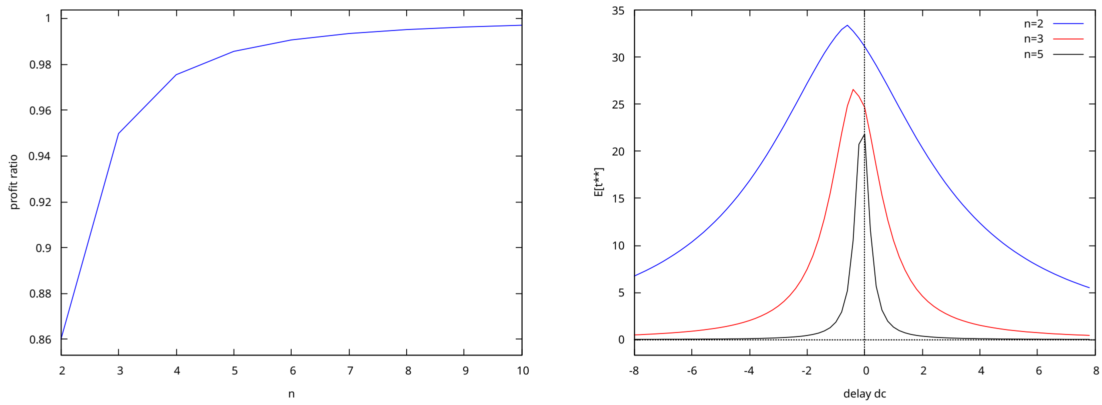

Figure 8: Profit ratios and expected delays with increasing number of firms

We should not just look at the absolute delay times t^{**}_{n-1}, but also consider that with increasing n each time when a firm starts to adjust, the relative contribution to an adjustment to the reset price level P^*, the average Stackelberg price level after the shock, declines. In addition, once when one or more firms keep their old price, the best response to it differs from the corresponding Stackelberg price. For example, in a duopoly, the first mover plays best response to a not-adjusted price of the rival: in case of a cost increase (decreases), the "waiting" firm keeps the old too low (high) price. Hence, the best response price is lower (higher) than the fully adjusted leader price. This effect is even stronger with $n = 3$ firms because the first mover plays best response against two rivals with too low (high) prices. Hence, a best response price of the first mover always contributes less than $1/n$ of the corresponding Stackelberg reset price level, and is not yet clear how long it will take until e.g. 70% of the final reset price level P^* will be reached. We know that the final reset price will be achieved earlier, but the first adjustment steps are smaller with large n than for $n = 2$, hence it could take even longer before reaching a certain percentage threshold of P^*.

We do not repeat the analysis for iso-elastic demand schemes because the nested numerical approximation of Stackelberg solutions gets computationally very expensive for $n > 2$. But as the slope of the best response function (see eq. (5)) negatively depends on n like in case of a linear demand function, one should expect the same qualitative result. As a consequence, the idea of strategically delayed price adjustment might be convincing in principle, but it will have a negligible impact once when n is large. Hence, one can question its role as an alternative to friction-based models such like Calvo, if n is large.

However, as briefly discussed in section 3, an alternative assumption is a market structure which is characterized by few dominant firms, engaged in Stackelberg oligopoly, and fringe firms which sets prices as if being under monopolistic competition due to their low market power (Cherry (2000), Tasnádi (2000)). The idea of fringe firms draws back to Stackelberg himself (see Etro (2014)). The rise of few powerful firms with large market shares while the majority of rival firms remain small, also seems to be an empirically relevant phenomenon which is consistent with high and dispersed markups, and skewed firm size distribution (De Loecker et al. (2020), Autor et al. (2020)). Such market forms – oligopoly plus fringe – enjoy growing importance also in endogenous innovation and growth models (see e.g. Acemoglu (2023), Cavenaile and Schmitz (2022)).

In absence of frictions, the fringe would always respond to a shock immediately while few dominant firms exhibit strategic delay. Consider, for example, a market with n firms where $(n-2)$ firms are a fringe, and we have one leader and one follower (duopoly plus fringe). The fringe firms set their price simultaneously in a monopolistic-competitive manner. The idea of leader-follower structures in price competition is that prices and markups are larger than in Bertrand-Nash or in a competitive solution. When firms are symmetric, this leads to a contradiction: fringe firms have lower prices but at the same time a low market share. Hence we need to allow for some *cost heterogeneity* and thus relaxing the assumption of symmetry of firms. As a result, the market form of heterogeneous oligopoly plus some clustering of firms – a block of many similar firms with lower productivity, small market shares and thus non-strategic behavior, and few more productive firms which are strategic price-setters with markups above the monopolistic-competitive level – is even "more generic" than just an oligopoly with symmetric firms. And it is also closer to the empirical picture that average markups have grown significantly in the recent decades while the median markup was more or less stable. This indicates that there is more market power in the upper tail in the distribution which means: few firms became more dominant and have higher markups compared to the rest (De Loecker et al. (2020)), and firm size distribution is highly skewed (Sutton (2007)).

Therefore, we relax the symmetry assumption and consider, instead, that the majority of (fringe) firms have cost c_f which are higher than the cost of oligopolistic (for sake of simplicity: duopoly) firms: $c < c_f$. As factor prices are the same for all, the cost advantage can be seen as a result of higher productivity or a different optimal combination of input factors (e.g. capital intensity). A simple way to establish a price index such that the fringe has a constant market share is to assume a *representative* fringe whose market share is then split up to $(n-2)$ single firms. The price level which enters the duopolist's profit function is

$$P = \left({P_F}^{1-\theta} + {P_L}^{1-\theta} + \beta {P_{fr}}^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{6}$$

where β reflects the relative influence of the fringe's price P_{fr} on the price level as the fringe represents several firms with a limited market share. As each fringe firm charges the monopolistic competitive price, independent of n, the calculus of the duopolists (or in general: dominant firms) does no longer depend on n. The result is that Stackelberg profits and expected delay times do not at all depend on the number of fringes, but only on the *number of dominant firms.*

With these assumptions about the underlying market structure – few firms in leader-follower structure plus a block of non-strategic fringe firms – the model predicts, adding point (g) to the list of stylized results from section 2.3, an increase of expected delay times if less firms are strategically important players, or in other words: having more concentration and market power at the upper tail of firm size distribution. This is in line with empirical findings such like Dias et al. (2015) who find more price stickiness for large than for small firms. The nexus between market power and delay has the same root than in Wang and Werning (2024), namely the degree of strategic complementarity, but is based on a different transmission mechanism without frictions.

4 Aggregated price dynamics

For the case of one industry, we have seen that – due to the distribution of idiosyncratic shocks – the delay times t^{**} are approximately Γ-distributed. If we consider a continuum of (structurally identical) industries, all exposed to the same shock, we can interpret $\Gamma(t)$ as the *share* of industries which have adjusted to the new reset price P^*, comparable to the Poisson arrival rates in the Calvo model. While in the Calvo model we have a constant share ϕ of non-adjusting firms in a sector with monopolistic competition, the price level is given by $P_t = ((1-\phi)(P_t^*)^{1-\theta} + \phi P_{t-1}^{1-\theta})^{\frac{1}{1-\theta}}$ from which we can derive the approximation $\pi_t = (1-\phi)(p_t^* - p_{t-1})$ with p_t^* as the reset log price after a shock, and p_{t-1} as the log price of the previous period. The goal is to derive a corresponding law of motion for the inflation rate for the strategic delay model.

Consider that in each industry we have a fringe firm with a relative weight β within the price index, and a duopoly which arranges a Stackelberg equilibrium after some strategic delay. The CES price aggregate is a weighted combination of fringe prices as well as Stackelberg prices in industries which have adjusted already to the reset prices, and the transitory prices of industries where we still have strategic delay, both weighted with the corresponding shares:

$$P(t) = \left[\beta(P_{fr}^{*})^{1-\theta} + (1-\Gamma(t))\left(P_{BR}^{1-\theta} + P_{S}^{1-\theta}\right) + \Gamma(t)\left((p_{L}^{*})^{1-\theta} + (p_{F}^{*})^{1-\theta}\right)\right]^{\frac{1}{1-\theta}} \quad (7)$$

where the upper index $*$ denotes reset prices, and $P_S = \frac{1}{2}(P_L + P_F)$ is the average Stackelberg price prior to the shock. We use the average for simplicity as it is ex ante not clear which of the two firms will strategically delay the adjustment. During the delay period it is P_{BR} the price of the leader who plays best response to the rival's old price. At time t, the share $\Gamma(t)$ of industries has duopolists which successfully arranged a Stackelberg reset price scenario. Once when $\Gamma(t)$ converges to 1 we have the full reset price level as in eq. (6).

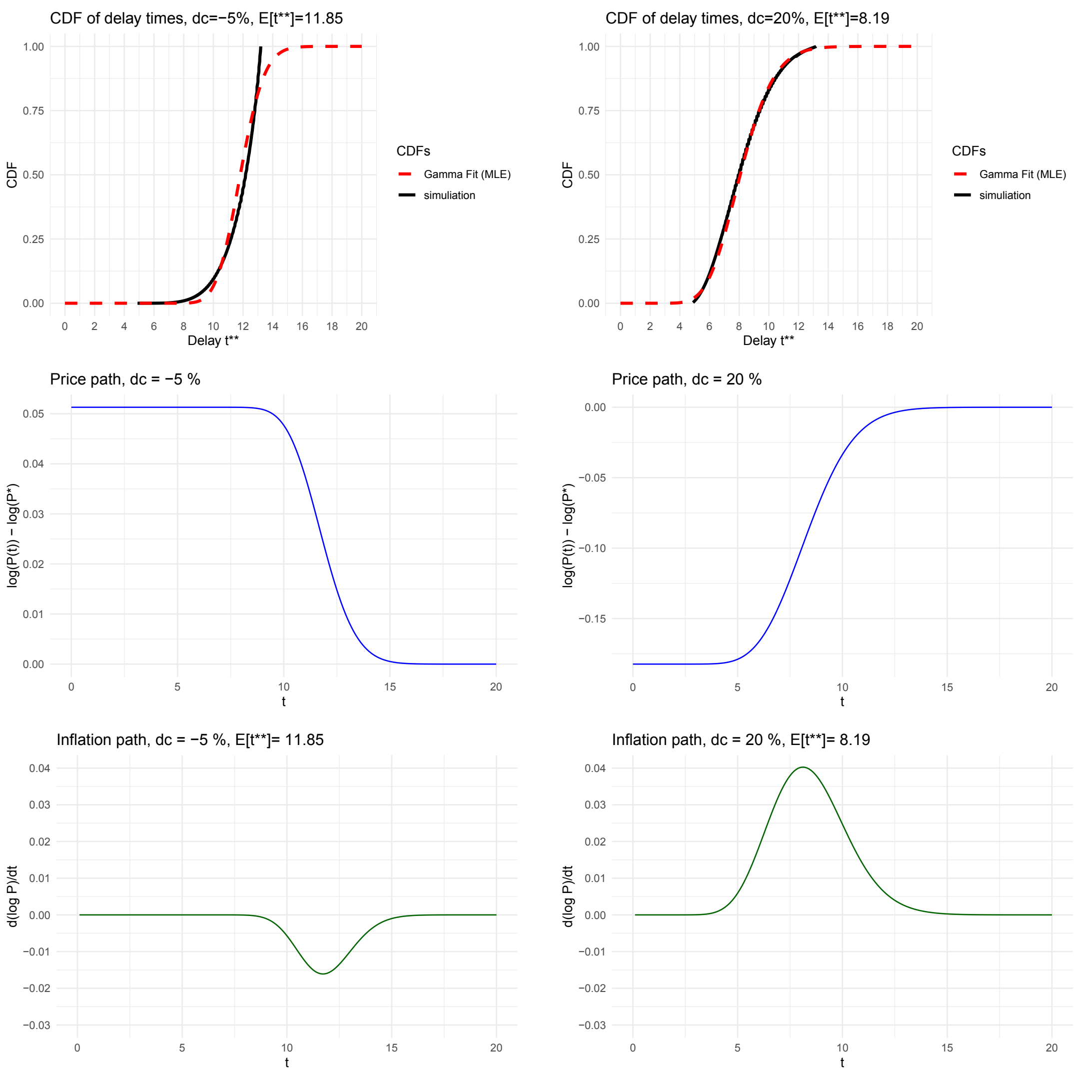

Figure 9: Price and inflation dynamics for a negative and a positive shock

Given the iso-elastic demand function[3] (4), and neglecting the fringe for simplicity ($\beta = 0$) as the fringe always responds immediately, figure 9 shows the price dynamic for the cost shocks $dc = -5\%$ (left) and $dc = +20\%$ (right) in the middle panel. It depicts the percentage deviation from the final reset price level. Recall that the leader starts with playing best response to the delaying firm, not with the leader's reset price. The top panel shows the simulated CDFs of delay times and their approximation by a Gamma-CDF. The latter is taken for calculating the price dynamics. The resulting inflation dynamics, obtained by numerical differentiation of eq. (7), is depicted in the bottom panel.

A log-linear approximation of the inflation dynamics can be achieved as follows: eq. (7) can be written as

$$P(t) = \left[(1-\Gamma(t))P_T^{1-\theta} + \Gamma(t)(P^*)^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

with $P_T = \left(\beta(P_{fr}^*)^{1-\theta} + P_{BR}^{1-\theta} + P_S^{1-\theta}\right)^{\frac{1}{1-\theta}}$ as the transitory price level, and $P^* = \left(\beta(P_{fr}^*)^{1-\theta} + (p_L^*)^{1-\theta} + (p_F^*)^{1-\theta}\right)^{\frac{1}{1-\theta}}$ as the full reset price level. Note that P_T and P^* do not depend on time, but time dependency of $P(t)$ only comes from $\Gamma(t)$, unlike the Calvo model. In order to obtain $\pi(t) = d\ln(P(t))/dt$ we calculate the time derivative of the log of the r.h.s., leading to the non-linear expression:

$$\pi(t) = \frac{\gamma(t)}{1-\theta}\frac{(P^*)^{1-\theta} - P_T^{1-\theta}}{(1-\Gamma(t))P_T^{1-\theta} + \Gamma(t)(P^*)^{1-\theta}}$$

Log-linearization at zero inflation, as common in the literature, gives

$$\pi(t) \approx \gamma(t)(p^* - p_T) \tag{8}$$

where $p^* = \ln(P^*)$ and $p_T = \ln(P_T)$. This result is analogous to the Calvo model, except for that here the bracket term is constant and the coefficient is time-dependent, while it is the other way round in the Calvo model.

Let μ be the *average* markup of leader and follower so that we can write $P^* = (2((1+\mu)MC_1))^{1-\theta})^{\frac{1}{1-\theta}}$ with MC_1 as the marginal cost after the shock. As we do not know ex ante which of the two firms will be in the waiting position, we consider the same markup μ for the firm in the waiting position where the price is $P_W = (1+\mu)MC_0$ with MC_0 as the marginal cost prior to the shock. For sake of simplicity assume that the markup of the best response player in the transitory period has a markup which is similar to the average Stackelberg one: $\mu_{BR} \approx \mu$ so that $P_T \approx (((1+\mu)MC_1)^{1-\theta} +$

[3]Given the baseline parameterization from section 3.3 but with $\theta = 3$ and $\sigma = 2$.

$((1+\mu)MC_0)^{1-\theta})^{\frac{1}{1-\theta}}$. Calculating the differences of the log prices we obtain

$$p^* - p_T = \frac{1}{1-\theta} \ln \left(\frac{2MC_1^{1-\theta}}{MC_0^{1-\theta} + MC_1^{1-\theta}} \right) \approx \frac{1}{2} \ln \left(\frac{MC_1}{MC_0} \right)$$

where the last step is a log-linearization at the steady-state of zero inflation which implies no changes of marginal cost ($MC_1 = MC_0$). Hence, the aggregated inflation dynamics can be approximated by the impulse response function

$$\pi(t) = \gamma(t, \cdot) \frac{1}{2} \widehat{MC} \tag{9}$$

with $\widehat{MC}$ as the percentage cost shock. Most importantly, the shape and the scale parameter of $\gamma(t, \cdot)$ depend on the size and direction of the shock as well as of demand elasticity θ and the other model parameter discussed in the previous sections, including the number of strategically behaving (large) firms. An empirical strategy of estimating inflation IRF (9) thus needs to explore the dependency of $\gamma(t, \cdot)$ on these parameters. Unlike the Calvo model, we do not have a “deep structural” parameter ϕ but a set of measurable parameters, determining the delay distribution. Also unlike the Calvo model, we do not have any forward-looking terms as price flexibility allows to adjust at any desirable time, and delay is intentional.

In case of a permanent shock *process*, new shocks arrive once when firms have not yet set reset prices in response to the previous shock. Given that the parameterization of the model doesn't change, any further shock will not affect the expected profits of any of the Stackelberg stages, henceforth $E\pi^F$ and $E\pi^{rand}$ will depend only on the idiosyncratic component which has a zero mean. But a new shock which arrives at t prior to full adjustment to P^* affects the profits in the waiting position and therefore delays t_i^*. The same shock has a different impact on a player who has been still in the waiting position after the previous shock, compared to the player who plays best response. But this is equivalent to the case that both would be exposed to different idiosyncratic shocks in a previous Stackelberg equilibrium. Henceforth, one could expect that equation (9) is also applicable to a persistent shock process $\widehat{MC}(t)$ rather than a single cost shock. This points into the direction of a Phillips Curve which relates inflation rates to *persisting* marginal cost changes which can be derived from output gaps.

5 Concluding remarks

The main contribution of this paper is to show that it is not necessary to assume *ad hoc* frictions in order to arrive at aggregate price stickiness. Empirically relevant phenomena such like dispersed and sticky prices can also be a result of strategic delay of price adjustment. The roots are not frictions but market power of oligopolists so that we do not need to give up the assumption of price flexibility. Contrary, the ability to delay presumes the ability to change prices at *any* strategically desirable point in time.

By establishing a simple mechanism, based on credible delay signals which allows firms to re-arrange a leader-follower structure after a shock, we have seen that delays are asymmetric with respect to small and large shocks, but also with respect to positive and negative cost shocks. Moreover, the delays depend on price elasticity of demand and the discount factor in a reasonable manner. This allows for explaining a variety of empirical facts. Also the number of firms (degree of competition) has an impact on delay times. We relaxed the assumption of symmetry, and considered a market structure with many small non-strategic fringe firms, and few dominant strategically deciding oligopoly firms. Market concentration in the "long tail" of firm size distribution will then result in more price stickiness.

It is possible to derive an equation for the aggregate price dynamics. As delay times follow a Gamma distribution, the CDFs of delay times can be interpreted as shares of adapting firms, similar to the Poisson arrival rates in the Calvo model. However, the CDFs vary in time, and the aggregated price dynamic is not forward-looking as firms are always able to respond to observed shocks. Moreover, the CDFs depend on direction and size of the shock. What has not been analysed in this paper is the case of a permanent shock process where shocks hit firms which have not yet achieved a Stackelberg equilibrium. As the response to positive and negative shocks is asymmetric while a shock process may have no trend, we eventually might arrive at a kind of trend inflation process.

One should see this model not as a complete substitute for friction-based approaches. Both are complementary concepts. However, besides the variety of empirical stylized facts consistent with the strategic delay approach, I see it's main merit on a conceptual basis: the view that a frictionless and seamless Arrow-Debreu world is the benchmark, and only some sort of distortive ad hoc deviations from it lead to Keynesian features, is challenged. Instead, a world with *heterogeneity* and *strategically* acting firms, keeping neoclassical assumptions of rationality and price flexibility intact, is the *more general case* which implies already Keynesian features.

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Appendix

With the linear demand scheme given in the text, one can easily compute the expected profits $E\pi^F, E\pi^L, E\pi^W, E\pi^{rand}$ for a duopoly, using eq. (1). As the waiting profits depend on the prior price (leader or follower), we obtain two critical values t_i^* from equation (3). Without loss of generality, assume that $i = 1$ is the former follower, and $i = 2$ is the former leader.

$$t_1^* = \frac{\ln\left(\frac{8y^2+\left(8\bar{dc}+6dc_1\right)by+3b^2\sigma^2+\left(16\bar{dc}^2+16dc_1\bar{dc}+3dc_1^2\right)b^2}{15y^2+\left(8\bar{dc}+8dc_1\right)by+2b^2\sigma^2+\left(16\bar{dc}^2+16dc_1\bar{dc}+2dc_1^2\right)b^2}\right)}{\ln\beta}$$

$$t_2^* = \frac{\ln\left(\frac{7y^2+2dc_2by+3b^2\sigma^2+\left(16\bar{dc}^2+16dc_2\bar{dc}+3dc_2^2\right)b^2}{14y^2+4dc_2by+2b^2\sigma^2+\left(16\bar{dc}^2+16dc_2\bar{dc}+2dc_2^2\right)b^2}\right)}{\ln\beta}$$

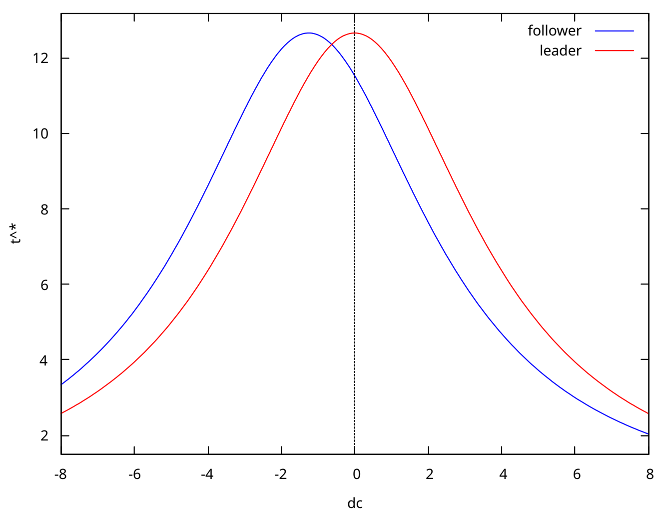

Figure 10: Delays t_1^*, t_2^* without idiosyncratic shocks

In absence of idiosyncratic shocks ($dc_1 = dc_2 = 0$), one can directly see that these delays are singe-peaked in the common shock $\bar{dc}$, and the peak is for $\bar{dc} \leq 0$:

$$\frac{\partial t_1^*}{\partial \bar{dc}} = 0 \qquad \Rightarrow \qquad \bar{dc} = -\frac{y}{4b}$$
$$\frac{\partial t_2^*}{\partial \bar{dc}} = 0 \qquad \Rightarrow \qquad \bar{dc} = 0$$

The entire function $t_2^*(\bar{dc})$ is thus a shift $t_2^*(\bar{dc}) = t_1^*(\bar{dc} + y/4b)$, reflecting that both players in different prior Stackelberg positions are hit by the same shock in a different manner in the waiting position, or hit in the same manner by a different ("shifted") shock. Further, the curves have a unique intersection point at $\bar{dc} = -y/8b$. Recall, that $t^{**} = \min(t_1^*, t_2^*)$ (see figure 10). Hence, this explains the asymmetry between small and large shocks, and between positive and negative shocks, as well as the result that for positive shocks we observe more often a leadership switch (as here it is $t_1^* < t_2^*$), while for negative shocks the positions are often preserved (as here we have $t_1^* > t_2^*$).

One can calculate the partial derivatives of t_1^*, t_2^* with respect to b, σ, β for the case of $dc_1 = dc_2 = 0$. The signs of the derivatives confirm the results from chapter 3 where we computed expected delays with idiosyncratic shocks.

A replication package for all analytical and numerical computations and graphics is available. The code is written in `R`. The analytical results regarding t_i^*, partially used in the R code, have been computed with `wxmaxima`, an Open Source software for symbolic and numerical mathematics.

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