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An Agent-based Approach

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Price Rigidity and Strategic Uncertainty
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Abstract

The phenomenon of infrequent price changes has troubled economists for decades. Intuitively one feels that for most price-setters there exists a range of inaction, i.e. a substantial measure of the states of the world, within which they do not wish to modify prevailing prices. However, basic economics tells us that when marginal costs change it is rational to change prices, too. Economists wishing to maintain rationality of price-setters resorted to fixed price adjustment costs as an explanation for price rigidity. In this paper we propose an alternative explanation, without recourse to any sort of physical adjustment cost, by putting strategic interaction into the center-stage of our analysis. Price-making is treated as a repeated oligopoly game. The traditional analysis of these games cannot pinpoint any equilibrium as a reasonable "solution" of the strategic situation. Thus there is genuine strategic uncertainty, a situation where decision-makers are uncertain of the strategies of other decision-makers. Hesitation may lead to inaction. To model this situation we follow the style of agent-based models, by modelling firms that change their pricing strategies following an evolutionary algorithm. Our results are promising. In addition to reproducing the known negative relationship between price rigidity and the level of general inflation, our model exhibits several features observed in real data. Moreover, most prices fall into the theoretical "range" without explicitly building this property into strategies.

Keywords: Agent-based modeling, Evolutionary algorithm, Price rigidity, Social learning, Strategic Uncertainty

JEL Classification: L13, C63, B52

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Ármerevség és stratégiai bizonytalanság: egy ágens alapú megközelítés

Somogyi Róbert – Vincze János

Összefoglaló

Régóta foglalkoztatja a ritka árváltoztatások problémája a közgazdászokat. Intuíciónk szerint léteznie kell egy nem triviális „tétlenségi” tartománynak, vagyis az állapotok egy olyan halmazának, amelyen a vállalatok annak ellenére nem módosítják az áraikat, hogy a releváns körülmények változása miatt a közgazdasági alapelvek is ezt diktálnák. A közgazdászok megoldása a problémára az egyösszegű árváltoztatási költségek bevezetése volt, ami racionális döntéshozás mellett is produkálhat ármerevséget. Ebben a tanulmányban egy alternatív megoldást javasolunk, amelyben nincs szerepe a változtatási költségeknek, hanem az árazók stratégiai kölcsönhatásainak van kulcsszerepe. Az árazást oligopol játéknak tekintjük. A hagyományos játékelméleti elemzés nem képes egyértelmű „megoldást” találni ebben a játékban, általában számos magatartás van összhangban a Nash-egyensúly kritériumával. Itt tehát létezik valódi stratégiai bizonytalanság, a döntéshozók szükségképpen bizonytalanok a többiek viselkedését illetően. Ezt a szituációt úgy modellezzük, hogy a vállalatok az árazási stratégiáikat egy evolúciós algoritmus segítségével változtatják, vagyis adaptálódnak a környezetükhöz. A modellel elért szimulációs eredményeink ígéretesek. Reprodukáljuk a negatív kapcsolatot az infláció szintje és az ármerevség között, valamint a valós adatok egyes további tulajdonságait. Ezen kívül az árak túlnyomó része az „elméletileg” ésszerűnek tekinthető tartományba esik anélkül, hogy ezt explicite a modellre kényszerítettük volna.

Tárgyszavak: ágens alapú modellezés, evolúciós algoritmus, ármerevség, társadalmi tanulás

JEL kódok: L13, C63, B52

1 Introduction

Everyday observations tell us that some prices are changing almost continuously. Financial asset prices, of foreign exchange or of stocks, are obvious examples. Though most people do not buy commodities regularly, it is also well-known that the prices of crude oil, gold, or grain behave similarly. On the other hand most prices we meet in shops or kiosks seem familiar, we expect that they do not move from one day to another.

Infrequent price adjustment has troubled economists for decades. The problem is not the lack of change in itself, but the conviction that prices are kept fixed for much longer than market conditions, costs, and competitors' prices would justify. Intuitively, there exists a range of inaction for most price-setters, i.e. a substantial range of "the states of the world", where they do not wish to modify prevailing prices. Meanwhile basic economic theory instructs us that, at least, when marginal costs change it is rational to adjust prices, even in not fully competitive markets.

According to the prevailing wisdom the stickiness of money prices is the root of the ability of monetary policy to affect (significantly) real - as opposed to merely nominal - variables. It is perhaps less in evidence, but the same phenomenon is a concern for competition authorities, too, as it may signal collusion among market participants..

Economists wishing to maintain the rationality assumption for price-setters resorted to price adjustment costs ("menu costs") as an explanation of price rigidity. The basic idea is that, for instance, the everyday reprinting of an elegant menu for a restaurant is not a reasonable option, being too costly. Certainly, similar issues may be relevant for many other businesses. However, what about meal prices written on a blackboard at a pub's entrance? These prices appear to exhibit the same stickiness, despite the fact that overwriting them each day does not entailing any additional cost. Magazine prices have been one of the foremost examples of unreasonably strong price inflexibility, but printing a different price on each new edition would not entail even a negligible extra cost.

It must be the case that the rigidity of prices has more than one reason. In this paper we propose an alternative, though admittedly partial, explanation, without having recourse to any sort of physical adjustment cost. Rather, we focus on the possible role of strategic uncertainty, and put strategic interaction into the center-stage in our analysis.

The main idea of our approach can be summarized as follows. Price-making can be considered a repeated game, as firms usually act in markets where there exist identifiable competitors. The traditional analysis of these games cannot pinpoint any equilibrium as a reasonable "solution" of the strategic situation. Thus there is genuine strategic uncertainty, a situation where decision-makers cannot know for sure the strategies of other decision-makers. Strategic uncertainty may cause hesitation. If I cut the price would it be interpreted as a signal for a "price-war"? Or if I raise the price shall I lose market-share? Hesitation may lead to inaction, as we all know too well. To model this situation we follow the style of agent-based models. While traditional economics rely on full rationality and on an equilibrium concept, we model boundedly rational agents, thus must assume something about learning. To achieve our goal we adopted an evolutionary algorithm.

In Section 2 we give a survey of the price rigidity literature, followed by notes on agent-based modeling as applied to economics problems. In Section 3 a traditional approach to oligopoly pricing is surveyed. In Section 4 the agent-based oligopoly model is set up, and the learning algorithm is discussed. Section 5 presents the analysis of the model, and the concluding Section summarizes, pointing out paths to further research.

2 Literature Survey

The Rigidity of Prices

The most salient fact conflicting with price flexibility this presumption has been termed the PPP (Purchasing Power Parity) puzzle (Rogoff, 1996), this is the general observation that there are large variations across currencies in purchasing power parity, induced by nominal exchange rate changes. Due to this and similar empirical findings, price rigidity has become a fundamental assumption in New-Keynesian macroeconomic models, that are sometimes called the “workhorse” of modern macroeconomics (Gali, 2008). New-Keynesian Phillips curves are derived from individual profit maximization, whereby prices are set by monopolistically competitive firms that face costs of price adjustment. As not all prices are raised immediately following a positive money injection demand increases, and output becomes - temporarily - higher than normal. (The same with opposite signs happens after a monetary contraction.) Prices follow suit eventually resulting in a positive correlation between growth and inflation. Price adjustment costs imply – in contrast to some former theories - that even foreseeable monetary policy changes have real effects. However, a recent, surprising, finding is that prices posted on the Internet, which can be changed very easily, are not necessarily more flexible than traditional brick-and-mortar prices (Lünnemann & Wintr, 2006). This, in itself, shows that adjustment costs cannot be the only explanation for price rigidity.

Several types of price adjustment costs models have been proposed in the literature. The aggregate implications of these models are similar, though in no case identical (Roberts, 1995) Researchers have frequently shown a lack of concern for looking for the "right" pricing model, as long as the implications seemed to be in line with macroeconomic data, and one should say, with *a priori* beliefs.

In the last decade a series of systematic studies was launched to find out from microdata how firms "in reality" set their prices. This literature is surveyed by Mackowiak & Smets (2008). One of the studies (Fabiani et al., 2007) was conducted by nine Eurosystem central banks, through standardized surveys. It covered more than 11,000 firms. Of the conclusions we cite only those pertinent to our paper. First: "The results, robust across countries, show that firms operate in monopolistically competitive markets, where prices are mostly set following markup rules ..." Though the authors talk of "monopolistically competitive markets", we believe that the evidence cannot really distinguish between "monopolistic competition" and oligopoly. What is important for us is the prevalence of markup rules. Second: "Price stickiness is mainly driven by customer relationships -- explicit and implicit contracts -- and coordination failure." In this paper we do not address customer relationship, but emphasize "coordination failure". Indirectly this sentence vindicates our previous claim with respect to oligopolistic versus monopolistic competition. To wit: there is no reason for coordination in monopolistically competitive markets. As a response to the failure of adjustment cost models Rotemberg (2011) proposed an alternative in the behavioral economics style. Essentially he made intelligible the idea that price stickiness can be caused by a concern for fairness (customer relationships). Third: "Firms facing high competitive pressures review their prices more frequently." Below in the sensitivity analyses we check whether our model exhibits a negative relationship between the degree of competition and price rigidity.

Spiegler (2011) also analyzes the question of price-setting by a behavioral economics approach. In his model consumers are antagonized by unexpected price hikes, i.e. facing a higher price than their “sampling-based” reference price reduces their utility. He finds that this kind of loss aversion (manifested solely in the price dimension of the product, as opposed to the previous studies he heavily relies on, which are Kőszegi & Rabin, 2006 and Heidhues & Kőszegi, 2008) can reduce a monopolist’s optimal price range thus implying price rigidity.

It is an interesting question to ask what makes prices change if anything. Papers that have addressed this issue usually found that cost changes are more likely to be responsible for price change than variation in demand (Bils & Klenow, 2004).

Recent research has yielded quantitative results as well. Several authors calculated price-rigidity statistics for different time-periods, and areas. On a consumer-price data base for the US Klenow & Krystov (2008) found that 36 % of all prices are changed in every month, and that the mean duration of prices is 6.9 months. More substantial price rigidity was detected by Dhyne et al. (2005) for the Euroregion. The respective statistics are 15 %, and 13 months. These studies have found substantial heterogeneity across sectors, and as expected, a negative relationship between the level of overall inflation and the degree of price rigidity.

In our model we use the results of Eichenbaum, Jaimovich & Rebelo (2008), who analyzed the price and cost data of a large American chain store retailer. They found substantial rigidity for "reference" prices, remaining unchanged on average for a year. What is important for us is the finding that reference prices are adjusted whenever they differ significantly from a target price defined as average cost times a "required" markup. The authors calculate the tolerance level as 20 %. Below we will model exactly this type of pricing strategy.

Agent-based modeling in economics

Agent-based models have been used for some time in economics. General surveys are available (Tesfatsion, 2001; Tesfatsion, 2006; LeBaron, 2006). The paper by Heath, Hill & Ciarallo (2009) can be consulted mainly from the methodological point of view. Researchers would, in general, like to resolve two issues of traditional economic analysis with the help of agent-based models. First, economists rather than studying complicated market mechanisms usually resorted to shortcuts, as the idea of the Walrasian auctioneer. These shortcuts have been regarded increasingly unpalatable. However, as oligopoly pricing models have a simple exchange structure (prices are posted, then buyers arrive and buy or not), we are only marginally concerned with this branch of the literature. Second, traditionally economic models assumed something that, with some lack of precision, has frequently been called full rationality. This means essentially that agents apply strategies that maximize utilities under constraints, and have an objective (probabilistic) understanding of their environment. Full rationality has been seriously put into doubt both in laboratory environments and on the field. Despite continuing efforts to save the rationality assumption it has become accepted that other research programs have significant promise (Kahneman & Tversky, 1979; Gigerenzer & Selten, 2001). Agent-based economic models share a bounded rationality philosophy, where decisions are "practically computable", excluding thereby behaviors that even the modeler cannot determine. Learning models have a long history in economics (Evans & Honkapohja, 1999). But one may say that learning is, strictly speaking, meaningless in traditional models – excluding Bayesian updating of probabilities. On the other hand agent-based models frequently allow for an endogenous updating of strategies. Learning in the agent-based setting was several times reviewed (Brenner, 2006; Duffy, 2006). Though many types of learning models are in use one of them draw particular attention in economic applications: evolutionary learning (Arifovic, 2000). Our approach belongs to this branch of the literature.

Oligopolistic markets have been studied by agent-based models. The article by Midgley et al. (2007), is an example that addresses the problem from an operations-research perspective. The paper whose approach is the closest to ours was written by Chen & Ni (2000). The authors explore the "ecology" generated by evolutionary learning in repeated oligopoly games. Their focus is on the "cooperation versus price wars" issue, and they constrain the set of feasible prices to high (cooperative) and low (punishing). Thus their findings are only tangential to the problem of price rigidity.

3 The traditional oligopoly pricing model

There are N (i=1,...N) firms in the industry, where N is a constant. Time is measured in discrete units. Firms produce differentiated goods, and have constant marginal cost in period t, evolving according to $c_{it} = P_i c_{i0}$, where P_t is interpreted as the overall price level in the economy, and let p_{it} be the price chosen by firm *i* in *t*. For the demand framework we adopted the logit demand function system (Anderson & de Palma, 1992), which can be written as

$$D_{it} = K \frac{e^{-\frac{p_{it}}{\nu P_t}}}{\sum_{j=1}^{N} e^{-\frac{p_{jt}}{\nu P_t}} + e^{\frac{V}{\nu}}} \qquad \forall i, \forall t.$$

Here K can be interpreted as the absorption capacity of the market. The parameter ν ($\nu > 0$) controls for the degree of differentiation. When $\nu \to 0$, products become more and more homogenous, and slight differences in prices result in large shifts in demand. Like in Bertand-competition, in the limit buyers purchase only at the lowest price. On the other hand, when $\nu \to \infty$, consumers buy randomly, each firm faces the same demand. To save space in the description below we set *K=1*, and ν *=1*, but in the sensitivity exercises we treat the general case. The role of the last term in the denominator is to make the optimal collusive price finite. If it were *0*, total demand would be equal to K whatever the prices are, therefore cooperating firms could set "infinitely" large prices. The formula implies that demand depends on prices relative to the general price level.

Then the per-period profit functions are given by:

$$\pi_{it} = (p_{it} - c_{it})D_{it}.$$

These data define in every period a Bertrand-Chamberlin oligopoly game, for which there exists a static Nash-equilibrium. For the case of common costs Anderson & de Palma (1992) established the following relationship:

$$p_t^* = c_t + P_t + \frac{P_t}{N - 1 + e^{\frac{p_t^*}{P_t} + V}},$$

where p_t^* is the (common) Nash-equilibrium price. Though there does not exist an explicit solution, this equation is easy to solve numerically. Furthermore one can derive the following relationship for the optimal (static) collusive price:

$$p_{k,t}^* = c_t + P_t + \frac{NP_t}{e^{\frac{p_{k,t}^*}{P_t} + V}}.$$

These formulas show that as N increases the non-cooperative price monotonically decreases, whereas the collusive price monotonically increases. The non-cooperative and collusive prices will be important benchmarks during the analysis of the agent-based model in the following section.

The analysis of the repeated oligopoly game is potentially very complicated (Abreu, Pearce & Stacchetti, 1985). It depends largely on the assumptions made on the exogenous processes (marginal costs and general price level). Analytic results are usually available for specific and simple driving processes. To summarize results briefly: sub-game perfect supergame (repeated game) equilibria lie between the static Cournot-Nash equilibrium, and the collusive (joint profit maximizing) outcomes. In general there exists a bewildering variety of Nash-equilibria, if strategies are allowed to be any function of the observable history of the market. While repeated oligopolistic pricing games can produce "collusive" equilibria with rigid prices in peculiar circumstances (Athey, Bagwell & Sanchirico, 2004). In the next section we approach the problem from the perspective of boundedly rational agents.

4 Oligopoly Pricing by Boundedly Rational Agents

We model firms as boundedly rational agents that do not pretend to find out what an optimal pricing strategy would be, as optimality depends heavily on the reaction of competitors, as well as on the uncertainties of the marginal cost process. They know their current costs, but otherwise they have only vague ideas on their rivals' behavior. Thus they know that they can "mark up" costs, in other words in a differentiated oligopoly setting prices can be profitably set above marginal cost, even if competitors would remorselessly maximize profits. They also know that there is a remote possibility to collude tacitly, and by effectively forming a powerful cartel prices can be set "high enough" above marginal costs to achieve maximal profits for the whole industry. Furthermore, they know that there is an upper limit, even the omniscient cartel would not set infinitely high prices. On the other hand they are skeptical, and are aware of strategic uncertainty, i.e. they are uncertain about how their competitors behave and react. This reasoning leads these firms to formulate pricing strategies in the following way.

1. Start with a target markup range, where the lowest markup is higher than 1.

2. Observe the marginal cost and calculate the target price range.

3. Check whether your latest price falls into the target range or not.

4. If yes, do not change the price.

5. If no, set the new price as a weighted average of your latest price and the middle of the target range.

6. Observe how strategies work in the market over several periods. (Any strategy consists of the target markup range (two parameters) and the weight of the old price.) Then try to imitate successful strategies, or maybe experiment with a new one.

The change of strategies is based on a specific evolutionary algorithm, i.e. on a generic learning mechanism that has been applied in several contexts within, and, mostly, without economics. The learning mechanism used in this study has certain specific features. We call it evolutionary, because in spirit it is very similar to the class of algorithms surveyed for instance in Arifovic (2000). More precisely it is a modified form of a standard genetic algorithm (Haupt & Haupt, 2004).

For the formulation of such an agent based-setup we have to develop strategies, evaluation functions, and evolutionary operators. We must start with the definition of strategies. Decisions must depend on current marginal costs as a minimum, therefore we can transform the pricing problem into a markup-determination problem. (Price equals marginal cost times markup.) Based on the informal argument presented in the Introduction we limit the strategy space to three dimensions:

1. Setting the lower limit of the markup, μ_{it}^{l} (a positive real number)

2. Setting the upper limit of the markup, μ_{it}^{u} (a positive real number)

In fact it is more convenient to work with a transformation of the two real variables: setting a markup target, and a percentage deviation from the markup target. In any case for given marginal costs and markup limits one can determine a range of prices, whose lower and upper bounds are $p_{it}^{l} = c_{it}\mu_{it}^{l}$, and $p_{it}^{u} = c_{it}\mu_{it}^{u}$, respectively.

3. Setting the weight of the latest price (β) in the calculation of the new price when it is not between the lower and upper bounds for the markup (a real number between *0* and *1*).

Then the strategy (decision function) is the following.

1. If the prevailing price is between the lower and the upper bounds the price is not changed.

$$p_{it} = p_{i,t-1}.$$

2. If the prevailing price is below the lower bound, or above the upper bound:

$$p_{it} = \beta p_{i,t-1} + (1-\beta)\frac{p_{it}^{l} + p_{it}^{u}}{2}.$$

It must be emphasized that this strategy set is obviously "much smaller", than the set of all feasible strategies. It is also more restricted than the set of available Markov-strategies. Still, these are not overly simplistic strategies, either. As we have argued in the previous subsection due reflection can lead someone to opt for these strategies in an oligopolistic situation with strategic uncertainty, thus they are far from being naive.

We start by giving more or less reasonable initial values to the three strategic variables. The initial values of the lower and upper limit of the markup are set to be equal in order to avoid the suspicion of building price rigidity into the model. These values are uniformly distributed among firms between *0* and *0.5,* while the initial weight of the latest price ranges from *0.2* to *0.8*. In the initial period firms act according to these (almost) random strategies. However, the evaluation phase of each run is preceded by a warm-up phase, exactly in order to minimize the noise caused by these initial values.

Evolution requires a measure of fitness. An obvious candidate is actual profits, however, intuitively measuring fitness by a single run of profits would be unreasonable. Thus we define fitness as the average of profits obtained by a strategy with exponentially declining weights.

$$\Phi_{it} = \lambda\Phi_{i,t-1} + (1-\lambda)\pi_{it}$$

We assume that after period 1 firms calculate the fitness of all strategies (not only their own). However, the evaluation phase of each run is preceded by a warm-up phase, exactly in order to minimize the noise caused by these initial values. At the beginning of period 2 the strategy of each firm possibly undergoes changes, according to evolutionary operations. The first operation is selection or reproduction. We define the survival probability of the *i*th strategy by the Boltzmann-selection criterion as

$$Pr_{it} = \frac{e^{\Phi_{it}/H}}{\sum_{j=1}^{N} e^{\Phi_{jt}/H}}, \quad i = 1,2..N,$$

where H is the Boltzmann-constant, frequently referred to as "temperature". At high temperatures the selection pressure is low, whereas at low temperatures it is high (i.e. "only the best can survive"). Notice, that survival depends on the relative fitness of a strategy in the population, thus we model a sort of social learning process. For this purpose, we use the fitness-proportionate method, also referred to as roulette wheel sampling. Thus chance determines if a strategy survives or not. A possible interpretation is noise in observation, i.e. the selection probability comes about from two reasons: firms can observe the fitness of strategies existing in the market only imperfectly, but tend to choose those that are perceived more successful.

Then the surviving strategies may undergo mutation: each of the three elements can be changed randomly. To implement mutation all variables are given a transition probability, called the mutation rate. In addition, we specify a continuous probability distribution for the mutation. We assume that it is normal, with mean *0*, and variance σ^2. Thus here we must only specify the variance. All mutation parameters are exogenous, and they do not change over time.

After disposing of the problem of strategies surviving selection one has to deal with firms whose previous strategy was dropped after the selection process. Our approach is to form a convex combination of the old (dropped) strategy, and one of those that have been selected repeatedly. This operation is not customary in the literature, one can interpret it as giving a certain individual and conservative flavor to the learning process. The weight of the dropped strategy is an exogenous parameter of our model.

5 Simulations

The Baseline Scenario

In this section, first, we report the baseline scenario values of parameters. Then we describe the results of this benchmark model which is followed by a sensitivity analysis in which the effect of changes in individual parameter values is checked.

1. Number of firms (*N*): In the baseline model there are 10 competing firms.

2. Degree of product differentiation (ν): 1

3. Scale of demand(*K*): 1

4. V in the demand system. In the baseline model its value is -1.5*c*.

5. Boltzmann-constant (*H*): In the baseline model *H* is set to 1.

6. Fitness function: In the baseline model its quotient is $\lambda = 0.5$.

7. Mutation parameters: The mutation rate is 5% for all the variables. The standard deviation of the mutation is 0.01 for the markup target, 0.02 for the weight of the old strategy and the deviation from the markup target.

8. Weight of the repeatedly selected strategy: The baseline weight of the latter is 0.55.

9. Inflation environment: The overall annual inflation rate is a normally distributed random variable with an expected value of 3% and a 1 percentage point standard deviation.

Baseline Results

An important question was how prices generated by the model are related to "theoretical" prices, the Cournot-Nash and collusive equilibrium prices. Using the baseline parameterization described above in the 100 test runs all prices our model produced fell within the interval defined by those two values,

Another test of the model is to compare its results to actual statistics. This exercise can also be regarded as a first attempt to externally validate the model. With the baseline parameters the average duration of prices is 6.39 months, and its standard deviation is 2.88. We were able to compare these figures with actual inflation data for three different regions.

Table 1 Inflation data and percentage of prices within the theoretical region

	Monthly inflation (%)	Standard deviation. of inflation	Percentage of prices within the theoretical region
USA	0.27	0.36	94.7
Eurozone	0.16	0.20	98.8
Hungary	0.40	0.69	98.2

The sources of these statistics are Klenow & Kryvstov, 2008 (Table I and VI, p. 871 and 886) for the US data and Dhyne et al., 2008 (Table 2, p. 12) for the European data, and Bauer, 2008 for the Hungarian data.

As it can be seen in Tables 2-3, showing average results of 100 runs, the model's estimates are realistic. The actual statistics themselves are only broad averages of substantially different sectoral data (see Nakamura & Steinsson, 2008, Table 2, p. 1433).

Table 2 Percentage of prices changed

	Fact	Model
USA	36.2	19.8
Eurozone	15.3	12.7
Hungary	24.7	29.8

Average duration is a standard and intuitive measure of price rigidity, it is simply defined as the average time lag between two price changes of the products in the sample.

Table 3 Average duration

	Fact	Model
USA	6.8	5.7
Eurozone	13.0	9.5
Hungary	3.8	3.7

Another interesting question is the model’s behavior at different levels of inflation. When the inflation rate is 0, almost total price rigidity arises, i.e. after on average 255 periods, none of the firms change their price for very long. On the other hand, in a hyperinflation environment, using the Hungarian inflation data of July 1946, the model produced full price flexibility. These two experiments accidentally prove that the model is not “empty”, price stickiness is not a “built-in” feature of it, but can arise in reasonable scenarios.

Sensitivity Analysis

The number of firms is frequently regarded as one facet of the competition on a given market.

Somewhat surprisingly increasing the number of firms causes less variability, but average rigidity is left unaffected.

Table 4 Sensitivity analysis – Number of firms

Number of firms	Average duration	Standard deviation of duration

5	6.40	3.27
50	6.48	1.39
100	6.10	1.19

For a given number of firms, and with a given degree of differentiation increasing the size of the market may lead to more security.

Table 5 Sensitivity analysis – Scale of demand

Scale of demand	Average duration	Standard deviation of duration
0.5 times baseline	6.54	2.92
10 times baseline	5.63	2.18
100 times baseline	3.39	0.80

We can see that less uncertainty increases price flexibility, which is in accordance with our intuition.

In oligopolistic models less differentiation means more intense competition.

Table 6 Sensitivity analysis – Degree of differentiation

Degree of differentiation	Average duration	Standard deviation of duration
0.1 times baseline	11.076.40	6.22
0.5 times baseline	7.25	3.08
10 times baseline	6.13	2.84

One can see that in this agent-based model with strategic uncertainty this translates into more hesitation, and more price rigidity.

Low temperature is equivalent to high selection pressure.

Table 7 Sensitivity analysis – Temperature

Temperature	Average duration	Standard deviation of

		duration
0.5	6.99	2.98
2	6.61	3.93
5	6.44	2.65

Apparently selection pressure affects price rigidity only marginally.

The weight in the fitness function can be considered as "memory".

Table 8 Sensitivity analysis – Fitness weights

Fitness weights	Average duration	Standard deviation of duration
1/3	6.07	2.18
1/10	6.29	2.72
1/100	6.11	2.21

The memory parameter does not seem highly relevant, which is good, since this lends some robustness to our results.

Increasing the mutation rates clearly raises uncertainty, and, especially, strategic uncertainty.

Table 9 Sensitivity analysis – Mutation rates

Mutation rates	Average duration	Standard deviation of duration
0.01	3.31	1.09
0.1	7.62	2.97
0.2	10.07	4.91

Our interpretation of the model is confirmed by finding that higher uncertainty is accompanied by more price rigidity.

6 Conclusions

Microeconomic research has, in general, had a dim conclusion for adjustment costs models: each of them seems to be irreconcilable with some salient features of microdata. Our attempt to explain price rigidity by strategic uncertainty of boundedly rational agents is new in the literature. We wish to make sense of the idea that "coordination failure" is a major, though certainly not unique, source of price rigidity

The oligopoly model in which we tried to substantiate our claim is fairly standard, and can be generalized in several directions. For example we made the simple assumption of common marginal costs, but we have checked that individually different marginal costs would not change the results qualitatively.

It is quite promising to see that the model produces sensible results, along several dimensions. First, it reproduces the negative relationship between the level of overall inflation and price rigidity. Second, most prices fall into the theoretical "range" without explicitly building this feature into strategies. Third, price rigidity statistics are even quantitatively similar to actual data. Fourth, the sensitivity analysis shows that parameter changes that intuitively correspond to higher strategic uncertainty cause indeed more inflexibility in prices.

Obviously, this simple model cannot explain all phenomena concerning oligopolistic price setting. Its extension into several directions would test its robustness. There remains one important feature of data that the model cannot replicate: price wars. To address this issue should be our next concern.

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