Examining Models of Collusion: the Market for Lysine

Nicolas de Roos*
University of Sydney

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Abstract

We compare the experience with collusion in the market for lysine with the predictions of theory. The lysine market provides an ideal setting following the confessions of cartel participants in anti-trust investigations. Data availability allows demand and cost functions to be estimated and observed mark-ups compared with predictions. We find that several integral aspects of collusion in the lysine market are not adequately addressed in the literature: the dynamics associated with entry and investment; persistent asymmetries between firms; the cartel's bargaining problem; and the existence of cheating in equilibrium. These issues are likely to have much wider applicability beyond the lysine market.

*Nicolas de Roos: School of Economics and Political Science, Merewether Building H04, University of Sydney, Sydney, NSW 2006, Australia, e-mail: n.deroos@econ.usyd.edu.au, phone: +61 (2) 9351 7079, fax: +61 (2) 9351 4341

1 Introduction

Economic theory admits a spectrum of predictions of cartel behaviour, depending on the specific modelling assumptions employed.[1] This paper examines the recent history of collusion in the lysine market, in which it is known that collusion took place, discussing the ability of available models of collusion to replicate the observed dynamics of the market.

By October 1996, the major participants in the market for lysine had confessed to fixing prices. From the proceedings of the various anti-trust cases, data on lysine prices and quantities as well as the marginal costs of one of the participants are available over the period of conspiracy. This makes the market for lysine an ideal test case for models of collusion. In addition, the history of collusion is a particularly interesting one, with the substantial entry of Archer Daniels Midland (ADM) and two dramatic price wars. The homogeneous nature of the product also greatly simplifies the analysis.

If the operating environment of the lysine cartel does not match up well with common modelling assumptions, then our test is a difficult one for collusion models to pass. We could equally consider the exercise in terms of two interrelated questions. First, does the cartel's environment match closely with typical modelling assumptions? Second, do the predictions of theory match the empirical observations in the lysine market? Our examination thus combines a test of the predictions of collusion models with a test of whether the key features of the lysine market match factors identified as important in the literature.

The exercise reveals that the observed dynamics of the lysine cartel departed markedly from the predictions of theory in several respects. In particular, the nature of the price wars departed from those commonly examined in the literature; the level of the markup of prices over marginal costs during phases of collusion was much lower than we may have expected; and cheating on the cartel agreement was observed or at least strongly suspected. Substantial divergences between the lysine cartel environment and modelling assumptions commonly adopted appear to underly these differences. Key features of the lysine cartel environment include heterogeneity in firm characteristics and information sets; dramatic variation in market structure due to entry and investment; and an evolving cartel operating mechanism.

Section 2 outlines some background information on the market for lysine. This includes a discussion of the salient features of the market and the history of the operation of the lysine cartel. Section 3 relates the operating environment of the cartel to a selection of the collusion literature. In Section 4, models of lysine demand and costs are discussed. Based on demand and cost estimates, section 5 compares the behaviour of the mark-up of a major lysine producer to that predicted by different models of collusion and discusses alternative explanations for key events in the lysine market. Finally, concluding remarks are offered in section 6.

[1] See Pearce (1992) for a survey of cooperation in repeated games of symmetric and asymmetric information.

2 The Lysine Market[2]

Lysine is an essential amino acid for the lean muscle development of hogs and poultry.[3] Being a chemical compound, lysine is as close as we get to a homogeneous product. Farmers can obtain the required nutrients either through the use of soybean meal, or through the combination of corn and lysine. Manufacturers of animal feeds account for the bulk of lysine demand. Wholesalers of farm supplies and individual farmers also purchase some lysine. Industry experts suggest that there are no substantial costs involved in switching between these two nutrient sources. The shadow price of the alternative feed source (henceforth the "ceiling price") can be approximated by a weighted average of corn and soybean meal prices. In the demand estimation results below, we will characterise demand as being relatively inelastic.

Firms face capacity constraints. There is a great deal of heterogeneity in firm capacities, locations, and costs. On the surface, prospective entrants appear to face substantial entry barriers. There are patents on the lysine production processes, and building a lysine plant takes two to three years and entails large initial sunk costs. On the other hand, some small scale entry occurred during the life of the cartel, two other firms were planning to enter the market until ADM's dramatic entry, and large scale entry occurred after the cartel was dissolved. In addition, the switching of capacity between the production of different amino acids appears possible, although the costs to doing so are not known.[4]

Prices and volumes of lysine suppliers are not directly observable, although we shall argue that the cartel made efforts to compel disclosure. As we shall describe below, there was a great deal of uncertainty about costs and capacities of rival firms at the time of ADM's entry, but the extent of uncertainty diminished over time.

While firms did negotiate prices with all major buyers, it is not clear that price represents the appropriate strategic variable of choice. The existence of capacity constraints and other adjustment costs in production suggests that quantity could also be considered the strategic choice variable. Contracts of most large buyers specified annual volumes and contained 30-day price protection clauses. Given the global nature of the cartel, we might also presume that advertising and distribution contributed to adjustment costs in output. However, for the majority of the period under consideration, firms held excess capacity.

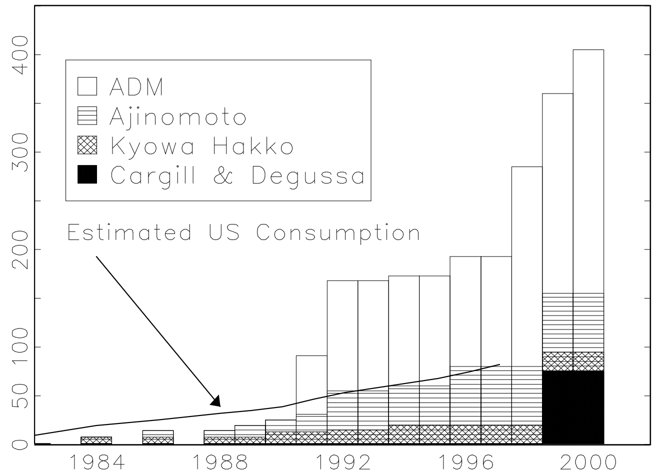
By the 1960s, Japanese biotechnology firms had discovered a bacterial fermentation technique that transformed the production of lysine. It involves the fermentation of dextrose into lysine and is considerably cheaper than conventional extraction methods. Throughout the 1980s, Asian firms imported large quantities of dextrose from the U.S. and exported lysine back to the U.S. The first U.S. based lysine plants were built in the mid-1980s. By the end of the 1980s, there were three major players in the lysine market: Ajinomoto and Kyowa Hakko based in Japan; and Sewon based in South Korea. The U.S. market was supplied by Ajinomoto's and

[2]This section draws heavily on work done by Connor (1998, 2000, 2001a), where a detailed description of the evolution of the lysine conspiracy can be found.

[3]It is also important for the development of fish, but this can account for only a small fraction of the demand for synthetic lysine in the United States.

[4]As Connor (2000, p. 29) notes, at least two Asian plants were used to produce both lysine and MSG. In addition, Ajinomoto was able to switch an MSG plant into lysine production.

Figure 1: U.S. Lysine Production Capacity



Kyowa's U.S. plants, their imports from Japan, Mexico and France, and Sewon's South Korean plant. Testimony by officials at Ajinomoto suggests that the lysine industry fixed prices in its early history.[5] Figure 1 depicts the evolution of rated lysine production capacity in the U.S.[6]

In 1988, ADM acquired[7] a fermentation technique for lysine and, observed by its incumbent rivals, began production of the world's largest lysine factory in 1989. ADM's plant began production in February 1991, precipitating a severe price war. This can be seen in Figure 2, which depicts the evolution of lysine prices and the ceiling price dating from before ADM's entry to after the cessation of the cartel.[8] Competing explanations for this price war and other major events will be discussed in Section 5.

During the price war, Ajinomoto and Kyowa Hakko tried unsuccessfully to raise prices several times. Subsequently, ADM suggested the formation of a lysine trade association. The trade association was to be a facade for discussions of the lysine cartel. The first meeting, attended by Ajinomoto, Kyowa Hakko, and ADM, took place in June 1992. Sewon and Cheil Jedang, an Indonesian firm that also began production in 1991, were subsequent participants.

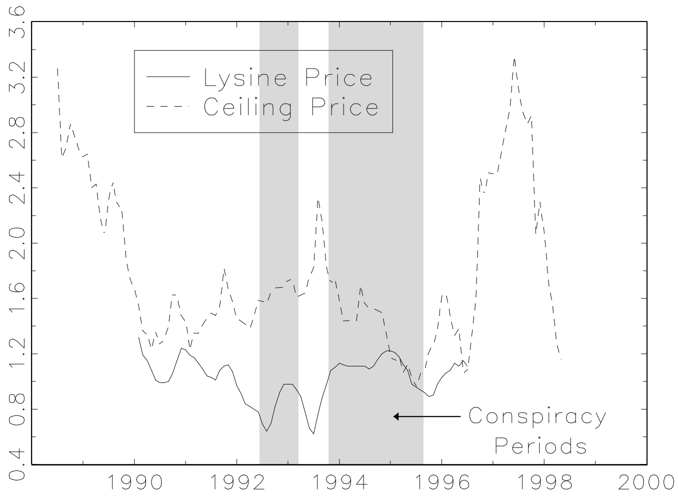
[5]Connor (2001a, pp. 6-7) notes that price-fixing had occurred in Japan (in the early 1970s and late 1980s), Europe, and the United States (in the period 1986-1990) prior to ADM's entry.

[6]The data in Figure 1 is derived from Tables 2 and 6 in Connor (1998). The zero capacities depicted in 1983, 1985, and 1987 indicate missing data. Rated capacity refers to the maximum production of the plant as specified by the plant owner. Its calculation is based on a fixed weekly operating time (e.g. weekdays for a specified period). Hence, there are two main sources of uncertainty for rival firms: capacity does not describe how much could actually be produced if the firm operated the plant full time (7 days a week, 24 hours a day); and the firm could strategically misrepresent capacity.

[7]It has been suggested that ADM's production technology may have been stolen rather than purchased (Connor, 2001a).

[8]Data sources for Figure 2 are discussed in Section 4.2 and in the Appendix.

Figure 2: Lysine and Ceiling Prices



Following the meeting, prices rose, but by less than envisaged at the meeting. There is some disagreement about both the time period over which the cartel operated and its contribution to this price rise.[9] Alternative, competitive explanations for the price rise include movements in the ceiling price, and demand seasonality (colder temperatures tend to require higher feed use). Movements in the ceiling price do not seem, by themselves, a satisfactory explanation of the lysine price rise because the ceiling price was considerably above the lysine price at the time. The demand results, below, do not suggest a major role for seasonal factors.

A second price war began early in 1993, and was resolved through discussions between the participants later that year. Prices rose from a trough approaching $0.60 per pound to plateau at about $1.10-$1.20, where they would stay for the majority of the cartel's remaining operations. This appears to be the most successful phase of the cartel. In June 1995, the FBI simultaneously raided the headquarters of the participating firms. Prices were falling at the time, perhaps in response to a drop in the ceiling price, but actually rose subsequently. In July 1997 Degussa and Cargill, two large biotechnology firms, announced a joint venture with a large scale plant in Nebraska originally due for production in 1999.[10]

There were two distinct phases of the cartel. The first began with the first meeting of the lysine association and ended with the onset of a price war. During this period, there were regular meetings of the participants. However, no consensus was reached on the operating mechanism of the cartel. Price targets were set, commencing in July 1992, but market shares were not allocated. ADM favoured an allocation of global volume quotas with independent auditing of

[9] See Connor (2001a) and White (2001) for alternative views on these issues.

[10] According to a Cargill press release of September 20, 2000, production actually commenced in late June, 2000.

sales volumes. Sewon initially favoured a price agreement. Even once a volume allocation was later agreed to, Ajinomoto and Sewon preferred an allocation of regional monopolies instead of global volume quotas.[11] There was little cooperation in the monitoring of member sales and prices. There appeared to be considerable uncertainty about rivals' costs and capacities during this period. Capacities tended to be overstated and costs understated. ADM ultimately conducted tours of its plant in June 1992 for Sewon and in April 1993 for Ajinomoto. Finally, there was widespread suspicion of cheating.[12]

By contrast, the second phase of the cartel, beginning in late 1993 and concluding with the FBI raid in June 1995, was characterised by considerably less uncertainty. A system of global volume quotas was agreed to, loosely based on current market shares. There were no regional quotas. Monthly scorecards were prepared and discussed at quarterly meetings, based on reported sales volumes of each firm. To verify reported sales volumes, international trade statistics were available. Moreover, it appears that external auditors were used to help enforce the volume agreements, although cartel members may have sought to hide sales from the auditors (Connor, 2001b).There also seemed less uncertainty about rivals' costs and capacities. Finally, a compensation scheme involving intra-cartel sales operated for those firms not achieving their designated quotas. That is, a firm that did not meet its sales quota for the year was permitted to sell the remainder to any firms exceeding their quotas, with sales taking place at the agreed cartel price.[13]

We could therefore characterise the cartel environment as follows. Heterogeneous (in terms of costs, capacities, and locations) firms operated in the market for a homogeneous product with an inelastic demand, constrained by the availability of a natural substitute. Entry and investment played a dramatic role in the evolution of the cartel. Firms communicated explicitly at cartel meetings, but were unable to directly observe rival actions and key characteristics of rivals. In the first phase of the cartel, price targets were agreed to, but there were no quantity allocations, monitoring was informal and uncoordinated, and uncertainty was unresolved. In the second phase of the cartel, volume quotas were adopted, a monitoring mechanism was implemented, characteristics of rivals were substantially learned, and a compensation scheme was instituted. The different character of the two phases suggests a potential explanation for their relative success in sustaining cooperation among participants. The first phase broke down abruptly into a price war, while the second phase encompassed a sustained period of stable collusive prices, interrupted only by the intervention of the anti-trust authorities.

[11] There were at least two potential problems in allocating regional monopolies. First, there were considerable divergences in the growth rates of different regions, making the allocation a contentious one. Second, dividing the market in this way may have alerted customers or the antitrust authorities to the cartel (Connor, 2001b).

[12] This is documented in Connor (2000, 2001b). The majority of concerns appear to have arisen in the first phase of the cartel before volume allocations were agreed to and improved monitoring was implemented, although some concerns persisted into the second phase.

[13] This scheme removes the incentive to secretly cut prices, provided monitoring and enforcement of output quotas is adequate. However, the consequences of a systematic breach of the cartel agreement remain unclear.

3 Models of Collusion

In this section, we will briefly characterise some prominent models of collusion, outlining some of the empirical predictions, and contrasting their modelling assumptions with the operating environment of the lysine cartel.

It is well established that repeated interaction between firms can foster cooperative behaviour through a regime of punishments and rewards. Commonly, rewards for cooperation take the form of more restrictive output and higher attendant profits, while punishments include temporary or permanent reversion to the Cournot-Nash equilibrium or minimaxing deviating firms.[14] Once we allow for the possibility that firms cannot perfectly monitor the behaviour of their competitors, the character of cooperative equilibria changes. Green and Porter (1984) (hereafter, GP) demonstrate that price wars can be observed on the equilibrium path if demand is stochastic and firms are unable to observe the actions of their competitors. Should they encounter an adverse profit realisation, firms face an inference problem to distinguish a negative demand shock from a deviation by a rival from the optimal cartel output. On the equilibrium path, firms never cheat on the cartel agreement, but in order to maintain adequate incentives for cooperation, punishment takes place whenever a negative demand shock occurs. Abreu, Pearce and Stachetti (1986) (hereafter, APS) generalise the model of GP, characterising optimal collusive equilibria. Both models predict that a firm's mark-up over marginal costs will follow a step function, given by a punishment mark-up in non-cooperative periods, and a higher mark-up, approaching the monopolistic mark-up, in cooperative periods. However, under APS both the reward and punishment phases will be more extreme than their counterparts in GP.

Rotemberg and Saloner (1986) demonstrate that the introduction of demand variation can lead to price wars, even when monitoring is perfect. In their model, each period i.i.d. demand shocks are observed by participating firms before prices are set. The maximum sustainable collusive price is found to be lower in peak demand periods because the benefits to cheating are increased, while the expected returns to collusion are unaffected. Price wars do not reflect punishment, but a recognition that a lesser degree of collusion can be sustained. Introducing persistence in demand variation, Haltiwanger and Harrington (1991) find that collusive prices are higher in times of rising demand, while Bagwell and Staiger (1997) find that collusive prices are procyclical.

Uncertainty about costs and capacities of rivals played an important role in the lysine cartel, and a number of authors have examined a cartel's problem under cost uncertainty. Cramton and Palfrey (1990) and Kihlstrom and Vives (1992) examine the problem of cartel design when firms have private cost information, but are able to communicate and make side payments. Cramton and Palfrey (1990) show that efficient collusion is attainable in which the lowest cost firm is allocated full production and the monopoly price is set. However, a majority voting rule is adopted, in which the most efficient firm would in fact prefer not to participate. If unanimity is required, efficient collusion is unattainable if there are sufficiently many firms in the cartel.

Athey and Bagwell (2001) examine collusion in the presence of i.i.d. private cost information, observable actions, and the possibility of future market share favours. They find that if

[14] See Friedman (1971) on the use of Cournot-Nash threats to enforce collusive equilibria, and Abreu (1986) on the use of "stick and carrot" incentive schemes to generate extremal collusive equilibria.

firms are sufficiently patient an optimal level of collusion can be supported without recourse to price wars. Indeed, if perfect collusion cannot be achieved, firms prefer to sacrifice productive efficiency rather than cut prices. If firms can communicate, but cannot make side-payments, the incentive to communicate costs truthfully is provided by the granting of future market share favours. Athey, Bagwell and Sanchirico (2004) consider a similar context, but restrict attention to symmetric equilibria in which future market share favours are unavailable. They find that if firms are sufficiently patient, collusion can be sustained without the need for price wars. However, all firms in the cartel charge the same price regardless of their cost, implying that the cartel sacrifices productive efficiency. The empirical implications of the two models differ: Athey and Bagwell (2001) predict a negative correlation between a firm's market share over time, while Athey *et al.* (2004) predict fixed market shares.

Slade (1990) also examines collusion with private cost shocks and observable actions, arguing that price wars are possible. According to Slade, simple carrot and stick strategies may be incapable of preventing cheating if particularly favourable cost conditions are observed.[15] By contrast, Athey *et al.* (2004) argue that price wars are unnecessary in equilibrium, but rather that, if firms are not overly patient, equilibrium strategies dictate that firms with especially favourable cost shocks are afforded a temporary escape clause to set a lower price.

In a recent working paper, Athey and Bagwell (2004) extend their earlier work to consider a cartel's problem in the presence of persistent hidden cost information, while maintaining observable actions, communication, and side payments in the form of market share favours. They find that a pooling equilibrium in which all firms charge the same price and share the market equally is optimal (in an ex ante sense) if firms are sufficiently patient and costs are almost perfectly persistent. Interestingly, they also identify equilibria in which a signaling phase reveals cost types in advance of the determination of market shares and prices, and identify circumstances in which such equilibria may dominate the pooling equilibria. We shall briefly return to this issue in section 5.4.

Athey and Bagwell (2004) capture several important elements of the lysine cartel. Uncertainty about persistent cost asymmetries played an important role in the lysine cartel, firms communicated regularly, and the cartel's compensation scheme appears to resemble the market share favours adopted by Athey and Bagwell (2001, 2004). However, the compensation scheme may actually be quite different in motivation. Athey and Bagwell's market share favours provide the incentives to truthfully report costs in order to achieve productive efficiency. The lysine compensation scheme instead appears to be an attempt to remove the incentives for cheating and avoid the costly and contentious exercise of devising case by case penalties for firms breaching their quotas. That is, the scheme was simply a part of the enforcement mechanism for the agreed volume quotas. With the scheme in place and a sound monitoring regimen, firms knew exactly how they would be punished for breaching their allotment.[16] The scheme could therefore contribute to productive efficiency by permitting market shares to fluctuate within the year (but only

[15] However, as Slade notes, given that such cheating is part of the specification of equilibrium strategies, it is unclear that cheating is the correct interpretation.

[16] Note that resorting to the scheme was indeed a punishment because it stipulated that transactions would occur at agreed cartel prices, while offending firms may have sold at lower prices. However, if firms refused to participate in the scheme ex post, the precise repercussions are unclear.

to the same extent that an annual volume agreement would do so), but not between years. In practice, firms were very good at meeting their quotas, without recourse to the scheme.[17] This means either that firms were at pains to avoid using the scheme for intertemporal market share variation, or that there were no major firm-specific shocks during cartel operation.

The preceding models of collusion presume a fixed market structure in evaluating the prospects for collusion. However, entry and investment played a crucial role in the lysine cartel. More generally, we might expect a feedback relationship between market structure and firm behaviour. Fershtman and Pakes (2000) develop a model in which firms with heterogeneous product quality explicitly consider the impact of their decision of whether to collude on the entry, exit, and investment decisions of incumbents and potential competitors. It is found that collusion is particularly hard to sustain if one of the firms is likely to exit in the near future, both because it is difficult to punish such a firm, and because exit can be hastened by predatory behaviour. Fershtman and Pakes assume that the terms of the collusive agreement are determined by a static Nash bargaining game in each period. By contrast, de Roos (2004) adopts the market sharing rule that prevailed in the lysine market, that firms maintain their market shares throughout the collusive agreement. Price wars result following entry as the entrant attempts to build up market share in advance of a collusive agreement. Allowing for the possibility of a competitive fringe operating outside the cartel, de Roos (2001) finds that entry does not immediately induce a price war. However, a cartel may be gradually worn down as an entrant grows into a substantial competitor.

4 Lysine Demand and Cost

This section contains two empirical exercises that inform our further discussion. First, we use lysine price and quantity data to estimate the market demand for lysine. The market demand elasticity is an essential ingredient in the calculation of the mark-up on marginal costs predicted by theories of collusion. Second, we estimate a cost function for ADM, allowing for learning by doing, in order to facilitate future modelling of the lysine market. This exercise establishes the existence of learning by doing, and allows us to test whether marginal costs are constant once learning has ceased.

4.1 Specification

4.1.1 Demand

Being an essential ingredient in the diets of hogs and poultry, the demand for lysine is necessarily a derived one. Additional explanatory variables include the ceiling price, determined by the prices of corn and soybean meal; feed efficiency ratios, which capture the rate at which animals transform feed into muscle development; and seasonal factors.

Log-linear and linear demand specifications are considered:

[17] See, for example, Connor (2001b, p. 207).

$$\ln Q_t = X_t\beta - \alpha \ln P_t + \varepsilon_t \quad (1)$$

$$Q_t = X_t\beta - \alpha P_t + \varepsilon_t, \quad (2)$$

where Q_t and P_t denote market quantity and price in period t; X_t contains a vector of explanatory variables; and ε_t captures unobserved demand errors. The vector X_t includes a constant, a trend, corn prices, soybean meal prices, hog inventories, broiler slaughter, feed efficiency ratios and monthly dummies. In the log-linear model, logs are taken of all price and quantity variables. Data construction is described in the next section, while data sources are listed in the Appendix. The parameter α determines the elasticity of demand.

The ceiling price, described previously, is intended to capture the shadow price of an alternative source of lysine. For both the log-linear and linear models, two alternative specifications involving this shadow price were considered. The first included the prices of lysine, corn, and soybean meal without restriction. The second explicitly recognises that corn and lysine are used together in animal feed.[18] A weighted average of corn and lysine prices is included together with the soybean meal price. This specification has the advantage that the price of corn represents a ready instrument for this weighted price.

Feed efficiency ratios describe the rate at which animals transform feed into weight gain. Feed efficiency ratios have improved over time as the fraction of animals that have been genetically improved to increase lysine absorption increases. The supply of poultry has been saturated by the genetically improved variety for some time, but there was a gradual increase in the ratio of genetically improved hogs over the sample period. Hence, the feed efficiency ratio for hogs is included as a potential explanatory variable. It is suggested that colder temperatures necessitate greater feed use. Therefore, monthly dummies were incorporated to allow for demand seasonality.

Lysine price and quantity are jointly determined by equation (1) or (2) and a supply-side relationship dependent on the nature of competitive behaviour. Estimating equation (1) or (2) by ordinary least squares could therefore lead to simultaneity bias. Accordingly, equations (1) and (2) are also estimated by instrumental variables. Instruments considered for lysine prices include the variables contained in X_t, and a vector of cross-country exchange rates between the U.S. and countries holding major lysine plants. Bilateral exchange rates were included for their potential role as cost shifters for firms based overseas.[19]

4.1.2 Marginal costs

Cost data are available for ADM over the period July 1991 to June 1995. ADM experienced some production teething troubles (difficulties with early production) which appear evident on casual inspection of these data. Consequently, a cost equation allowing for the possibility of learning by doing is examined in equation (3). Some limited variation in ADM's U.S. lysine

[18] A third specification was also examined. This included the lysine price and the ceiling price, implicitly restricting soybean meal and corn prices to enter in a fixed ratio. No role was found for the ceiling price. This stems from the highly non-linear role played by the ceiling price in lysine demand.

[19] Other available cost shifters, such as the price of dextrose and wage rates, were not useful instruments owing to their lack of variation over the sample.

production capacity is exhibited over the sample. Therefore, to allow for the possibility that marginal costs rise as the lysine plant approaches its capacity, capacity utilisation was adopted rather than quantity as the explanatory variable.[20]

$$MC\left(k_{i,t},u_{i,t}\right)=ck_{i,t}^{\gamma}\left[1+A_0e^{-a\sum_{\tau=0}^{t}k_{i,\tau}}\right]+u_{i,t} \tag{3}$$

where MC represents marginal costs, $k_{i,t}$ is the capacity utilisation of firm i in period t, and $u_{i,t}$ is an unobservable, firm-specific error.[21] Factor prices are omitted from equation (3) because there is almost no variation in available data on relevant factor prices such as the price of dextrose and wages. The parameters A_0 and a capture the impact of learning by doing, with A_0 describing its extent and a its rate of diffusion. A finding of $\gamma = 0$ would imply a constant marginal cost once learning has ceased.[22]

4.2 Data

Data sources are discussed in the Appendix. Here, the construction of the data is discussed. The lysine price is a weighted average of the prices charged by the largest four firms in the lysine market. These data are available monthly from January 1990 to June 1996. Quantity data are obtained by combining several sources. Total annual lysine sales values for the four largest firms is divided by the monthly prices to obtain a monthly quantity series. However, with all the within-year variation in quantity determined by prices, this will bias any estimates of demand elasticity toward -1. To circumvent this problem, quantity data for ADM, available from July 1991 to June 1995 were integrated into this series. ADM's annual United States market share was almost constant for the four years for which data was available. Hence, these data were used in the period August 1991 to June 1995, scaled up to reflect ADM's market share.[23]

To calculate the ceiling price, it was assumed that 100 lbs of soybean meal was a nutritional substitute for 97 lbs of corn supplemented with 3 lbs of lysine. Therefore, the ceiling price was calculated as follows:

$$P_t^C=\frac{100P_t^{SB}-97P_t^{Corn}}{3}, \tag{4}$$

[20] An alternative formulation using quantity rather than capacity utilisation as a dependent variable was also examined. Similar results were obtained, suggesting that the variation in ADM's capacity was not too substantial. However, with this formulation, our conclusions on marginal costs are ambiguous. In particular, relative to the results of Table 2, the LR test now rejects the hypothesis of $\gamma = 0$ at the 10% level, while the Wald test does not reject this hypothesis at the 10% level.

[21] Note that in equation (3), $k_{i,t}$ refers to the *production* of firm i divided by capacity, while in equations (1) and (2), Q_t refers to market *sales volume*. Production and sales volumes will differ if there is substantial time variation in the holding of inventories or the volume of exports.

[22] A possible objection to equation (3) is that output and costs are simultaneously determined by movements in factor prices and shocks to the production technology. Given that factor prices are omitted from (3), this could lead to an endogeneity problem. However, there is almost no variation in relevant factor prices in the sample. Further, the majority of the variation in marginal costs appears due to initial production troubles. Owing to the unavailability of valid instruments for output that are uncorrelated with the error term, we proceed without the use of instruments.

[23] It appears that in July 1991, ADM's production was yet to come fully online. This observation was not thought representative of market sales and was not used.

where P^{SB} and P^{Corn} are the prices of soybean meal and corn, respectively. The weighted average corn and lysine price, included in some demand specifications, is calculated as follows:

$$P_t^W = 0.97P_t^{Corn} + 0.03P_t. \tag{5}$$

Hogs are fed lysine from weaning until they are ready for slaughter, usually at the age of five to six months. To reflect the farmer's time horizon, quarterly hog inventories are considered as an explanator. Poultry are typically slaughtered between the ages of six and eight weeks. Consequently, broiler slaughter data are also considered. Feed efficiency ratios measure the volume of feed required to generate a given volume of final animal weight. Hence, a decrease in the feed efficiency ratio corresponds to an improvement in feed efficiency. An annual feed efficiency ratio was interpolated geometrically to form a monthly series.

Exchange rates were thought to act as cost shifters for importers of lysine and therefore were considered as potential instruments for prices. Monthly bilateral exchange rates (in U.S. dollars) for Japan, South Korea, Italy, France, and Indonesia were used.

On the cost side, marginal costs, fixed costs, production, and domestic sales are available from ADM production and sales reports over the period July 1991 to June 1995. Marginal costs, expressed per unit of production, are determined primarily by energy costs and raw material costs. They were constructed by summing reported variable costs, raw material costs and a (negligible) "by-product credit". There is a high probability that this marginal cost series is in fact average variable costs. Therefore, based on the parameter estimates reported below, marginal costs could be slightly overstated. Fixed costs reflect depreciation and an allocation of total overhead costs.

4.3 Estimation Results

4.3.1 Demand

Equations (1) and (2) were estimated by ordinary least squares (OLS) and instrumental variables (IV). Insignificant seasonal dummy variables were eliminated. Table 1 summarises the results.[24] The ordinary least squares and instrumental variable results are very similar. Two factors may have contributed to this. First, most of the variation in price and quantity over the sample may have resulted from variation in firm behaviour rather than demand variation. This seems likely given the dramatic nature of the documented price wars. A second possibility is that marginal costs are almost invariant to sales, once learning has ceased. The cost results, below, tend to support this idea. In each specification, demand appears relatively inelastic over the sample. This would appear to rule out the possibility of unconstrained joint profit-maximisation by the participating firms.

The restriction that lysine and corn prices enter together is rejected. Little role can be found for either corn or soybean meal prices if this restriction is not made. Over the sample, the ceiling price never dips significantly below the price of lysine (see Figure 2). This may explain why

[24] Similar results were obtained using a restricted sample in which ADM quantity data was available. This suggests that constructing quantity data by dividing annual sales by monthly prices over the remainder of the sample had little effect on the results.

Table 1: Demand Results[a]

	Log-linear				Linear			
	Model 1		Model 2		Model 3		Model 4	
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Constant	-20.90	-21.03	-8.949	-13.95	-137.4	-121.0	-12.18	-12.24
	(8.638)	(9.876)	(8.131)	(8.786)	(47.83)	(60.39)	(35.87)	(37.84)
Trend	0.012	0.011	0.008	0.007	0.153	0.139	0.089	0.075
	(0.003)	(0.001)	(0.002)	(0.003)	(0.036)	(0.046)	(0.035)	(0.037)
Lysine price	-0.738	-0.671			-11.53	-10.55		
	(0.140)	(0.213)			(2.168)	(3.165)		
Corn price	-0.054	-0.101			6.728	-10.63		
	(0.192)	(0.229)			(53.66)	(63.16)		
Lysine and			-0.903	-0.714			-153.1	-129.5
corn price			(0.192)	(0.221)			(35.87)	(40.04)
Soybean meal	0.247	0.316	0.799	0.746	24.20	36.85	131.5	123.1
Price	(0.234)	(0.289)	(0.162)	(0.177)	(38.71)	(47.16)	(26.94)	(28.79)
Hog inventories	0.861	0.811	-0.008	0.470	0.210	0.177	-0.027	0.046
	(0.729)	(0.820)	(0.721)	(0.795)	(0.178)	(0.199)	(0.182)	(0.197)
Broiler quantity	0.987	1.131	1.296	1.357	0.025	0.028	0.033	0.034
	(0.300)	(0.339)	(0.303)	(0.328)	(0.007)	(0.008)	(0.008)	(0.008)
Feed efficiency	0.020	0.017	0.001	-0.001	0.338	0.292	0.005	-0.008
	(0.009)	(0.012)	(0.007)	(0.007)	(0.126)	(0.163)	(0.093)	(0.098)
October	-0.118	-0.135	-0.161	-0.176	-1.546	-1.789	-2.174	-2.287
	(0.060)	(0.068)	(0.062)	(0.067)	(0.818)	(0.919)	(0.877)	(0.924)
Observations	66		66		66		66	
R^2	0.818	0.769	0.788	0.751	0.789	0.736	0.742	0.713
$\bar{R}^2$	0.792	0.737	0.762	0.721	0.760	0.699	0.711	0.678
Dep var sum of sq	5911.3				12373.9			
Sum of sq errors	0.820	1.038	0.956	1.120	156.7	196.2	192.1	213.8
Autocorrelation	0.007	0.062	0.099	0.141	0.046	0.078	0.113	0.137
Durbin-Watson	1.987	1.876	1.789	1.715	1.914	1.847	1.754	1.713
F-test for			9.452				12.86	
restriction[b]			{0.003}				{0.001}	

[a] Figures in parentheses () are standard errors. Figures in brackets {} are p-values.

[b] F-test for the restriction that corn and lysine prices enter in the fixed ratio of equation (5).

Table 2: Cost Results[a]

	Model 1			Model 2		
	Coeff	Std err[b]	Std err	Coeff	Std err[b]	Std err
Marginal costs (c)	0.505	0.019	0.020	0.527	0.008	0.007
Power term (γ)	-0.097	0.078	0.082			
Learning extent (A_0)	1.783	0.246	0.233	1.933	0.219	0.199
Learning diffusion (a)	0.577	0.077	0.056	0.577	0.080	0.061
Observations	48					
Dep var sum of sq	18.55					
Sum of sq errors	0.132			0.138		
Wald test				1.386	{0.239}	
LR test				2.006	{0.157}	

[a] Figures in brackets {} are p-values.

[b] Under the assumption of correct specification.

soybean meal prices fail to play a role. However, given that corn represents a substantial share of the price of feed, we would have expected a role for corn prices.

Coefficient estimates suggest a mild trend rise in demand over the sample. As expected, demand for lysine increases with poultry consumption. However, hog inventories were not found to be a significant determinant of demand. A possible explanation is that lysine demand has risen over the sample, while hog consumption has been stable and poultry consumption has risen markedly. Finally, the feed efficiency ratio is found to be a positive determinant of demand in some specifications, suggesting that as the efficiency of the feed absorption process improves, the demand for lysine declines. The OLS results of Model 1 (corresponding to equation (1)) are used for the purpose of analysis, below.

4.3.2 Marginal costs

Equation (3) was estimated by non-linear least squares. The results are summarised in Table 2. In the unrestricted model, Model 1, marginal costs decline mildly with output, or more specifically, with capacity utilisation. Model 2 incorporates the restriction that $\gamma = 0$. Wald and LR tests suggest that we cannot reject this restriction at the 10 per cent level, implying that marginal costs are constant once learning has finished. The coefficient, c, then captures post-learning marginal costs. The size of A_0 suggests that there is substantial learning, while the size of the coefficient a suggests that learning is achieved rapidly.

5 Discussion

Armed with estimates of demand and costs, in this section we examine informally the ability of theories of collusion to explain major stylised facts of the lysine market. First, we test for the existence and examine the nature of the price wars observed in the lysine market. Second, we examine the level of the mark-up over marginal costs charged by lysine producers. Third, we consider the behaviour of market participants following the breaking up of the cartel. Finally, we briefly consider the final form taken by the cartel.

5.1 Price Wars

The models of collusive behaviour discussed in Section 3 yield predictions about the time path of the mark-up of prices over marginal costs. To assess model performance, we can compare the observed markup in the lysine market to these predictions. ADM's markup is calculated by dividing the weighted average lysine price by ADM's marginal costs. First, we present a test of the Cournot model that also serves as a test for the existence of price wars. Finding the existence of price wars, we then briefly discuss their potential underlying causes.

Equation (1) implicitly defines an inverse demand function, $P(Q_t, \varepsilon_t)$. Under perfect information, the Cournot model predicts that firm i chooses an output such that its mark-up is given by

$$\frac{P(Q_t, \varepsilon_t)}{MC(k_{i,t}, u_{i,t})} = \frac{1}{1 - \frac{q_{i,t}}{Q_t}\alpha^{-1}}. \tag{6}$$

The lysine market departs from the assumptions of the majority of models discussed in Section 3 in that firms are heterogeneous and face capacity constraints.[25] We examine whether the flavour of their results carry over, nevertheless. To capture variation in firm conduct, a dummy variable, χ_t, is constructed based on the results of discussion at the regular lysine association meetings. A value of 1 is assigned to periods in which it is deemed that firms were behaving "cooperatively", and a value of 0 is assigned otherwise.[26] Such cooperative spells might correspond to reward phases in the imperfect monitoring models of GP and APS, or periods in which a high degree of collusion can be sustained in the model of Rotemberg and Saloner (1986).

That we would expect a higher mark-up during cooperative phases in these models is a departure from the Cournot model and joint-profit maximisation, which postulate a mark-up depending simply on the market demand elasticity. To test for the existence of price wars , we estimate a mark-up equation of the following form:

$$\frac{P(Q_t, \varepsilon_t)}{MC(k_{i,t}, u_{i,t})} = \phi_0 + \phi_1\chi_t + \upsilon_{i,t} \tag{7}$$

[25] Several authors have examined the sustainability of collusion in the presence of capacity constraints, without explicitly modelling price wars. For example, Brock and Scheinkman (1985) argue that increasing industry capacity by increasing the number of operating firms will have a non-monotonic affect on the maximum sustainable collusive price. Benoit and Krishna (1987) allow capacity to be chosen endogenously, finding that excess capacity is required to sustain collusive behaviour in order to deter deviations. In fact, Benoit and Krishna (1991) find that, in a similar context, entry deterrence can be facilitated by a commitment to a low capacity for this reason. Examining semi-collusive equilibria, in which firms are able to collude in price but not capacity decisions, Davidson and Deneckere (1990) find that collusion is easier to sustain if firms are more patient and if capacity installation is cheaper. Compte, Jenny and Rey (2002) find that a cartel is more difficult to sustain in the presence of asymmetric capacity constraints.

[26] Choosing the periods characterised by cooperation is a somewhat controversial exercise. See Connor (2001a) and White (2001) for contrary views. The results, below, are robust to alternative choices.

We examine two versions of equation (7). In Model 1, the dependant variable is the realised mark-up, $P(Q_t, \varepsilon_t)/MC(k_{i,t}, u_{i,t})$. In Model 2, we use an ex ante expected mark-up as the dependant variable:

$$E_{\varepsilon,u}\left[\frac{P(Q_t,\varepsilon_t)}{MC(k_{i,t},u_{i,t})}\right] = \left(\frac{P(Q_t,\varepsilon_t)}{MC(k_{i,t},u_{i,t}) - u_{i,t}}\right)\left(\frac{e^{\frac{\varepsilon_t}{\alpha}}}{E_\varepsilon\left(e^{\frac{\varepsilon_t}{\alpha}}\right)}\right), \tag{8}$$

where expectations are calculated based on the realised distributions of ε_t and $u_{i,t}$ over the sample. This is a somewhat *ad hoc* way of allowing for the possibility that unanticipated variation in demand and cost conditions contributed to the variation in observed markups.[27]

To test the possibility that χ_t is endogenous to either demand or cost conditions, it was included additively as an explanatory variable in both equations (1) and (3), and found to be insignificant.[28] The results of estimating equation (7) are summarised in Table 3. In both the formulations considered, the conspiracy dummy variable is statistically significant at the 1% level, indicating that we could reject the hypothesis of the absence of price wars.

Figures 3 and 4 provide further illustration of these results. Figure 3 plots the realised mark-up against the mark-ups implied by Models 1 and 2. Throughout 1991 and early 1992, ADM was battling production teething troubles, and hence their mark-up may appear artificially low. This is indicated by the shaded region labelled “learning by doing”. Removing this period from estimation does not qualitatively affect the results of Table 3. Figure 4 depicts ADM’s observed mark-up together with the Cournot mark-up implied by equation (6). Analogous to Model 2, we also include a variation on the Cournot mark-up under the assumption that firms do not observe the demand and cost errors in equations (1) and (3), but choose output to maximise expected profits, given the outputs of their competitors. Given the functional forms of equations (1) and (3), this leads to an implied mark-up of

$$\frac{P(Q_t,\varepsilon_t)}{MC(k_{i,t},u_{i,t})} = \left(\frac{e^{\frac{\varepsilon_t}{\alpha}}}{E_\varepsilon\left\{e^{\frac{\varepsilon}{\alpha}}\right\}}\right)\left(\frac{MC(k_{i,t},u_{i,t}) - u_{i,t}}{MC(k_{i,t},u_{i,t})}\right)\left(\frac{1}{1-\frac{q_{i,t}}{Q_t}\alpha^{-1}}\right). \tag{9}$$

Again, expectations are calculated based on the realised distributions of ε_t and $u_{i,t}$ over the sample. The figures suggest that price wars explain a substantial component of the variation in the mark-up over the sample. This rules out the possibility of unconstrained joint-profit maximising behaviour.

We turn next to the underlying causes for the observed price wars. First, let us consider the initial price war. This can be seen in Figure 2, beginning in early 1991 and extending to June

[27] Effectively, we are modelling a situation in which firms face i.i.d. demand and marginal cost shocks. Firms know that the distributions of the demand and cost shocks are given by the empirical distributions of ε_t and $u_{i,t}$, respectively. However, firms choose output before observing the shocks.

[28] Note that this appears inconsistent with the empirical predictions of several price-war models. For example, the Rotemberg and Saloner (1986) model and its variations predict a relationship between demand conditions and price wars that depends on the persistence of demand variation. While the Green and Porter (1984) model suggests that an unanticipated demand shock could *precipitate* a price war, the relationship between demand conditions and whether or not a price war is currently taking place is not clear.

Table 3: Mark-up Equation[a]

Dependent variable	Model 1 $\frac{P(Q_t,\varepsilon_t)}{MC\left(k_{i,t},u_{i,t}\right)}$	Model 2 $E_{\varepsilon,\mu}\left(\frac{P(Q_t,\varepsilon)}{MC\left(k_{i,t},u\right)}\right)$
Constant	1.350	1.387
	(0.067)	(0.094)
Conspiracy	0.615	0.611
dummy (χ_t)	(0.085)	(0.118)
Observations	48	48
R^2	0.533	0.367
$\bar{R}^2$	0.523	0.353
Dep var sum of sq	152.4	161.7
Sum of sq errors	3.721	7.247
Autocorrelation	0.634	0.460
Durbin-Watson	0.801	1.078

[a] Figures in parentheses () are standard errors.

Figure 3: Mark-up Equation

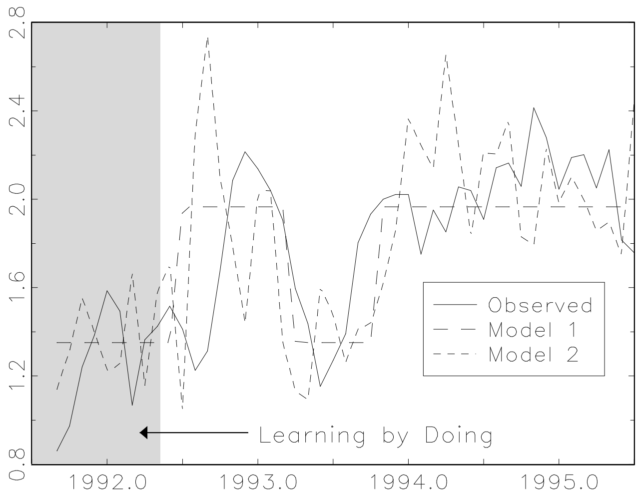
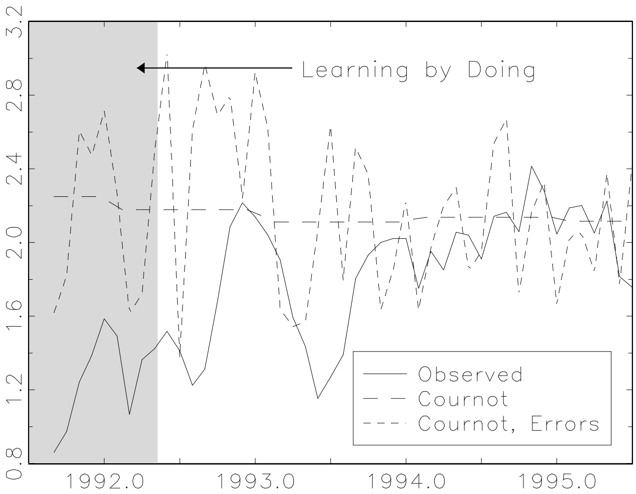


Figure 4: Actual and Implied Mark-ups



1992. The price war began when ADM completed the construction of its production facility and commenced production, and ended with the formation of the lysine cartel. There are several potential explanations for this initial price war. First, adjustment costs in production and/or sales for the incumbent firms may have led to inertia in the sales of these firms in response to ADM's entry.[29] This explanation is unconvincing given the advanced warning received by the incumbent firms of ADM's intentions to enter the lysine market. ADM acquired a fermentation patent in 1988 and began construction of its production facilities in 1989. It began production operations only in 1991, leaving ample warning for incumbent firms to adjust sales. Moreover, the incumbent firms were actively preparing for the entry of ADM.[30]

Second, the price war may have resulted from attempted predation as ADM and/or the incumbent firms tried (and failed) to force out their competitors. The fact that the incumbent firms were the first to attempt to raise prices suggests that either the incumbent firms were more inclined to accommodate ADM's entry or that they were quickly dissuaded from efforts at predation.

A third possibility is that ADM wished to collude from the outset, but understood that the terms of any negotiated collusive agreement could be influenced by strategic action prior to the agreement. Especially after the entry of a new competitor, we might expect information asymmetries to play a prominent role. In fact, a great deal of uncertainty about costs and capacity pervaded the lysine market following ADM's entry.[31] Consequently, ADM may have wished

[29] One explanation offered by White (2001, p. 28) is that incumbent firms refused to adjust output in response to ADM's entry.

[30] As Connor (2001a) notes, Ajinomoto began planning a strategy for ADM's entry as early as April 1990.

[31] Uncertainty about costs and capacity appear to have been acute initially, and diminished but did not disappear following the initial cartel agreement. See Connor (2000, pp. 26-28) for further details.

to signal that it would be a formidable competitor in the absence of a collusive arrangement. Signaling could have occurred across many dimensions. Potentially fruitful dimensions for signaling include marginal costs, capacity, and patience. The idea of ADM wishing to signal it was a low cost operation in advance of collusion is supported by the fact that ADM conducted guided tours of its new plant for the benefit of Ajinomoto and Kyowa Hakko executives.

On a related note, the price war may reflect attempts by ADM to build up its market share prior to a collusive agreement.[32] The terms of the collusive bargain in the lysine market stipulated that firms would maintain their global market shares throughout the agreement.[33] If ADM anticipated this type of arrangement, then this provides an incentive to engage in a price war in order to build up market share.[34] However, this sort of market sharing rule is clearly suboptimal. An alternative proposal in which ADM understood that its market share would rise gradually over time would obviate the need for a painful initial price war. That an optimal arrangement of this sort was not adopted reflects a bargaining problem faced by firms in which the existing market shares provide a natural focal point.[35] Allowing for the degree of uncertainty about costs and capacity characteristic of the lysine market, this bargaining problem only becomes more acute. The only way to credibly convey the entitlement to a particular market share may be to actually achieve that market share in advance.[36]

Some combination of the above explanations is also possible. For instance, ADM may have been unsure about whether to attempt to force its competitors (or a subset of them) to exit, or to accommodate them in a future collusive agreement, with its decision resolved through learning of its rivals' cost parameters.The timing of the decision to opt for collusion may have been influenced by a cost/capacity shock to ADM. ADM experienced unexpected (at the time of plant construction) production teething troubles, which temporarily raised costs and restricted available production capacity. This shock appears to have been observed by ADM, but not its rivals (Connor, 2001a, p. 9).

The second price war began in early 1993 and lasted through the middle of that year. Again, there are several potential explanations for this price war. First, there were reasons for distrust

[32]This argument is presented in more detail in de Roos (2004).

[33]This is not explicit until the second, more successful phase of the cartel. At an October 1993 meeting between Ajinomoto and ADM, actual 1993 production volumes were used to calculate market shares for 1994 (Connor, 1998, p. 31). Similar arrangements applied in other recent price fixing cases. In citric acid, market shares for 1991 were allocated based on realised market shares between 1988 and 1990 (Connor, 2001b, p. 136). Industry experts confirm that global market shares were set in the same fashion in the recent vitamins price fixing cartel in the markets for vitamins C, E, A, and B2 (Riboflavin).

[34]Clearly, the existence of adjustment costs in production or sales is required for this argument. Klepper (1996) introduces convex adjustment costs in a similar context. Examples of such costs include physical capacity constraints, advertising, customer search, or distribution costs.

[35]ADM's strategic goal was to obtain a market share equal to its largest competitor. In conceding a smaller cartel market share than Ajinomoto (in accordance with prevailing market shares), ADM originally negotiated an equal share of market growth with Ajinomoto. This would then provide for a gradual rise in ADM's market share. Subsequently, however, this agreement was overlooked and market shares were retained throughout the second phase of the cartel (Connor, 2000).

[36]The protracted nature of the disagreement over market shares between ADM and Ajinomoto is highlighted in *United States v. Michael D. Andreas et al.*, United States Court of Appeals for the Seventh Circuit (2000), pp. 5-8.

among the participants. For example, Ajinomoto believed that ADM had stolen its patented micro-organisms. This explanation does not appear particularly appealing as there is no indication of how the environment changed between the time the collusive agreement was first successfully negotiated and the time it apparently broke down.

Second, there were differences in opinion about the appropriate form of the cartel. ADM wanted an explicit market share agreement with external production auditing, which the other firms resisted. There was some disagreement about the appropriate market shares. Again, we could argue that these differences did not prevent the negotiation of the initial collusive agreement. As discussed above, in the initial phase of collusion, the operating mechanism of the cartel was not fully worked out. Price targets were set, but explicit market shares were not negotiated and information sharing was scant. By contrast, the second phase involved fixed global market shares and much improved information sharing practices. It is possible that firms learned over time about the inherent weaknesses of the first phase of collusion, and consequently disagreements over the appropriate rules of the cartel became more urgent. This leads us to the next explanation.

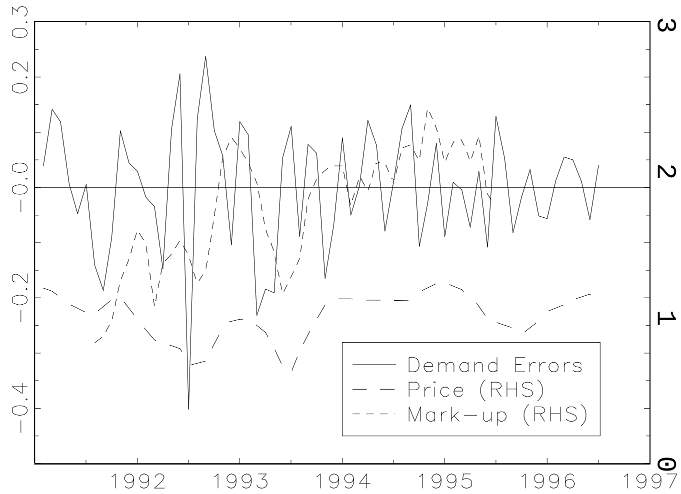
Third, there was widespread suspicion of cheating.[37] The demand estimation exercise revealed no major shifts in demand conditions over the sample. However, the second price war could have coincided with a slight downturn in demand. Figure 5 depicts the observed lysine price and mark–up, and the demand errors, ε_t, from equation (1). It can be seen that the most persistent negative demand shock of the sample occurred at the start of the second price war. It is possible then that suspicions of cheating were exacerbated by a negative demand shock, precipitating the price war.

Given the common suspicion of cheating, it seems that the Rotemberg and Saloner (1986) model of price wars provides little guidance for this particular price war. As discussed above, a potential explanation is given by the price war models of GP and APS. To pursue an explanation of this flavour, we may wish to depart slightly from the philosophy of these papers. Their models describe incentive compatible mechanisms for enforcing optimal collusion. In both models, firms never cheat on the agreement and only last period's market price is relevant in deciding whether to collude. By contrast, in the lysine market, especially in the first phase of the cartel, the collusive mechanism was, at best, imperfect. In fact, there is no evidence in the public record of a well-defined enforcement mechanism at all in this phase of the cartel, beyond vague allusions to the mobilisation of excess capacity. Suspicion of cheating was widespread, suggesting that the mechanism was not incentive compatible. In addition, as we discuss in section 5.2, the cartel's price targets were systematically not met, despite the possibility that cartel participants overestimated the elasticity of demand over the sample period. This provides further evidence for the prevalence of cheating.

In this context, it may be more fruitful to examine the implications of the prevailing cartel mechanism and accept the existence of cheating, rather than imposing an incentive compatible mechanism. We may then expect inferences on the extent of cheating to be based on the entire history of market prices rather than just last period's price. For example, if firms are uncertain about the exact preferences of their rivals or the efficacy of monitoring technology, they will be

[37]This is documented in Connor (2000). The majority of concerns appear to have arisen in the first phase of the cartel before volume allocations were agreed to and improved monitoring was implemented.

Figure 5: Demand Errors



unsure about whether a particular agreement is sustainable. As learning takes place, the cartel could be strengthened, or it could unravel depending on firms' actual preferences.[38] While Slade (1990) finds the existence of cheating in equilibrium, we might expect the nature of cheating to be temporary in Slade's model as firms opportunistically exploit transitory cost shocks. Cheating appears to have been more widespread and persistent in the lysine market.

The second price war ended in the middle of 1993 and was followed by a successful phase of collusion until the authorities intervened. Several conceivable explanations for the resumption of the collusive agreement offer themselves. First, in the spirit of GP and APS, the end of the punishment phase in a price war model may have been reached. That is, punishment had ensued for sufficient time to maintain the incentives for collusion. As discussed above, this explanation presupposes an incentive compatible enforcement mechanism and a high degree of coordination.[39] Particularly in the first phase of the cartel, this does not seem to have existed in the lysine market.

Second, as can be seen in Figure 2, there was a substantial increase in the ceiling price in 1993. A rise in the ceiling price could have made collusion more attractive by raising the potential collusive price. However, the ceiling price was already well above the lysine price at the onset of the price war. In addition, it appears to have been falling at the time collusion was renegotiated.

A third explanation is that during the price war, cartel participants were negotiating a more

[38] It is unclear whether learning would in fact take place because a firm with an incentive to cheat in the absence of learning may seek to mimic the behaviour of a firm without such an incentive.

[39] Technically, these models do not require explicit communication. However, given the extent of disagreement evident between cartel participants in the initial phase of the collusion, tacit coordination on such schemes appears even less likely.

appropriate form for the cartel. Resolution of these discussions paved the way for a subsequent phase of collusion. As discussed previously, there were many apparent problems with the first phase of the cartel. It is highly likely that these problems contributed to the breakdown of the cartel. There was thus potential for future mutually beneficial cooperation, should these problems be ironed out.[40]

5.2 The Level of the Markup

Having argued the existence of price wars, in this section we examine the level of the observed mark-up, both during phases of collusion and during price wars. As can be seen from Figure 4, under the punishment phase the mark-up is well below the Cournot mark-up. This suggests that the GP model based on Cournot reversion is not an appropriate description. If price rather than quantity were the strategic decision variable, then prices would approach marginal costs in the punishment phase in the GP model. However, the level of the mark-up in the reward phase is more troubling. Even under the reward phase, the mark-up appears to be commonly below that predicted by the Cournot model. Neither GP nor APS suggest an explanation for this. Several alternative explanations are possible.

First, cartel participants were wary of approaching the ceiling price. As can be seen in Figure 2, there were periods in the cartel's history in which the lysine price became quite close to the ceiling price, notably in early 1995. The proceedings of the conspiracy meetings reveal that, when setting price targets, the participants were quite wary of the ceiling price and anticipated movements in the ceiling price (Connor, 2000, pp. 23-24). However, for the majority of the collusive periods, the ceiling price was well above the lysine price.

Second, the participants may have been wary of detection by anti-trust authorities, and may have tempered price targets accordingly.[41] While well aware of the activities of the anti-trust authorities, cartel participants adopted a rather brazen attitude to them.[42] However, cartel members do appear to have demonstrated care in not attempting to raise prices too rapidly. In both phases of collusion, prices did not rise precipitously, but increased over a period of approximately six months. In addition, anti-trust concerns may have prevented cartel members from allocating individual customers (Connor, 2000, p. 163).

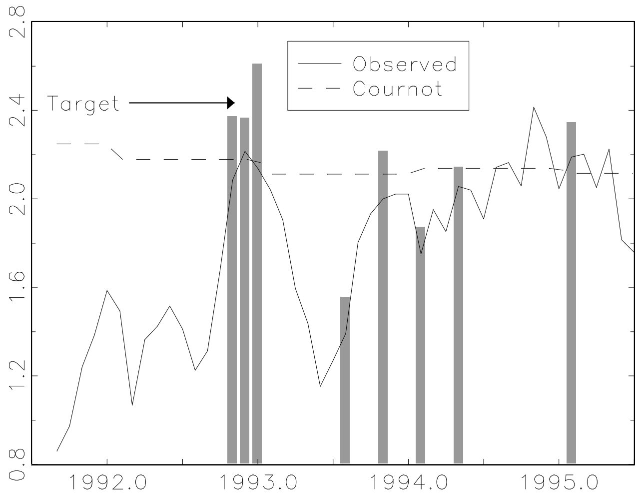
Third, participants may have been wary of potential entry. For this to influence price-setting behaviour requires that a low price act as a signal of market parameters unknown to potential

[40] See note 36 *supra*. The extent of the bargaining problems during this period is also documented in Connor (2000). Surveying a selection of cross-section and case studies of collusion, Levenstein and Suslow (2002) find that bargaining problems are faced by most cartels.

[41] Harrington (2004b, forthcoming) analyses a cartel's price setting problem when anti-trust detection is possible. Harrington (forthcoming) argues that detection driven by price movements rather than price levels induces more plausible empirical predictions. He argues that a cartel will strive for a gradual rise in prices, and if penalties include damages, prices will converge to a steady state that is below the monopoly price. Harrington (2004b) generalises this work to allow the cartel's incentive compatibility constraints to bind. With this change, it is possible that the antitrust authority can in fact raise the cartel's prices by relaxing the cartel's incentive compatibility constraints.

[42] This can be seen dramatically in a publicly available United States Department of Justice (2000) videotape containing excerpts of some of the lysine trade association meetings.

Figure 6: Target Mark-ups



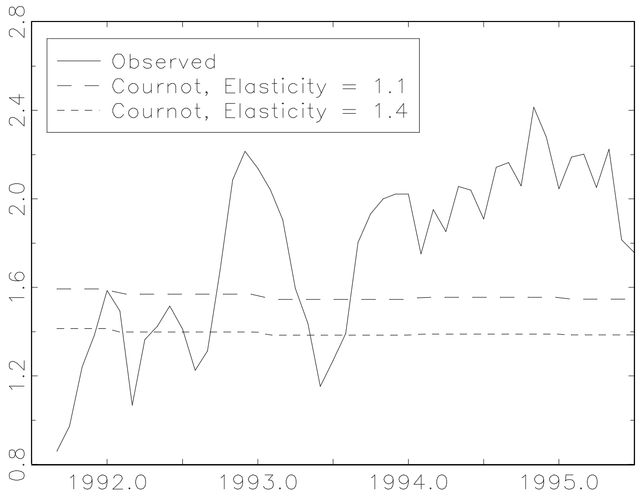
entrants.[43] Potential parameters could include costs and capacities of incumbents. Alternatively, if the existence of collusion were not known outside the cartel, cartel members might wish to mask their collusive tendencies. The inferences we might draw from the subsequent entry of a joint venture between Cargill and Degussa is ambiguous in this regard. On the one hand, future collusion would be made more difficult after the anti-trust authorities were brought in to play. On the other hand, entry occurred after the history of collusion had been revealed, suggesting the possibility of future (presumably tacit) collusion.

Fourth, target prices were not achieved (Connor, 2000, Table A8). This implies that target mark-ups were higher than realised mark-ups. Figure 6 compares the observed mark-up with the implied target mark-up using target prices agreed in lysine cartel meetings obtained from Connor (2000, Table A8). It can be seen that, particularly in the first phase of collusion, firms tried but failed to set higher mark-ups.

Finally, perceptions of market demand elasticity may have differed from α. Participants in the cartel may have had a different model of demand or may have observed a longer period of data, implying a different demand elasticity. Mark Whitacre, the head of ADM's biotechnology division and a major player at the price-fixing discussions, suggests a demand elasticity varying between about -0.95 at a market price of \$0.95 and between -2.6 and -3.6 at a price of \$1.05, while Kanji Mimoto, a more experienced sales officer with Ajinomoto, disagreed with Whitacre and suggested an elasticity of between -1.1 and -1.4 at this price (Connor, 2000, pp. 22-23). Figure 7 compares the observed mark-up with those predicted by the Cournot model based on

[43]Conversely, Benoit and Krishna (1991) argue that a low capacity and high price might be employed to deter entry. This result follows from their finding that holdings of excess capacity can serve to sustain collusive outcomes.

Figure 7: Cournot Mark-up Using Perceived Elasticities



the elasticities suggested by Mimoto. With a higher perceived demand elasticity, the cartel appears to have been more successful in raising prices in the collusive phases.

5.3 Post-Cartel Prices

The behaviour of prices following the FBI intervention also warrants discussion. Subsequently, prices actually rose (Figure 2). One potential explanation appeals to the global nature of the cartel. Different geographic markets were characterised by differences in demand elasticities and in other demand determinants. If the cartel could effectively prevent international arbitrage, regional pricing differences might persist.[44] Following the breakdown of the cartel, we would then expect higher priced markets to be supplied first. This explanation is supported by a surge in U.S. exports following the FBI raid,[45] but is unlikely to explain continuing high prices in the U.S.

A second possible explanation is that an implicit understanding may have developed between the cartel participants, facilitating the continuation of collusive behaviour, albeit tacitly. After several years of repeated interaction and explicit communication cartel members could have learned about the characteristics and strategies of rivals.[46] Further, given that recourse

[44]Connor (2000, p. 22) notes that cross-market arbitrage was a concern of the cartel, with European prices commonly higher.

[45]United States exports approximately doubled over the period 1995 to 1997 (Connor, 2000, Table 13).

[46]The theoretic literature on collusion has made little distinction between tacit and explicit collusion. For example, GP and APS specify tacitly collusive equilibria without addressing how firms might coordinate on collusive strategies in the absence of explicit communication. Several authors have attempted to discern the role of communication in collusion. While GP and APS characterise the cartel's problem as one of imperfect monitoring with

to meetings became riskier following the cartel breakup, firms may have been more careful to avoid further price wars because they would be particularly difficult to resolve.

Finally, if cartel members were well versed in anti-trust prosecution proceedings, they may have had an additional incentive to raise prices. When assessing damages in cartel prosecutions the prices prevailing before and after a cartel's operations are commonly used as "but-for" (counterfactual) prices. Damages are then based on the difference between the prices set by the cartel and these but-for prices.[47]

5.4 The cartel mechanism

A final question relates to the nature of the cartel. The cartel's methods evolved over its working life. Was its final form one that we may have expected? In the second phase of the cartel, once differences in costs and capacities had been learned to some extent, the cartel dealt with asymmetries in firm characteristics by fixing market shares at existing levels. Cartel participants communicated regularly and instituted a monitoring and compensation program. This context most closely resembles that studied by Athey and Bagwell (2004). The signaling equilibria they identify appear to resemble the lysine cartel quite closely. In equilibrium, low cost firms charge a lower price in the initial period, obtaining a greater market share in this and all subsequent periods. This could be interpreted as an initial price war that determines market shares. In the lysine market, the price war was only subtly different. Firms set approximately equal prices in the initial price war, and it was the market shares obtained in this price war rather than the prices set that determined subsequent market shares. de Roos (2004) obtains price wars of this character by imposing the market sharing rule adopted by the lysine cartel and incorporating capacity constraints that can be stochastically determined through investment.

6 Concluding Remarks

An examination of the experience of collusion in the lysine market suggests several challenges for researchers, some of which relate specifically to the lysine market, but many of which apply to a more general setting. First, it is impossible to discuss the lysine history without explicit account of the differences between market participants, both in terms of fundamental characteristics and access to information. Differences between firms were an integral ingredient in the first price war, leading both to a difficulty in coordinating an optimal cartel agreement and, relatedly, engendering an atmosphere of acute uncertainty about key strategic characteristics of

public signals, Kandori and Matsushima (1998) argue that signals are privately observed. Communication could then facilitate a collusive equilibrium. However, as Kandori and Matsushima note, communication is a sufficient condition for a collusive equilibrium in this setting, but it remains an open question whether it is a necessary one. Athey and Bagwell (2001) argue that the ability to communicate can improve the profitability of a cartel where members have private cost information. Genesove and Mullin (2001) argue that communication played a key role in the sugar-refining cartel. Given the complexity and diversity evident in the cartel, they argue communication provided transparency and afforded the cartel flexibility to respond to shocks.

[47]Harrington (2004a) argues that the incentive to maintain cartel prices remains for the duration of litigation, and that a similar pattern of post-cartel pricing applied in the recent graphite electrodes price-fixing conspiracy.

rivals. Preliminary steps have been taken in examining collusion amongst asymmetric firms, where differences relate to costs (Schmalensee (1987) and Harrington (1991), Athey and Bagwell (2004)), patience (Harrington (1989)), capacities (Compte, Jenny and Rey (2002) and de Roos (2001, 2004)), and product quality (Fershtman and Pakes (2000)).

Second, the lysine cartel cannot be fully understood without a dynamic perspective. Most models of collusion take the prevailing market structure as given. However, entry and investment dramatically altered the experience with collusion in the lysine market. Adjustment costs in quantity also appear to have played a major role. Again, only formative steps have been taken towards examining some of these difficult dynamic issues. Rotemberg and Saloner (1986) introduce demand variation into the cartel's problem, while more recent work has endogenised entry and exit decisions and allowed firms to invest to stochastically influence the evolution of product quality (Fershtman and Pakes, 2000) and capacity (de Roos, 2001,2004)).

Third, while price wars have been a common theme in the literature, the nature of the price wars in the lysine market suggest additional issues for consideration. Both price wars contain elements of a bargaining or negotiation problem. Disagreements persisted about the appropriate market shares for the participants as well as the fundamental issue of exactly what form the cartel should take. In surveying the literature on case studies of collusion, Levenstein and Suslow (2002) note that bargaining issues plagued most cartels and contributed to the breakdown of about one quarter of collusive episodes. A second such issue relates to the existence of cheating in the lysine market. It appears that cheating occurred or was at least heavily suspected by cartel participants. As Levenstein and Suslow note, cartels typically take pains to design a cartel so that cheating will not be secret, and hence cheating is infrequently observed.[48] However, where cheating is a problem for a cartel, this suggests the lack of an incentive compatible enforcement mechanism.

In addition to these issues, the lysine market highlights the complexity of the firm's constrained maximisation problem. As well as the standard incentive compatibility constraints, a cartel will commonly be constrained by capacity, participation constraints, concerns about the entry of a competitor, and detection by the anti-trust authorities.

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[48]This issue is discussed in some detail by Genesove and Mullin (2001) in the context of the sugar institute cartel.

A Data Sources

ADM cost data. $US/lb. Exhibits 60-67, Transcript of *United States v. Michael D. Andreas et al.*, U.S. District Court, Northern District of Illinois, Eastern Division, No. 96 CR 762, July to September 1998.
ADM lysine quantity. lbs. Exhibits 60-67, Transcript of *United States v. Michael D. Andreas et al.* U.S. District Court, Northern District of Illinois, Eastern Division, No. 96 CR 762, July to September 1998.
Broiler slaughter. Thousands. USDA, National Agricultural Statistical Service, *Poultry Slaughter*, Table 69, various issues.
Corn prices. $US/lb. Corn, no. 2 yellow; Central Illinois, obtained from the USDA, Agricultural Marketing Service, *Grain and Feed Market News*, Appendix Table 14, various issues.
Exchange rates. Monthly bilateral exchange rates obtained from Datastream.
Feed efficiency ratios. Pounds of feed required to generate one hundredweight of pork. Based on trials on approximately 700 hog farms in the United Feeds Swine Record Program. Annual data were interpolated geometrically to form a monthly series.
Hog inventories. Thousands. USDA, National Agricultural Statistical Service, *Hogs and Pigs*, various issues. Quarterly data were interpolated geometrically to form a monthly series.
Lysine price. $US/lb. Connor (1998). Connor obtains these data from *In re Amino Acid Lysine Antitrust Litigation*, Plaintiff's Interim Report.
Lysine production capacities. Thousand metric tonnes/yr. Connor (1998, Tables 2 and 6).
Lysine sales, annual. $US. Connor (1998). Connor obtains these data from *In re Amino Acid Lysine Antitrust Litigation*, Plaintiff's Interim Report.
Soy bean meal price. $US/lb. Soybean meal, 44% protein, Decatur, obtained from the USDA, Agricultural Marketing Service, *Grain and Feed Market News*, various issues.

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