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***ESTIMATING BACKWARD INTEGRATION IN A PRIMARY INPUT  
MARKET: THE CASE OF U.S. HOG INDUSTRY***

***James G. Pritchett and Donald J. Liu***

**University of Minnesota**

**University of Bologna**

**University of Padova**

**University of Perugia**

**University of Firenze**

**University of Piacenza**

**University of Wisconsin**

**University of Siena**

**University of Alberta**

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Estimating Backward Integration in a Primary Input Market:

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James G. Pritchett and Donald J. Liu

Department of Applied Economics  
University of Minnesota  
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## **Executive Summary**

The U.S. pork sector is evolving from an industry of small, independent firms vertically linked by spot markets to one of substantially larger firms vertically connected through contractual agreements and integration. Potential benefits to this tighter vertical arrangement include lower consumer pork prices, although the true nature of this benefit is still under debate. At the same time, there is concern of market foreclosure because highly vertically integrated industry may prevent independent hog producers from having access to open markets in which to sell their output. Boehlje underscores the need for empirical answers to questions related to the above structural change in the pork industry.

The objective of this paper is to estimate econometrically the extent of backward integration by pork processing firms into the upstream hog production stage, taking into account the oligopsonistic nature of the processors, and to simulate the effect of vertical integration on consumer and producer prices and welfare. Following Perry, backward integration is defined as the fraction of the upstream limiting production factor (e.g., farm land, feedlot facilities and water supply) that the downstream processors own. This economic measure of vertical integration is richer than the traditional measure which is a ratio of internal intermediate input production (by the upstream subsidiary) to the total intermediate input usage (by the downstream processor). Rather than an economic measure of backward integration, this accounting ratio reflects the resolution of vertical integration and, by itself alone, does not give insight into the price and welfare effects of the structural change.

The procedure of this study is as follows. An individual processor's profit maximization problem consists of maximizing revenue from a variety of pork products and minimizing the hog input expenditures, where the latter sub-problem involves a division of the total hog input procurements between open market purchases and internal production by the upstream subsidiary. From the optimization, one derives the optimal pork output supply, total hog input demand, and open market hog input purchases. These behavioral equations of the individual processor are aggregated and estimated in conjunction with the pork product demand equations of consumers and the open market hog supply equation of independent hog producers. The aggregate model is then used as a basis for simulating price and welfare effects of vertical integration. Possible estimation problems arising from the complexity of the optimal solutions are anticipated and coping strategies devised. In addition, data are unavailable on open market hog quantities; as a result theoretical restrictions derived from the model are used to transform this variable so as to utilize the slaughter data published by the USDA.

## **Estimating Backward Integration in a Primary Input Market:**

### **The Case of U.S. Hog Industry**

Beginning with Tom Urban's comments on "the industrialization of agriculture," there has been a renewed interest into the structural impacts that result from the application of modern technologies to agricultural production, marketing, and distribution. The U.S. pork sector exhibits some of the most recent evidence of industrialization (Hurt) and, in particular, is evolving from an industry of small, independent firms vertically linked by spot markets to one of substantially larger firms vertically connected through contractual agreements and integration. Potential consumer benefits to this tighter vertical arrangement include higher quality pork products (Martinez et al.) which are sold at a lower prices, although the true nature of this particular price benefit is still debated among economists [Abiru, Greenhut and Ohta (1976, 1979), Quirmbach, Warren-Boulton, and Westfield]. At the same time, there is concern that a highly consolidated, vertically coordinated industry will threaten the economic viability of independent producers and processors (Lawrence et al.). This concern is supported in part by a theoretical argument that vertical integration may lead to market foreclosure, a situation in which independent producers no longer have open markets in which to sell their output (Salinger). Consequently, the evolution of the pork industry presents a dilemma for policy makers who must weigh the potential benefits of industrialization against its costs when making decisions affecting the pork industry (Barkema and Cook).

Boehlje underscores the need for empirical answers to questions related to the above structural change in the pork industry. Yet, surprisingly little empirical research has considered the topic. Barkema and Cook observe a trend toward a more integrated

industry and cite consumer preferences, new technology, and better information as sources of change, but the authors stop short of empirically analyzing the impacts of the trend. Ward examines the relative level of vertical coordination in the pork, poultry, and beef industries to suggest, descriptively, the extent of future vertical integration. Quantitative analyses, in contrast to the above-mentioned qualitative studies, have mainly focused on surveys of large hog producers and processors. Grimes and Rhodes find that contract production of slaughter hogs in the U.S. has increased from approximately twelve to sixteen percent of total volume for the period 1989-1992, an increase of thirty percent. Azzam and Wellman, in a separate survey, find that eight percent of hog supplies were owned by the largest packers in 1992. Furthermore, a 1992 survey by Hayenga and Kimle suggests that packers plan to dramatically increase their use of integrated production and marketing contracts. The telephone survey of large producers and processors in Lawrence et al. predicts that marketing contracts will grow sharply from eleven percent to twenty-five percent of total volume during the next five years.

The previous research provides useful insight into the status and trend of vertical integration/coordination in the pork industry. Additional insight on the impacts of vertical integration/coordination can be gained by rigorous empirical analysis. The objective of the current paper is to estimate econometrically the extent of backward integration by pork processing firms into the upstream hog production stage, taking into account the oligopsonistic nature of the processors,<sup>1</sup> and to simulate the effect of vertical integration on consumer and producer prices and welfare. The model developed in this study combines an oligopsony market power measure taken from the new empirical industrial

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<sup>1</sup> The pork industry consists of few large processors and many small producers as cited by USDA.

organization literature (NEIO)<sup>2</sup> with the literature of vertical integration based on the theoretical work of Perry, and recently adapted by Azzam in his study of the processor's incentive for backward integration in the U.S. fed cattle industry. While Azzam's work is pioneering, the current study differs substantially from the previous empirical effort. First, Azzam presumes monopsony exists in regional cattle markets but data limitations force the estimation of a national model. While monopsony may be appropriate in regional markets, oligopsony is better suited for describing a national market. Secondly, Azzam assumes a fixed proportions technology for downstream processors.<sup>3</sup> However, as shown by Wohlgenant, the fixed proportions assumption may not be appropriate for some agricultural industries and as a result, fixed proportions for the processing technology is tested for rather than assumed in the current model. Third, the current study considers a multiple output technology as a more general alternative to Azzam's single processing output. Fourth, the current study explicitly accounts for the difference between the total slaughter hog quantity and open market hog quantities. Theoretical restrictions derived from the model are used to transform the variable associated with unavailable open market hog quantities in order to utilize the USDA slaughter data. Finally, while Azzam's work centers on beef processing, the focus of the current study is pork processing.

Before proceeding, a brief discussion on the relationship between this study's model and the various forms of vertical arrangements in the U.S. pork processing sector is in order. In the model, two extreme cases of vertical relationships between hog producers and processors are considered; vertical integration and open market transaction. A

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<sup>2</sup> See Durham and Sexton for a succinct review of the various types of NEIO models.

parameter  $\lambda$  is introduced to represent the proportion of vertical integration and, hence,  $1 - \lambda$  the non-integrated portion of the industry. As will be seen, competitive forces dictate that a vertically integrated hog producer receives an output price based on its marginal cost of production while independent producers receive an open market price oligopsonistically determined by downstream processors. The issue at hand is what the parameter  $\lambda$  captures when the industry is better described by the existence of both vertical integration and coordination (e.g., contracting) with the latter predominating (Lawrence et al.). Clearly, if a contract price is based on the open market price, as far as the pricing effect is concerned, this vertical arrangement belongs in the open market category of the model.<sup>4</sup> Analogously, if the contract price is based on the marginal cost of hog production, it belongs to the vertical integration category. A more complex case occurs when the contract price is a combination of the open market price and the production cost. However, this does not present a problem to the current model for the following reason. For any given industrial configuration in which firms are organized between the polar cases of vertical integration and open market transaction, a certain economic outcome would ensue. The modeling strategy of this research is to find a single parameter,  $\lambda$ , which parsimoniously partitions the continuous spectrum of vertical arrangements into two polar cases and reproduces the same economic outcome. Such an interpretation is in the spirit of the conjectural variations parameter commonly found in the NEIO literature in the study of market power.

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<sup>3</sup> The fixed proportions assumption is used in Azzam's article to gauge the incentive for backward integration of packers. Theoretical results have suggested that the incentive for vertical integration is limited when the technology is fixed proportions (Greenhut-Ohta, Vernon and Graham).



## Conceptual Framework

The model is composed of an upstream production stage and a downstream processing stage. In the upstream production stage, hogs are produced using farm inputs, while in the downstream stage the intermediate hog input is combined with other inputs to create a variety of processed pork products (e.g., hams, loins and bacon). The upstream stage consists of many individual producers who take farm input and hog output prices as given. On the other hand, the downstream stage is composed of a handful of pork processors who act competitively in all but the intermediate hog input market.<sup>5</sup> The downstream oligopsonists acquire the intermediate hog input from both independent producers and from their own upstream subsidiaries, two groups of producers that are assumed to share the same production technology. This hog production technology will be discussed first, followed by a discussion of an individual processor's maximization problem from which one derives the optimal pork output supply, total hog input demand, and open market hog input purchases. The behavioral equations of the individual processor are then aggregated and estimated in conjunction with the pork product demand equations of consumers and the open market hog supply equation of independent hog producers. The aggregate model is then used as a basis for simulating price and welfare effects of vertical integration.

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<sup>4</sup> This does not imply that this type of arrangement is equivalent to an open market transfer. In fact, vertical contracts typically contain provisions for risk sharing, quality control, etc. that are not reflected in open market transactions.

<sup>5</sup> This specification, used by others modeling imperfect competition in U.S. livestock sector (Koontz, et al.), focuses on the buying power in the intermediate hog input market abstracting from the potential selling power in the output market.

## Defining Vertical Integration

Following Perry, the technology of upstream hog producers is assumed to be constant returns to scale for all output levels, but the marginal production cost is increasing due to the limited availability of a specialized factor. The assumption of constant returns to scale is prevalent in many empirical studies centered on the U.S. livestock sector (e.g., Azzam(b); Koontz and Garcia) and the existence of a limiting factor in agricultural production is plausible (e.g., farm land, feedlot facilities and water supply).

Let  $C(x, \lambda)$  be the variable cost function of any subset of hog producers who produce  $x$  with a fraction  $\lambda$  of the limiting factor  $\{0 < \lambda \leq 1\}$ . Constant returns to scale in the production technology implies that  $C(x, \lambda)$  is linearly homogenous in its arguments. In particular,

$$(1) \quad C(x, \lambda) = \lambda * C\left(\frac{x}{\lambda}, 1\right).$$

The technology is such that producing  $x$  units of the hog output with  $\lambda$  of the limiting factor costs a fraction  $\lambda$  of the expense of producing the quantity  $x/\lambda$  with all of the limiting factor.<sup>6</sup> Notice that  $C(\bullet, 1)$  is equivalent to the industry's variable cost function.

Differentiating (1) with respect to  $x$ , it is apparent that the marginal cost of producing  $x$  units for the subset of producers who own  $\lambda$  of the limiting factor is equivalent to the industry's marginal cost of producing  $x/\lambda$  units of the output. That is:

$$(2) \quad \frac{\partial C(x, \lambda)}{\partial x} = \frac{\partial C\left(\frac{x}{\lambda}, 1\right)}{\partial x}.$$

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<sup>6</sup> For example, producing  $x$  with one third of the limiting factor is one third as costly as producing three times  $x$  with all of the limiting factor.

Given the assumption that hog producers are price takers in their output market, (2) indicates that the hog supply function for producers owning  $\lambda$  of the limiting factor is equivalent to the industry supply function shifted horizontally by  $\lambda$ . Thus, the upstream industry supply curve can be continuously and horizontally partitioned into supply curves of producers owning fractions of the limiting factor, and a downstream processor's backward integration can be defined in terms of the fraction of the upstream limiting factor that he owns (Perry). Specifically, let  $\lambda_i$  be the fraction of the upstream limiting factor owned by the  $i^{\text{th}}$  downstream processor and let  $\lambda = \sum \lambda_i$ . Then, as defined by Perry,  $\lambda$  is the extent of backward vertical integration in the industry. A  $\lambda$  near zero suggests the industry is relatively more disintegrated whereas a  $\lambda$  near one suggests the industry is nearly integrated. This economic measure of vertical integration may be contrasted with the traditional measure of the ratio of internal intermediate input production (by the upstream subsidiary) to the total intermediate input usage (by the downstream processor). While useful from an accounting perspective, the traditional measure, according to Perry, "defines vertical integration as the resolution of the firm's production decisions." On the other hand, the economic measure of backward integration,  $\lambda$ , is independent of production decisions and, hence, allows one to examine the impact of vertical integration on the production decisions and market prices.

### **The Processor's Profit Maximization Problem**

The  $i^{\text{th}}$  processor produces various pork outputs using a hog input ( $x_i$ ) and other processing inputs ( $l_i$ ). The hog input is obtained from two sources, open market purchases ( $x_i^o$ ) and internal production ( $x_i - x_i^o$ ) of the processor's upstream subsidiary

who produces the needed hogs at a minimum cost. The processor takes as parameters the price of pork products ( $P$ ) and the price of non-hog processing inputs ( $S_i$ ). Given the extent of backward integration ( $\lambda_i$ ), the processor maximizes profit by choosing total hog input quantity, open market hog purchases and the quantity of non-hog processing inputs. The maximization problem is written as:

$$(3a) \quad \max_{x_i, l_i, x_i^o} \left\{ R(x_i, l_i | P) - S_i l_i - C(x_i - x_i^o | \lambda_i, S_f) - W(x^o) x_i^o \right\},$$

where  $R$  is the revenue function for pork products, and  $C$  is the cost function of the upstream subsidiary who treats as parameters the farm input prices ( $S_f$ ). Notice that the oligopsonistic processor can influence the open market price of hogs ( $W$ ) via the linkage between  $x_i^o$  and  $x^o$  where  $\sum_i x_i^o = x^o$ . A unique feature of (3a) is that the revenue function treats hogs as an input while the subsidiary cost function treats hogs an output; consequently, analysis is always focused on the intermediate hog product. Also, the revenue function specification is conducive for examining the multiproduct case considered in this study as, via Shepherd's lemma,  $\partial R / \partial P_i$  is the processor's conditional output supply of pork product  $i$ . Without loss of generality, the optimization in (3a) can be decomposed into a revenue maximization problem and a hog input expenditure minimization problem where the latter involves an optimal choice between open market purchases and internal production of the hog input. Specifically,

$$(3b) \quad \max_{x_i, l_i} \left\{ R(x_i, l_i | P) - S_i l_i - \min_{x_i^o} \left\{ \Gamma_i \equiv C(x_i - x_i^o | \lambda_i, S_f) + W(x^o) x_i^o, \text{ given } x_i \right\} \right\}.$$

Hog expenditure minimization is considered first. Given the total hog input  $x_i$ , the processor allocates hog input expenditures to balance the marginal production cost of his upstream subsidiary with the marginal open market outlay which includes both the prevailing hog price and an oligopsony markdown. Differentiate  $\Gamma_i$  in (3b) with respect to  $x_i^o$  and set the resulting expression equal to zero to obtain the first order condition:

$$(4) \quad \frac{\partial C(x_i - x_i^o \mid \lambda_i, S_f)}{\partial x_i^o} = W + \frac{\partial W}{\partial x^o} \frac{\partial x^o}{\partial x_i^o} x_i^o$$

$$= W(1 + \theta_i \varepsilon),$$

where  $\theta_i \equiv \frac{\partial x^o}{\partial x_i^o} \frac{x_i^o}{x^o},$

and  $\varepsilon \equiv \frac{\partial W}{\partial x^o} \frac{x^o}{W}.$

As in the NEIO literature, the term  $\partial x^o / \partial x_i^o$  in (4) captures the conjectures that the processor has for competitors' responses to marginal changes in his own open market purchases. The term  $\frac{\partial W}{\partial x^o} \frac{\partial x^o}{\partial x_i^o} x_i^o$  represents the oligopsony markdown while  $\frac{\partial C(\bullet)}{\partial x_i^o}$  is the marginal production cost of the upstream subsidiary. The second line of (4) expresses the first order condition in terms of the conjectural elasticity ( $\theta_i$ ) of the processor<sup>7</sup> and the inverse supply elasticity or price flexibility ( $\varepsilon$ ) of independent hog producers.<sup>8</sup> From (4), the  $i^{\text{th}}$  oligopsonist's demand for open market hogs can be written as:

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<sup>7</sup> A conjectural elasticity of zero indicates the firm behaves as a price taker while a conjectural elasticity of one indicates monopsonistic behavior. Cournot competition with  $n$  identical firms is represented by a  $1/n$  conjectural elasticity.

<sup>8</sup> Equation (4) is a more general specification of Azzam's equation (6) because it allows for oligopsony competition rather than monopsony. Further, because of the interest in developing a structural model for the hog industry, (4) is a structural representation of the hog input allocation rule compared to Azzam's

$$\begin{aligned}
(5) \quad x_i^o &= x_i^o(x_i | W, \lambda_i, \varepsilon, \theta_i, S_f) \\
&\equiv x_i^o(x_i | W, \kappa_i), \\
\text{where } \kappa_i &\equiv \{ \lambda_i, \varepsilon, \theta_i, S_f \}.
\end{aligned}$$

Equation (5) illustrates how the oligopsonist divides total hog input procurements between open market purchases and production by its own upstream subsidiaries. Throughout the remainder of this paper, (5) will be referred to as the hog input allocation rule. Using (5),  $x_i$  may be substituted for  $x_i^o$  in the objective function (3b).<sup>9</sup> Before continuing with the optimization problem, the previous derivation will be made more concrete by considering a particular functional specification for the upstream cost function.

### Specific Functional Form

Following Azzam, specify the cost function for any hog producer whose output is  $q$  and owns  $z$  fraction of the limiting factor as:

$$(6) \quad C(q, z, S_f) = \frac{v}{\varepsilon + 1} \left( \frac{q}{z} \right)^\varepsilon q,$$

where  $v$  captures the impact on  $C$  of a set of supply shifters (e.g., input price,  $S_f$ ) and  $\varepsilon$  is the inverse supply elasticity as defined previously. The marginal production cost for the  $i^{\text{th}}$  processor's upstream subsidiary can now be written as:

$$\frac{\partial C(x_i - x_i^o | \lambda_i, S_f)}{\partial (x_i - x_i^o)} = v \left( \frac{x_i - x_i^o}{\lambda_i} \right)^\varepsilon.$$

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reduced form specification which replaces the open market hog price ( $W$ ) with the underlying cost function parameters.

<sup>9</sup> Expressing hog input usage in terms of  $x_i$  instead of  $x_i^o$  is conducive for empirical analysis because aggregate data are reported in terms of total hogs killed,  $\Sigma x_i$ .

The first-order condition in (4) is then specialized to:

$$(7) \quad v \left( \frac{x_i - x_i^o}{\lambda_i} \right)^\varepsilon = W (1 + \varepsilon \theta_i),$$

where  $\theta_i$  is the conjectural elasticity as defined before. Solving equation (7) for

$x_i^o$  in terms of  $x_i$ , one obtains:

$$(8) \quad x_i^o = x_i - \lambda_i \left( \frac{W}{v} (1 + \varepsilon \theta_i) \right)^{\frac{1}{\varepsilon}}.$$

Notice in (8) that as  $\lambda_i$  approaches zero then  $x_i^o$  approaches  $x_i$  suggesting that all of the processor's hog input is acquired from the open market. Equation (8) is the specific counterpart of the hog input allocation rule in (5).

### **The Optimal Input Demand and Output Supply**

Substituting (5) into  $\Gamma_i$  in the second part of equation (3b) provides the minimum hog expenditures:

$$(9) \quad E(x_i | \kappa_i) \equiv C(x_i - x_i^o(x_i | W, \kappa_i) | \lambda_i, S_f) + W x_i^o(x_i | W, \kappa_i).$$

The profit maximization problem in (3b) then involves a revenue function as well as the hog input expenditure function:

$$(10) \quad \max_{x_i, l_i} \left\{ R(x_i, l_i | P) - S_l l_i - E(x_i | W, \kappa_i) \right\}.$$

Differentiating the processor's objective function in (10) with respect to the remaining two choice variables and setting the resulting expressions equal to zero yields the first order

conditions for intermediate hog input and other processing inputs demands:

$$(11a) \quad \frac{\partial R(x_i, l_i | P)}{\partial x_i} - \frac{\partial E(x_i | W, \kappa_i)}{\partial x_i} = 0, \text{ and}$$

$$(11b) \quad \frac{\partial R(x_i, l_i | P)}{\partial l_i} - S_i = 0.$$

Solving the first order conditions in (11), the optimal demand for the hog input and other processing inputs can be expressed as:

$$(12a) \quad x_i = x_i(P, S_i, w, \kappa_i), \text{ and}$$

$$(12b) \quad l_i = l_i(P, S_i, w, \kappa_i).$$

One also seeks the output supply of pork products. Applying Shepherd's lemma to the revenue function obtains the conditional output supply vector:

$$(13a) \quad y_i^c(P | x_i, l_i) = \frac{\partial R(x_i, l_i | P)}{\partial P}.$$

The Marshallian supply vector can then be found by substituting the optimal input demands of (12) into (13a) for  $x_i$  and  $l_i$ :

$$(13b) \quad y_i = y_i(P, x_i(P, S_i, w, \kappa_i), l_i(P, S_i, w, \kappa_i)).$$

### The Aggregate Structural Model

To aggregate the previous model, follow Appelbaum's approach of assuming that the conjectural elasticities are the same for all processors ( $\theta_i = \theta, \forall i$ ). It is also assumed that each processor owns the same fraction of the upstream limiting factor ( $\lambda_i = \bar{\lambda}, \forall i$ ), and denote the sum of  $\bar{\lambda}$  across all processors as  $\lambda$ . Given these assumptions, the parameter  $\kappa_i$  in equation (5) becomes the same for all  $i$ ; that is,  $\kappa_i = \kappa \equiv \{\lambda, \varepsilon, \theta, S_f\}$ . It



follows that the aggregate versions of first order conditions (11), optimal input demand equations (12), and optimal pork supply equations (13) can be obtained by suppressing the  $i$  subscripts in those equations:

$$(11a') \quad \frac{\partial R(x, l | P)}{\partial x} - \frac{\partial E(x | W, \kappa)}{\partial x} = 0,$$

$$(11b') \quad \frac{\partial R(x, l | P)}{\partial l} - S_l = 0,$$

$$(12a') \quad x = x(P, S_l, w, \kappa),$$

$$(12b') \quad l = l(P, S_l, w, \kappa),$$

$$(13a') \quad y^c(P | x, l) = \frac{\partial R(x, l | P)}{\partial P}, \text{ and}$$

$$(13b') \quad y = y(P, x(P, S_l, w, \kappa), l(P, S_l, w, \kappa)).$$

Similarly, the processors' hog input allocation rule in (5) can be aggregated as:

$$(5') \quad x^o = x^o(x | W, \kappa).$$

Substituting (12a') into (5') for the optimal demand for hog input ( $x$ ) gives the open market demand for hogs:

$$(14) \quad x^o = x^o(x(P, S_l, W, \kappa), W, \kappa),$$

which has to be balanced by the output of independent hog producers whose supply curve, given the price taking assumption, coincides with their marginal cost curve:

$$(15) \quad W = \frac{\partial C(x^o, 1 - \lambda, S_f)}{\partial x^o}.$$

From (14) and (15) the equilibrium open market hog quantity ( $x^o$ ) and hog price ( $W$ ) is determined, given the required oligopsonistic markdown ( $W\theta\epsilon$ ) [see the second line of (4)].

The equilibrium conditions in the pork product market can be obtained by introducing into the model the consumer demand for the products:

$$(16) \quad y = y(P, \Psi),$$

where  $\Psi$  is a vector of demand shifters. Given the assumption of perfect competition in the final output markets, equilibrium pork prices and quantities can be obtained by solving (13b') and (16) simultaneously.

To summarize, the aggregate model of the pork industry has six equations including the total hog input demand in (12a'), the open market hog demand in (14), the open market hog supply in (15), the pork product supply in (13b'), the retail pork product demand in (16), and the optimal demand for other processing inputs in (12b'). There are six endogenous variables including the total hog input ( $x$ ), open market hog quantity ( $x^o$ ) and price ( $W$ ) [and hence the oligopsony markdown ( $W\theta\epsilon$ )], the pork product quantity ( $y$ ) and price ( $P$ ), and other processing input usage ( $l$ ).

The equations can, in principle, be estimated jointly as a system with the neoclassical restrictions associated with the revenue function in (10) tested or imposed. In practice, however, the input demand equations (12a') and (12b') are exceedingly complex as they are the simultaneous solutions of the first order conditions in (11a') and (11b'), and this complexity makes them difficult to estimate. This limitation can be overcome by estimating the first order conditions instead because all the parameters in

(12') also appear in (11'). Likewise, the empirical expression for the output supply equation in (13b') is very complex because it includes the simultaneous solution of the first order condition (11'). Instead of direct estimation, one can estimate the conditional output supply in (13a') and then use the estimated parameters to recover the Marshallian supply equation of (13b').

### **Empirical Framework**

The empirical specification for the upstream variable cost function is in (6) and the subsequent hog input allocation rule is in (8). The aggregate version of (8) is:

$$(8') \quad x^o = x - \lambda \left( \frac{W}{v} (1 + \varepsilon \theta) \right)^{\frac{1}{\varepsilon}}.$$

Equation (8') highlights the difference between the economic measure of vertical integration,  $\lambda$ , and the accounting measure  $(x - x^o)/x$  which is the ratio of internal production of the intermediate input to total input usage. This latter measure reflects the resolution of vertical integration and, by itself alone, does not give insight into the price and welfare effects of vertical integration.

Given the empirical specification of the cost function for the upstream production stage, the empirical counterpart of the open market hog supply function in (15) can be expressed as:

$$(17) \quad x^o = \left( \frac{W}{v} \right)^{\frac{1}{\varepsilon}} (1 - \lambda),$$

where, as mentioned in the discussion of (6),  $v$  captures the impact on upstream production costs of a set of supply shifters. The supply shifters include the price of feed, the price of feeder pigs, cost of labor, and dummy variables accounting for seasonal

variation in factors related to hog production. The open market supply equation in (17), however, is not amenable for empirical estimation because the data for  $x^o$  are not available; the slaughter hog series published by the USDA pertains to total hog kills,  $x$ . This data limitation can be addressed by making use of the allocation rule (8') derived from the hog expenditure minimization problem. Substituting (8') into (17), the supply of open market hogs is transformed into:

$$(18) \quad x = \left( \frac{W}{v} \right)^{\frac{1}{\varepsilon}} \left( 1 - \lambda + \lambda (1 + \theta \varepsilon)^{\frac{1}{\varepsilon}} \right),$$

which can be estimated using available data.

The empirical model also requires the specification of the processor's revenue function in (10). For ease of exposition and consistent with the aggregate model, subscripts will be used to denote processing inputs and outputs rather than individual processing firms. Three pork outputs (hams, loins, and bacon) are considered with their prices denoted by  $P_1$  for ham,  $P_2$  for loins, and  $P_3$  for bacon. The processing inputs include labor ( $l_1$ ), energy ( $l_2$ ), transportation services ( $l_3$ ), and the intermediate hog input ( $x$ ). Let  $z$  be a vector containing the four input quantities;  $z = (l_1, l_2, l_3, x)$ . Consistent with the notation in the conceptual framework, let the first three input prices be denoted as  $S_{l_i}$ ,  $i = 1, 2, 3$  and the intermediate hog input price as  $W$ . A quadratic form is chosen for the revenue function with  $P_1$  and  $P_2$  being normalized by  $P_3$ ; the normalization imposes linear homogeneity on the revenue function and eases estimation burden. Let  $\tilde{P}_j$  denote the normalized price for  $P_j$ ,  $j = 1, 2$  and let  $\tilde{R}$  be the corresponding normalized revenue:

$$\begin{aligned}\tilde{R}(z, P) = & \alpha_0 + \sum_{m=1}^4 \alpha_m z_m + \sum_{j=1}^2 \beta_j \tilde{P}_j + \frac{1}{2} \sum_{m=1}^4 \sum_{m'=1}^4 \alpha_{mm'} z_m z_{m'} \\ & + \frac{1}{2} \sum_{j=1}^2 \sum_{j'=1}^2 \beta_{jj'} \tilde{P}_j \tilde{P}_{j'} + \sum_{j=1}^2 \sum_{m=1}^4 \delta_{jm} \tilde{P}_j z_m ,\end{aligned}$$

where  $\alpha$ 's,  $\beta$ 's, and  $\delta$ 's are parameters.

With the above empirical specifications for the cost function and the revenue function, imposing the symmetry condition that  $\alpha_{mm'} = \alpha_{m'm}$  and aggregating, one obtains the empirical counterpart of the first order conditions in (11a') and (11b'):

$$(19a) \quad \alpha_4 + \sum_{m=1}^4 \alpha_{4m} z_m + \sum_{j=1}^2 \delta_{4j} \tilde{P}_j - W(2 + \theta \varepsilon) = 0, \text{ and}$$

$$(19b) \quad \alpha_i + \sum_{m=1}^4 \alpha_{im} z_m + \sum_{j=1}^2 \delta_{ij} \tilde{P}_j - S_{l_i} = 0 \quad i = 1, 2, 3.$$

The estimated coefficients of (19a) and (19b) are then used to construct the empirical counterparts of equations (12a') and (12b') which are the optimal input demands.

Similarly, the conditional supply function of the  $j^{\text{th}}$  pork product can be derived by differentiating the revenue function with respect to its output price, imposing the symmetry condition that  $\beta_{jj'} = \beta_{j'j}$  and aggregating:

$$(20) \quad \frac{\partial \tilde{R}}{\partial \tilde{P}_j} = \beta_j + \sum_{j'=1}^2 \beta_{jj'} \tilde{P}_{j'} + \sum_{m=1}^4 \delta_{jm} z_m \quad j = 1, 2.$$

Equation (20) is the empirical version of (13a') and its estimated parameters will be substituted into the empirical counterpart of (13b') to obtain the estimated form of the Marshallian supply equation.<sup>10</sup>

Finally, the empirical counterpart of the consumer demand equation for pork products in (16) is specified in double logarithmic form as:

$$(21) \quad \ln y_j = \gamma_o + \sum_{i=1}^4 \gamma_i \ln P_i + \gamma_5 \ln P_o + \gamma_6 \ln y_{j-1} + \gamma_7 \ln M \\ + \gamma_8 SEAS + \gamma_9 TREND + \gamma_{10} POP \quad j=1,2,3,$$

where  $y_j$  is the demand for the  $j^{\text{th}}$  pork product and  $P_j$  is its price,  $P_o$  is the price vector of other food items and non-food items,  $M$  is income,  $y_{j-1}$  is the lagged demand accounting for habit formation of consumers,  $SEAS$  is a vector of seasonal dummy variables,  $POP$  is a population variable, and  $TREND$  captures the impact of consumption trends such as the shift to leaner diets.

Equations (18) - (21) are estimated as a system using Three Stage Least Squares to account for endogeneity, contemporaneous correlation, and cross equation restrictions. Symmetry and price homogeneity conditions of the revenue function are imposed in the above derivation. The unrestricted version of the equation system will also be estimated and the restrictions tested. The convexity of the revenue function will also be verified via an LDL decomposition procedure as outlined in Moschini and others. Once the estimated

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<sup>10</sup> Note that because the revenue function has been normalized, not all output price parameters are given explicitly upon estimation. Economic theory suggests that the revenue function be both linearly homogenous in output prices and that cross price effects be symmetric. Given a quadratic specification for the revenue function, this requires, for instance, that  $\beta_{jj} = \beta_{j'j}$  for all  $j$  and that  $1 - \beta_1 - \beta_2 = \beta_3$ . The parameters of the output price coefficient may then be recovered using these restrictions after the estimation of the first order conditions.

versions of equations (18) - (21) are derived, appropriate simulation techniques will be used to determine the impacts of increasing vertical coordination on the slaughter hog price/quantity and producer pork price/quantity.

## **Data**

The empirical model uses quarterly data for a period ranging from the first quarter of 1975 to the final quarter of 1996. Data for the upstream hog producers is largely taken from publications of the U.S. Department of Agriculture (USDA). Data on the price and quantity of US slaughter hogs is taken from USDA's *Red Meat Yearbook* as is the price of feeder pigs. In particular, the livestock slaughter quantity data is based on USDA inspection of packing plants and is measured as the total amount of hogs slaughtered as opposed to the total amount of open market hogs available for slaughter. A quarterly price for corn and soybeans is reported by the USDA's Economic Research Service (ERS) in addition to a farm labor price index used to proxy hog producers labor costs. Dummy variables account for seasonal fluctuation in the supply of hogs.

The data for the downstream processing stage is a combination of USDA's *Red Meat Yearbook*, the Bureau of Labor Service's Data, Department of Energy's Energy Information Administration and the U.S. Census Bureau's *Annual Survey of Manufactures*. The prices of pork outputs (hams, loins, pork bellies) is reported as prices per hundredweight from the USDA's *Red Meat Yearbook*. The quantity of electricity (Kwh), expenditures on new capital and equipment, and hours of labor inputted, are taken from the US. Census Bureau's *Annual Survey of Manufactures*. Note that the data is for meat packing plants (SIC 2011) and is reported annually rather than quarterly. As a result, the data is made quarterly by dividing the annual level of inputs according to the

quarterly hog slaughter. For instance, if one-third of all hog slaughter in 1971 occurred in the first quarter, then one-third of the total labor hours used by SIC 2011 in 1971 is apportioned to the first quarter. The Department of Labor provides a labor price index for the manufacturing sector and the Department of Energy provides an energy cost index which proxies the cost of electricity to the processing sector. A capital price index is provided by the Bureau of Labor Statistics.

The consumer pork consumption data originates primarily from the ERS publications. Quantities and prices of pork products come from the *Red Meat Yearbook*, whereas as expenditure data on food is derived from the ERS *Food Consumption, Prices and Expenditures Data*. An annual population series is taken from the U.S. Census Bureau and made quarterly by multiplying the annual total by 0.25. A consumer price index is used to proxy alternative expenditures and seasonal dummies are used to account for cycling of demand for pork products.



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