ANALYSES OF MARKET POWER FOR US AND INTERNATIONAL BEEF MARKETS

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Abstract: This dissertation expands the conventional NEIO model by imposing the theoretical restrictions and proposes a method for measuring the degree of rivalry in contested markets.

The first empirical example estimates market power and social welfare loss in the US beef packing industry using an NEIO approach. This is differentiated from other NEIO studies in that this paper imposes zero-degree homogeneity on the US beef demand function and imposes concave curvature on the indirect cost function. The results confirm that there are significant effects of theoretical restrictions. When the homogeneity and the concavity condition are imposed simultaneously, market power and social welfare loss in the US beef packing industry are increased. Compared with other NEIO studies, the estimated market power and social welfare loss under the theoretical restrictions are significantly higher. This suggests that other NEIO studies may underestimate market power and social welfare loss. However, the estimated market power and social welfare loss may be overestimated as this study did not consider the cost efficiency effect of concentrated market structures, oligopsony power of beef packers, and marketing channels between beef packers and retailers.

The second empirical example estimates the degree of rivalry between the United States and Australia in the imported beef markets of South Korea and Japan. The proposed rivalry index is bounded between ‘0’ to ‘1’ indicating the market is perfectly competitive or perfectly collusive (cartel). Development of the index follows from a comparative static analysis of rivalry best response functions under Cournot and Stackelberg leader-follower assumptions in the case of quantity competition, and Bertrand and Stackelberg leader-follower assumptions under price competition. An empirical example estimates the degree of rivalry between the United States and Australia in the imported beef markets of South Korea and Japan. The results suggest that the best preferred models are quantity and price cartel for the Korean and the Japanese market. However, the rivalry index does not provide evidence of collusion between the United States and Australia. Trade barriers including high rated tariffs and safeguards and competition with importing country’s domestic beef suppliers may hinder the collusive behaviors of the US and Australia.

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CHAPTER I

INTRODUCTION

The term ‘market power’ has been used to characterize imperfect market competitiveness in industrial organization studies. On the demand side, market power usually refers to the markup of price above marginal cost, resulting from a concentration of producers or retailers in international or domestic industrial levels of the market. Industry concentration contributes to firm efficiencies through economies of scale, which may further narrow the number of competitors in a market. When concentration results in an imperfectly competitive market, there may be losses in consumer welfare.

Concern over market power in agribusiness have been extensively considered. Typical studies focused on agribusiness sectors exhibiting market power include the U.S. beef packing industry and international beef markets. Over the years, agricultural economists studying agribusinesses have turned away from perfect competition models, long regarded as a classic paradigm, and now focus on oligopolies and oligopsonies (Bonanno et al. 2018). Oligopolistic and oligopsonistic problems are well known and addressed by antitrust laws widely enacted at the beginning of the Sherman Act of 1890 to protect social welfare.

The U.S. agribusiness sector has experienced trends in increasing market concentration. For example, the largest four firm shares (CR4) of four major agribusiness sectors; wet corn milling, cane sugar refining, fluid milk processing, and steer and heifer slaughter changed from 63, 63, 18, and 36 to 86, 95, 46, and 85 respectively in 36 years between 1977 to 2012 (MacDonald 2018). In the international bovine meat market (Harmonized System (HS) codes: 20110, 20120, 20130, 20210, 20220, 20230), major beef exporting countries account for over 50% of the total traded value.

Specifically, the shares of the top five exporters: India, Brazil, the United States, Argentina, and Australia are 18.9%, 13.0%, 9.6%, 9.2%, and 9.1% in 2018 respectively (CEPII 2021). The share of the United States accounts for 52% and 44% of the 2018 exported beef markets in South Korea and Japan respectively. Likewise, Australia accounts for 44% and 49% of beef imports in South Korea and Japan.

Methods to quantify market power started with the structure-conduct-performance (SCP) model (Bonanno et al. 2018). The SCP approach uses empirical data on firm profit margins, prices, and costs. SCP analyzes which factors affect market concentration utilizing concentration measures such as the Lerner and CR indices, and Herfindahl-Hirschman index (HHI). The SCP paradigm dominated industrial organization studies from the 1950s to the 1970s. However, scholars raised critical issues related to data availability and endogeneity problems. First, accessing data for all firms on their unit costs of production is virtually impossible. Most of the accessible data are based on accounting profit, and not economic profit. Second, the SCP paradigm assumes that market structure is exogenous. Empirical studies suggest, however, that concentrated markets and their structure can be affected by the market power wielded by colluding firms. That is, firm behavior can further impact market structure, rendering market structure endogenous.

Applebaum (1982) proposed a different model for measuring and quantifying market power. The procedure estimates conjectural elasticities simultaneously with consumer demand. Tirole (1988) later termed this approach as the new empirical industrial organization (NEIO) framework. Many previous industrial organization studies followed and extended Applebaum's model because the approach offers an alternative method to overcome data availability and endogeneity problems. Moreover, the NEIO framework espoused by Applebaum and others provides testable hypotheses to detect competitive market status using statistical methods.

The objective of this research is to refine and expand conventional NEIO estimation approaches and to propose a new index that illustrates imperfectly competitive market conditions. Specially, this research (1) extends the Applebaum-type NEIO model using Bayesian estimation methods to impose cost function concavity and homogeneity restrictions in demand; (2) develops a novel index that characterizes market competition intensity under various structural assumptions in terms of price and quantity; and (3) measures the degree of market power in the US beef packing industry to understand how it affects market structure and social welfare.

Two essays accomplish these objectives. The first essay measures market power in the US beef packing industry using Bayesian estimation methods. This estimation strategy relaxes the 'hard constraints' required to impose theoretical restrictions on supply and demand curvature conditions that one would impose if estimation procedures, such as full information maximum likelihood or nonlinear least squares, were used to estimate Applebaum's model. In addition, changes in social welfare can be estimated simultaneously with the model parameters. In the NEIO models, the price elasticity of demand is an important parameter for determining conjectural elasticities. Failure to obtain a reliable estimate of the price elasticity leads to an unreliable conjectural elasticity that may render the NEIO model inoperable. Maximum likelihood estimation approach commonly runs into convergence problems due to the nonlinear inequality constraints required by the NEIO model. In practice, failure to converge renders standard errors inestimable. Due to these practical reasons, the concave curvature of the output cost function and zero-degree homogeneity of input and output demand are ignored. Bayesian estimation procedures are more flexible and are a solution for bypassing these issues by using informative priors on parameters, theoretical constraints, and their distributions (Poirier 1995; O'Donnell et al. 2007). The priors used in the first essay include information pertaining to the expected sign of parameters. This essay also uses hierarchical priors for the price elasticities of demand and supply. The advantage of using hierarchical priors is that it is a direct method to incorporate information from previous studies as external data into the estimation procedure (D'errico 2020). The hierarchical priors in this essay are from previous literature that estimated price elasticities of demand and supply for US beef products. Including hyper priors developed from previous studies improve the odds of an Applebaum type NEIO model converging, given the inherent nonlinearities of the model in addition to imposing concavity, symmetry, and homogeneity conditions.

The second essay proposes a novel index that characterizes the intensity of firm collusion and competition under Bertrand, Cournot, Cartel, and Stackelberg (BCCS) assumptions. This new index addresses a limitation of the NEIO framework by quantifying the intensity of collusion between market participants, including firms or exporters. The rivalry index is derived from the comparative statics results of profit maximizing conditions and concomitant best response functions. Similar to the NEIO conjectural elasticity, the rivalry index is bounded between 0 and 1, where '0' indicates strong BCCS collusion that is effectively cartel structure on the market, and '1' indicates the absence of BCCS behavior that is perfectly competitive market structure. The 'proof-of-concept' empirical example for this essay focuses on two major beef exporters; the United States, and Australia; and two importers, South Korea and Japan. Bayesian estimation procedures are used to recover best response parameters.

To achieve the three objectives, this research addresses the following hypotheses:

H1. There is no market power and no social welfare loss indicating a perfectly competitive market in the US beef packing industry.

H2. Theoretical restrictions such as concavity and homogeneity condition do not affect NEIO model results.

H3. Major beef exporters do not compete with each other in terms of price in the South Korean and the Japanese beef importing market.

H4. Major beef exporters do not collude either cooperatively or uncooperatively each other in the South Korean and the Japanese beef importing market.

These null hypotheses are tested in each of the essays. Results of this research contribute to an increased understanding of agribusiness environments, possibly suggesting appropriate policies to address the side effects of market power in the US and international beef market, if models indicate that it is present.

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CHAPTER II

DOES IMPOSING CONCAVITY AND HOMOGENIETY CONDITONS MATTER? AN EXAMPLE ESTIMATING MARKET POWER AND SOCIAL WELFARE EFFECTS IN THE US BEEF PACKING INDUSTRY

Abstract

This paper is different from previous NEIO studies in that the modeling procedure imposes zero-degree homogeneity on the US beef demand function and concavity on the indirect cost function. To confirm the effect of these theoretical restrictions on model estimates, this paper estimates Applebaum (1982)'s classic NEIO model using a Bayesian hierarchical modeling procedure. The Bayesian hierarchical procedure aids in the identification parameters derived from highly constrained, nonlinear systems. Results confirm that imposing curvature, homogeneity, and other theoretical constraints make a difference in terms of estimating key behavioral parameters as well as in measuring losses in social welfare. Estimates of market power and any associated social welfare loss in the US beef packing industry are larger when concavity and homogeneity constraints are imposed. This finding suggests that previous NEIO studies may have underestimated market power and its effects on social welfare.

Introduction

Applebaum (1982), Bresnahan (1982), and Lau (1982) proposed methods to measure and quantify market power by simultaneously estimating conjectural elasticities, firm demand for inputs, and consumer demand for firm outputs. This approach was eventually labeled the 'new empirical industrial organization' (NEIO) approach. Since its introduction, NEIO models have been used extensively to analyze the collusion between contested markets, social welfare, and competition (Tirole 1988).

Typical NEIO models are highly structured in their representation of the intersection between consumer demand, firm production, and firm pricing decisions (Alston, Sexton and Zhang 1999; Sexton and Lavoie 2001). An advantage of the highly structured nature of NEIO models is that they generate testable hypotheses pertaining to the detection and measurement of collusion and its effects on markets. The introduction of Applebaum's (1982) NEIO econometric procedure, also called the Production-Theoretic Approach (PTA), was a major innovation for NEIO methodology. Applebaum's PTA provided an alternative method for overcoming data limitations and endogeneity issues, two problems that impeded earlier empirical analyses of market power using NEIO methods (Sheldon and Sperling 2003). Since its introduction in the early 1980s, Applebaum (1982)'s PTA has been modified, extended, and used to document the effects of market power in 29 studies of commodities and industries (Table 1). What is remarkable about Table 1 is that many studies do not consider imposing curvature conditions on the cost function or homogeneity in demand functions. No study simultaneously imposed these theoretical restrictions.

Table 1. Previous NEIO Literatures Reviewed by This Study

	Year	Author(s)	NEIO PTA Model	Checking Curvature Conditions	Imposing Curvature Conditions	Imposing Homogen -eity
1	1982	Appelbaum	✓			
2	1982	Bresnahan				
3	1982	Lau				
4	1988	Schroeter	✓			
5	1990	Azzam and Pagoulatos	✓			
6	1990	Schroeter and Azzam	✓			
7	1992	Wann and Sexton	✓	✓		

8	1994	Chirinko and Fazzari	✓	✓		
9	1995	Bergman and Brännlund	✓			
10	1995	Murray	✓	✓		
11	1997	Azzam	✓			
12	1997	Bhuyan and Lopez	✓			
13	1998	Arnade, Pick and Gopinath	✓			
14	1998	Bhuyan and Lopez	✓			
15	1998	Hyde and Perloff				✓
16	1999	Millan	✓			
17	2000	Raper, Love and Shumway	✓	✓		
18	2001	Azzam and Rosenbaum	✓			
19	2001	Morrison Paul	✓			
20	2002	Lopez, Azzam and Lirón-España	✓			
21	2003	Quagrainie et al.	✓	✓		
22	2005	Kamerschen, Klein and Porter	✓			
23	2008	Mei and Sun	✓			
24	2009	Bakucs et al.	✓	✓		
25	2009	Hockmann and Vöneki	✓	✓		
26	2011	Tostão, Chung and Brorsen	✓			
27	2013	Perekhozhuk et al.	✓			
28	2015	Perekhozhuk et al.	✓			
29	2017	Ji, Chung and Lee	✓			
30	2017	Park, Chung and Raper	✓			
31	2017	Perekhozhuk et al.	✓			
32	2022	Koppenberg and Hirsch	✓	✓		
		Counts	**29**	**8**	**0**	**1**

Despite the theoretical and structural rigor NEIO methods bring to empirical analyses of contested markets, gaps are evident in the published literature with respect to model identification. Identification of an NEIO-type model requires that firm production decisions are cost minimizing (or profit maximizing) and consumer consumption decisions are expenditure minimizing. In empirical applications, these requirements are imposed though restrictions on behavioral parameters. On the firm side, theoretical restrictions include, for example, symmetry of the second order effects on prices or costs and zero-degree homogeneity of input demand or supply functions. On the side of consumers, similar restrictions apply with respect to income, prices, and consumption. Perhaps the most difficult restriction to enforce for both consumers and firms is imposing curvature over indirect cost or expenditure functions, or convexity for indirect profit functions.

Additional estimation problems for a theoretically consistent NEIO model relate to problems with model convergence. The inherent nonlinearities of typical NEIO models complicate their estimation with nonlinear least squares (NLS), general method of moments (GMM), or maximum likelihood (ML). Imposing simultaneously the theoretical restrictions of homogeneity, symmetry, and curvature when these estimators are used makes it even more difficult to achieve convergence since the restrictions are imposed though 'hard constraints'. For example, if a parameter is binding at an upper threshold of zero, then the parameter is effectively '0' with an inestimable standard error. Problems also arise with the calculation of standard errors when model convergence is not achieved. Some studies addressed these issues by using published output supply elasticities to parameterize their models (Azzam and Pagoulatos 1990; Mei and Sun 2008; Perekhozhuk et al. 2013). This procedure 'removes' a parameter from the model at the cost of one's ability to conduct inference with that parameter. For example, introducing price elasticities from other studies instead of estimating them simultaneously with other model components is inefficient because it ignores the information provided the system of simultaneous equations (Perekhozhuk et al. 2015). The forgoing reasons may be why many studies using the NEIO-PTA approach choose not to impose theoretical restrictions.

The main contributions of this study are threefold. First, a hierarchical Bayesian estimation procedure is proposed to impose curvature on the second-order effects (the Hessian) of an aggregate industry cost function. Curvature is typically imposed on the Hessian (**H**) for input prices by applying a Cholesky's decomposition of **H** and then directly estimating the Cholesky elements using ML or another minimum distance estimator. The additional nonlinear complexity of this approach introduces does not typically bode well with respect to achieving convergence. The proposed Bayesian estimation procedure performs remarkably well in terms of estimating posterior distributions of the Cholesky factors. In addition, applying theoretical priors pertaining to the sign of supply and demand parameters also helps with convergence but also aids in model identification.

A second and related contribution also addresses the potential convergence problems of restricted NEIO-PTA models even if without imposing curvature. The Bayesian hierarchical procedure, which is a model averaging approach suggested by Gelman et al. (2013), introduces external data on published price elasticities of demand and supply into the estimation procedure. This approach provides an efficient means of combining prior information about a parameter’s distribution with external data (D’Errico 2020) and aids in the identification of parameters in highly constrained, non-linear systems of equations. The procedure increases the likelihood of model convergence, and subsequently estimation of the impacts market power has on social welfare.

A third contribution is the simultaneous estimation of welfare effects and the NEIO model. Changes in social welfare are a function of demand and supply elasticities. The posterior distributions of the demand and supply parameters are concomitantly used to generate a posterior distribution for the change in social welfare during model estimation. Hypotheses on the net effect of market power on social welfare follows directly from the generated posterior for changes in welfare.

An empirical example illustrates these improvements to NEIO-PTA model estimation. The focus of the empirical application is on changes in welfare resulting from a concentrated United States (US) beef packing industry. The objective of the empirical example is to compare models with and without restrictions imposed, and to previous NEIO-PTA studies reporting changes in social welfare due to market power.

Literature Review

Indirect cost or profit functions are used frequently in the NEIO literature to model firm cost minimizing or profit maximizing behavior. Indirect approaches are preferred because the input demand and output supply functions are formulated directly from the application of duality results, and due to the relative ease at which theoretical restrictions such as homogeneity and symmetry can be imposed (Chambers, 1988). Generalized Leontief (GL), generalized Leontief-quadratic (GLQ), and translog (TL) functional forms are commonly used to approximate indirect cost or profit functions (Perekhozhuk et al. 2017). Examples include Appelbaum (1982, 1997), Lopez (1985), Schroeter (1988), Arnade, Pick and Gopinath (1998), Morrison Paul (2001), Kamerschen, Klein and Porter (2005), and Schroeter and Azzam (2006), all of which used GL or TL specifications of aggregate industry cost or profit functions.

A commonality shared by these previous NEIO studies is that, while they generally imposed the theoretical restrictions of linear homogeneity and symmetry of cost or profit functions, none verified the concavity of the cost function with respect to input prices, or convexity of the profit function in terms of input and output prices. Concavity of the indirect cost function with respect to input prices implies that input demand curves are downward sloping, while convexity of the indirect profit function implies that output supply curves are upward-sloping and input demand slope downward (Chambers, 1988). If curvature conditions fail, then it is difficult to claim that input use and output supply decisions by firms minimize cost or maximize profit. This issue is especially problematic since output supply elasticities derived from NEIO results are critical parameters for measuring market power and welfare effects. Curvature violations may also result in surprising signs for own-price input demand or output supply elasticities. Of the 27 studies that used NEIO-PTA model, only eight studies verified curvature conditions (Table 1). Many studies did not impose curvature conditions.

On the consumer side, few NEIO studies imposed homogeneity on demands for firm output. Exceptions include Hyde and Perloff (1998) in their analysis of one out of 30 reviewed

(Table 1). NEIO studies modeled consumer demand using a single demand equation, where aggregate quantities consumed are modeled as a function prices and income. Of the 32 studies reviewed, 31 studies did not impose homogeneity in prices or income (Table 1). Failure to impose the condition that consumer demand functions are homogenous of degree zero in prices and consumer expenditure could potentially produce inaccurate estimates of conjectural elasticities, which are another key parameter required for measuring the effects of market power on industry composition and welfare.

Moreover, to measure conjectural elasticities and to test market conditions using NEIO-type models, multiple nonlinear equations depicting consumer demand, firm supply, and firm demand for inputs are required. Errors are also correlated due to cross-equation restrictions on parameters. Estimation of the non-linear system of equations with correlated errors with maximum likelihood or non-linear least squares often fails (Perekhozhuk et al. 2017). Convergence using frequentist estimation procedures is even more difficult to achieve when economic-behavioral restrictions are imposed. Convergence failure makes inference difficult because standard errors are inestimable. Convergence problems may be another reason why many NEIO studies did not impose theoretical restrictions on firm and consumer behavior.

Methods and Procedures

Applebaum's (1982) demand-side NEIO-PTA model states firm i maximizes profit as:

$$\max_{y_i} \pi_i = p(Y) \cdot y_i - c_i(y_i, w) \tag{1}$$

where π_i is firm i's profit, y_i is a firm's output quantity that is identical good across all firms, Y is aggregate output ($Y = \sum_i y_i$), p is packed beef price, $c_i(\cdot)$ is firm i's cost function, and w is a vector of input prices. The corresponding first-order conditions are:

$$\frac{\partial p(Y)}{\partial Y} \cdot \frac{\partial Y}{\partial y_i} \cdot y_i + p(Y) - \frac{\partial c_i(y_i, w)}{\partial y_i} = 0 \tag{2}$$

The conjectural elasticity follows from the first order conditions:

$$\frac{\partial p(Y)}{\partial Y} \cdot Y \cdot \frac{\partial Y}{\partial y_i} \cdot \frac{y_i}{Y} + p(Y) - \frac{\partial c_i(y_i, w)}{\partial y_i} = 0$$

$$\frac{\partial p(Y)}{\partial Y} \cdot \frac{Y}{p(Y)} \cdot p(Y) \cdot \frac{\partial Y}{\partial y_i} \cdot \frac{y_i}{Y} + p(Y) - \frac{\partial c_i(y_i, w)}{\partial y_i} = 0$$

$$\left(\frac{\partial p(Y)}{\partial Y} \cdot \frac{Y}{p(Y)} \cdot \frac{\partial Y}{\partial y_i} \cdot \frac{y_i}{Y} + 1\right) \cdot p(Y) - \frac{\partial c_i(y_i, w)}{\partial y_i} = 0$$

Firm i's cost function, $c_i(y_i, w)$ is a Gorman-polar form:

$$c_i(y_i, w) = y_i \cdot c(w) + g_j(w)$$

where the term $c(w)$ is constant across firms and $g_j(w)$ is firm specific. An inverse supply function, $p(Y)$, depicts aggregate industry output:

$$\left(\frac{\theta}{\eta} + 1\right) \cdot p(Y) - MC = 0$$

$$p(Y) = \frac{MC}{\left(\frac{\theta}{\eta} + 1\right)} \tag{3}$$

where $\left[\frac{\partial p(Y)}{\partial Y} \cdot \frac{Y}{p(Y)}\right]$ is the inverse price elasticity of demand, $[1/\eta]$; and $\left[\frac{\partial Y}{\partial y_i} \cdot \frac{y_i}{Y}\right]$ is a market conjecture (θ) measuring market power. The industry marginal cost function, MC, is derived below using duality results (below). When all firms in an industry are Cournot oligopolists, $\theta = 1$. The industry is perfectly competitive when $\theta = 0$.

A generalized Leontief (GL) cost function is used here to represent aggregate industry costs as a function of a single output (Y), prices, and time. The GL cost function is (Diewert and Wales 1987):

$$\begin{aligned} c(Y, w, t) = {} & \textstyle\sum_j \sum_h b_{jh} \cdot w_j^{0.5} \cdot w_h^{0.5} \cdot Y + \sum_j b_j \cdot w_j + \sum_j b_{jt} \cdot w_j \cdot t \cdot Y + \\ & \textstyle\sum_j \alpha_j \cdot w_j \cdot t + \sum_j \beta_j \cdot w_j \cdot Y^2 + \sum_j \gamma_j \cdot w_j \cdot t^2 \cdot Y + o(\tau) \\ & b_{jh} = b_{hj}, \qquad j, h \in \{K, L, M\} \end{aligned} \tag{4}$$

where K, L, and M are capital, labor, and intermediate inputs, respectively, w are input prices, p is the output price, t indexes time, b and d are slope shifters, and $o(\tau)$ is a truncation reminder of expansion with zero mean and constant variance (Lambert et al., 2020). The b are symmetric

$(b_{jh} = b_{hj})$. Input prices are restricted to be homogeneous of degree zero $\left(\sum_n b_{jn} = 0\right)$. The marginal cost function of Equation (3) follows by differentiating Equation (4) with respect to output:

$$MC = \frac{\partial c(w,y,t)}{\partial Y} = \sum_j \sum_h b_{jh} \cdot w_j^{0.5} \cdot w_h^{0.5} + \sum_j b_{jt} \cdot w_j \cdot t + 2 \cdot \sum_j \beta_j \cdot w_j \cdot Y + \sum_j \gamma_j \cdot w_j \cdot t^2 + o \tag{5}$$

where o is an independent and identically distributed error derived from the differentiation of the truncation reminder.

Applying Shephard's lemma, the corresponding input demand equations are:

$$\frac{x_j}{Y} = \sum_h b_{jh} \cdot \left(\frac{w_h}{w_j}\right)^{0.5} + \frac{b_j}{Y} + b_{jt} \cdot t + \alpha_j \cdot \frac{t}{Y} + \beta_j \cdot Y + \gamma_j \cdot t^2 + \delta_j + \nu \tag{6}$$

where δ_j is an additional parameter Diewert and Wales introduce and ν is the truncation reminder distributed with zero mean and constant variance. These additional parameters add flexibility to the system by adding $\sum_j \delta_j w_j Y$ to the right hand side of Equation (4). Input demands are normalized by output to simplify the estimation procedure.

Imposing Concavity and Homogeneity conditions

Concavity is imposed on Equation (4) following Diewert and Wales (1987)'s and Ryan and Wales (2000)'s Cholesky factorization procedure. Imposing curvature ensures that the Hessian is negative semidefinite, a feature that corresponds with downward-sloping input demands. Curvature can only be imposed locally with the GL cost function. Imposing curvature locally at a specific reference point does not destroy the flexibility of the cost function's functional form. Local concavity is imposed by normalizing all prices, inputs, and output by their mean. The khth element of the cost function's Hessian $(\mathbf{H})$ on the average of data is:

$$h_{jh} \begin{cases} \frac{b_{jh}}{2}, & j \neq h \\ -\sum_{n \neq h} \frac{b_{jh}}{2} = \frac{b_{jj}}{2}, & j = h \end{cases}$$

The concavity condition is satisfied when:

$$b_{jh} = -(\mathbf{DD}')_{jh}$$

where $\mathbf{D}$ is a lower triangular matrix with elements d_{jh}. This procedure guarantees concavity of the cost function at t^*. The b_{kh} parameters enter the elements of $\mathbf{D}$ as Cholesky factors:

$$\mathbf{D} = \begin{bmatrix} d_{KK} & & \\ d_{LK} & d_{LL} & \\ d_{MK} & d_{ML} & d_{MM} \end{bmatrix}$$

with

$$b_{KK} = -d_{KK}^2 \qquad b_{LL} = -(d_{LK}^2 + d_{LL}^2)$$

$$b_{LK} = -d_{KK}d_{LK} \qquad b_{ML} = -(d_{LK}d_{MK} + d_{LL}d_{ML})$$

$$b_{MK} = -d_{KK}d_{MK} \qquad b_{MM} = -(d_{MK}^2 + d_{ML}^2 + d_{MM}^2)$$

where homogeneity in input prices ($\sum_n b_{jn} = 0$ and $b_{jh} = b_{hj}$ by the symmetry condition) is imposed as:

$$b_{MK} = -(b_{KK} + b_{LK})$$

$$b_{ML} = -(b_{LL} + b_{LK})$$

$$b_{MM} = -(b_{MK} + b_{ML})$$

The demand elasticity η is derived from the log-log linear equation:

$$\ln(Y) = \tau_0 + \eta \cdot \ln(p) + \lambda_1 \cdot \ln(p_{pork}) + \lambda_2 \cdot \ln(p_{broiler}) + \lambda_3 \cdot \ln(PMCE)$$
$$+\tau_1 \cdot \ln(POP) + \tau_2 \cdot t \tag{7}$$

where p_{pork} is pork price, $p_{broiler}$ is broiler composite price that is composite value based prices of while birds and chicken parts, Y is packaged beef; $PMCE$ is US expenditures on meat, POP is population, t is a yearly trend, η is the price elasticity of demand for beef, and τ and λ are parameters cross-price elasticities for pork and broilers. The homogeneity of degree zero requirement is imposed with the restriction $\eta + \lambda_1 + \lambda_2 + \lambda_3 = 0$. This restriction is imposed as:

$$\ln(Y) = \tau_0 + \eta \cdot \ln\left(\frac{p}{PMCE}\right) + \lambda_1 \cdot \ln\left(\frac{p_{pork}}{PMCE}\right) + \lambda_2 \cdot \ln\left(\frac{p_{broiler}}{PMCE}\right)$$
$$+\tau_1 \cdot \ln(POP) + \tau_2 \cdot t \tag{8}$$

and the meat expenditure elasticity, λ_3 can be recovered as $\lambda_3 = -(\eta + \lambda_1 + \lambda_2)$. All price variables are valued by dollars and deflated by the GDP deflator (2015=100). In total, there are six endogenous variables; x_K, x_L, x_M, Y, and p, and the other variables are exogenous.

Social Welfare Loss under Oligopoly

The method to measure social welfare loss follows Bhuyan and Lopez (1995) and Arnade, Pick and Gopinath (1998). This parametric procedure represents demand and supply curves with the iso-elastic functions:

$$\text{Demand Curve: } Y = p^{\eta}$$

$$\text{Supply Curve: } Y = MC^{\varepsilon} \tag{9}$$

where Y is industry output supplied and demanded; p is output price; MC is industry marginal cost to produce output; η is the price elasticity of demand; and ε is the price elasticity of supply.

Oligopoly output (Y_o) is derived by substituting the oligopoly price of Equation (3) into the industry demand equation:

$$Y_o = \left(\frac{MC}{\left(\frac{\theta}{\eta} + 1\right)}\right)^{\eta} \tag{10.1}$$

The industry marginal cost in Equation (10.1) is from the industry supply curve:

$$Y_o = \left(\frac{Y_o^{\frac{1}{\varepsilon}}}{\left(\frac{\theta}{\eta} + 1\right)}\right)^{\eta} \tag{10.2}$$

Solving Equation (10.2) for Y_o, industry oligopoly output is:

$$Y_o = \left(\frac{\theta}{\eta} + 1\right)^{\frac{\eta \cdot \varepsilon}{\eta - \varepsilon}} \tag{10.3}$$

Industry welfare loss is calculated as the area of the deadweight loss, and found by integrating under the demand curve as the difference between perfect competition and oligopoly:

$$L = \int_{Y=Y_o}^{Y=Y_{PC}} \left(Y^{\frac{1}{\eta}} - Y^{\frac{1}{\varepsilon}}\right) dY \tag{11}$$

where L is the industry welfare loss; the terms in inside the parentheses are inverse demand and supply functions respectively from Equation (9); Y_{PC} is the industry equilibrium output level under the perfectly competitive market assumption; and Y_o is the industry equilibrium output level under the oligopoly assumption of NEIO model. Y_{PC} equals '1' because the parameter θ of Equation (10.3) is '1' in the perfectly competitive market condition. This method of calculating industry welfare loss only requires the demand elasticity, η, from the output demand function (Equation (8)) and the supply elasticity, ε from the inverse output supply function. Using Equation (3) and (5), the supply elasticity ε is:

$$\varepsilon = \left(\frac{\partial p(Y)}{\partial Y} \cdot \frac{Y}{p}\right)^{-1} = \frac{\left(\frac{\theta}{\eta} + 1\right)}{\sum_j 2\beta_j w_j} \cdot \frac{p}{Y} \tag{12}$$

Following Bhuyan and Lopez (1995), the actual dollar value of the industry welfare loss due to the industry oligopoly is $(S \cdot L)/(y_o \cdot p_o)$, where S is the observed dollar sales in the industry. From the actual welfare loss formula, welfare loss is calculated as $L/(y_o \cdot p_o)$.

Empirical procedures

The system of equations includes the market supply (Equation 3), marginal cost (Equation 5), input demands (Equation 6), and output demand (Equations 8). The system of equations is:

$$\mathbf{Y} \sim MVN\big(\boldsymbol{\mu}, \mathrm{diag}(\boldsymbol{\sigma})\, \boldsymbol{\Omega}\, \mathrm{diag}(\boldsymbol{\sigma})\big) \tag{13}$$

$$\mathbf{Y} = \begin{bmatrix} p \\ x_K/Y \\ x_L/Y \\ x_M/Y \\ \ln(Y) \end{bmatrix} \tag{14}$$

where **Y** is a vector of the left-hand-side variables for the NEIO model that consists of Equation 3, 6, and 8, **μ** is a mean response vector that is the right-hand-side of Equation 3, 6, and 8, **σ** is a conformable matrix of model error standard deviations, and **Ω** is a correlation matrix that follows Lewandowski-Kurowicka-Joe (LKJ) distribution (Lewandowski, Kurowicka, and Joe 2009). Preand post-multiplying the vector of scalars with the correlation matrix ensures a positive-semidefinite residual error covariance matrix.

R-Stan's Hamiltonian Monte Carlo No U-turn Sampler (HMC-NUTS) (Stan Development Team 2022) is used to generate posterior distributions of the model parameters. The parameter priors are:

$$\left(d_{jh}, b_j, b_{jt}, \alpha_j, \gamma_j, \delta_j\right) \sim \text{Normal}(0, 10),$$

$$\beta_j \sim N_0^{\infty}(0, 10),\ \theta \sim \text{Beta}(2, 2),$$

$$(\tau_0, \tau_1, \tau_2, \lambda_1, \lambda_2) \sim \text{Normal}(0, 10),$$

$$\boldsymbol{\sigma} \sim \text{Exponential}(1),\ \boldsymbol{\Omega} \sim \text{LKJcorr}(2)$$

where $d_{jh}, b_j, b_{jt}, \alpha_j, \gamma_j, \delta_j$, and β_j are cost-shifting parameters for the marginal cost and input demand functions; θ is the oligopoly market power parameter; and $\tau_0, \tau_1, \tau_2, \lambda_1$, and λ_2 are demand-shifting parameters for the demand function. The prior for β_j is truncated positive to ensure the supply curve is upward sloping. The parameter θ is bounded '0' to '1', thus the prior for θ specified as beta distribution. Following the McElreath (2020)'s suggestion, the priors for $\boldsymbol{\sigma}$ are the exponential distribution with the rate parameter of '1'. This prior provides no more information than an average standard deviation from a mean. Lastly, the LKJ prior for $\boldsymbol{\Omega}$ is set to '2'.

Hierarchical Priors

Hierarchical priors are used to identify US beef elasticities for demand (η) and supply (ε). The beef price elasticity of demand (supply) should be negative (positive). One could simply take that average of published sources and use that value as a strong prior. The model averaging approach taken here, which is due to Gelman et al. (2013), uses elasticities reported in previous studies as data, which are presumably drawn from a normal prior distribution. In other words, the sampling variability of reported elasticities is used to generate hyper-priors, which are estimated simultaneously with all other model parameters.

Assume there are S previous studies ($s \in \{1,2,\cdots,S\}$ and $u \in \{1,2,\cdots,U\}$)) reporting US beef price elasticity of demand and supply, respectively. Study S and U's report elasticity parameters of demand η_s and supply ε_u, respectively. The data generating process are assumed to be normally distributed with standard errors σ_{η_s} and σ_{ε_u} as:

$$\eta_s|\vartheta_{\eta_s},\sigma_{\eta_s} \sim \mathrm{Normal}\left(\vartheta_{\eta_s},\sigma_{\eta_s}\right)$$

$$\varepsilon_u|\vartheta_{\varepsilon_u},\sigma_{\varepsilon_u} \sim \mathrm{Normal}\left(\vartheta_{\varepsilon_u},\sigma_{\varepsilon_u}\right) \tag{15}$$

where σ_{η_s} and σ_{ε_u} are the standard deviations reported in study S and U. Now, the means of η_s, ε_u can be expressed by a random variable under the normal distribution:

$$\vartheta_{\eta_s} \sim \mathrm{Normal}\left(\bar{\eta},\sigma_{\bar{\eta}}\right)$$

$$\vartheta_{\varepsilon_u} \sim \mathrm{Normal}(\bar{\varepsilon}\,,\sigma_{\bar{\varepsilon}}) \tag{16}$$

where $\bar{\eta}$ and $\bar{\varepsilon}$ are means of ϑ_{η_s} and $\vartheta_{\varepsilon_u}$, respectively that represent a common factor (belief) of explaining the elasticity across s's and u's study; $\sigma_{\bar{\eta}}$ and $\sigma_{\bar{\varepsilon}}$ are standard deviations of $\bar{\eta}$ and $\bar{\varepsilon}$, respectively that represents the difference of data and methodologies across *s*th and *u*th studies. In estimation procedure, $\bar{\eta}$ and $\bar{\varepsilon}$ is recovered by reparameterizing Equation (16) as:

$$\vartheta_{\eta_s} = \bar{\eta} + \sigma_{\bar{\eta}} \cdot z_{1s}$$

$$\vartheta_{\varepsilon_u} = \bar{\varepsilon} + \sigma_{\bar{\varepsilon}} \cdot z_{2u} \tag{17}$$

$$(\bar{\eta},\ \bar{\varepsilon}) \sim \mathrm{Normal}(0,10),\ \left(\sigma_{\bar{\eta}},\sigma_{\bar{\varepsilon}}\right) \sim \mathrm{Exponential}(1),\ (z_{1s},z_{2u}) \sim \mathrm{Normal}(0,1)$$

The hierarchical priors are $\bar{\eta}$ and $\sigma_{\bar{\eta}}$ for the demand elasticity, and $\bar{\varepsilon}$ and $\sigma_{\bar{\varepsilon}}$ for the supply elasticity allowing to use a common belief across the previous studies as priors. As priors of this study, η and ε are applied by:

$$\eta \sim \mathrm{Normal}\left(\bar{\eta},\sigma_{\bar{\eta}}\right)$$

$$\varepsilon \sim \mathrm{Normal}(\bar{\varepsilon},\sigma_{\bar{\varepsilon}}) \tag{18}$$

where η and ε are the price elasticity parameters on this study that takes into consideration of previous literature. Bayesian estimation procedure requires Equations (15, 17, and 18). Table 2 and 3 provide mean and standard errors from previous literature that measured US beef price elasticity of demand and supply. Due to limited number of studies that measured US beef supply elasticity, this study also includes the supply elasticities regarding long run supply elasticity for US cattle. The standard errors are calculated from t-values from the previous studies when there is no standard errors reported. The mean and standard errors provided from the previous literature are used as the data from Table 2 (for η_j and σ_{η_s}), and from Table 3 (for ε_s, and σ_{ε_u}) to estimate hierarchical priors.

Table 2. Previous Literature Estimating US Beef Price Elasticity of Demand

	Year	Author(s)	Mean	Standard Error
1	1983	Chavas	-0.617	0.060
2	1985	Huang	-0.617	0.048
3	1988	Schroeter	-0.527	0.064
4	1989	Moschini and Meilke	-1.050	0.064
5	1993	Brester and Wohlgenant	-0.450	0.130
6	1995	Brester and Schroeder	-0.560	0.074
7	1996	Park et al.	-0.438	0.164
8	1997	Kinnucan et al.	-0.444	0.081
9	2000	Huang and Lin	-0.354	0.032
10	2000	Chavas	-0.524	0.114
11	2001	Bryant and Davis	-0.597	0.133
12	2001	Lusk et al.	-0.633	0.180
13	2007	Tonsor and Marsh	-0.663	0.397
14	2010	Tonsor, Mintert, and Schroeder	-0.420	0.116
15	2011	Tonsor and Olynk	-0.493	0.110

Table 3. Previous Literature Estimating US Beef and Cattle Price Elasticity of Supply

	Year	Author(s)	Category of Elasticity	Mean	Standard Error
1	1985	Shonkwiler and Hinckley	Feeder Cattle (Long Run)	0.630	0.120
2	1988	Schroeter	Beef	1.689	0.145

3	1994	Marsh	Fed Cattle (Long Run)	3.240	0.041
4	1996	Brester	Beef (Long Run)	3.310	0.376
5	1997	Buhr and Kim	Slaughter Cattle (Long Run)	1.951	0.196
6	2000	Sarmiento and Allen	Fed Cattel (Long Run)	0.330	0.073
7	2001	Paul	Beef	0.951	0.049
8	2003	Marsh	Slaughter Cattle (Long Run)	0.593	0.093
9	2016	Kaiser	Beef	0.144	0.083
10	2017	Suh and Moss	Cattle	0.119	0.035
11	2019	Jeong	Fed Cattle (Long Run)	4.130	1.530
12	2020	McKendree et al.	Fed Cattle (Long Run)	0.240	0.100
13	2022	Hutchins and Hueth	Slaughter Cattle (Long Run)	0.821	0.149

Data

Monthly and annual data are from several data sources covering 1987 to 2019 period (Table 2). All prices and costs were converted to real values using the GDP deflator from Federal Reserve Bank Economic Research (FRED, 2022). US population was obtained from FRED (FRED, 2022). Annual US beef consumption is from the federally inspected beef production of Livestock and Meat Domestic Data compiled by the US Department of Agriculture: Economic Research Service (USDA-ERS 2022). Price data for meat including beef, pork, and broiler composites are from historical retail meat values reported by USDA-ERS (USDA-ERS, 2022). US personal meat consumption expenditures on beef, pork, and poultry are from the National Income and Product Accounts curated by the Bureau of Economic Analysis (BEA, 2022). Data on input quantities and prices for the US animal slaughtering and processing are from the Division of Productivity Research and Program Development tables reported by the US Bureau of Labor Statistics (BLS, 2022). US beef packing industry input demands for labor, capital, and intermediate are from employment, capital input, and intermediate purchases from the BLS database (BLS, 2022). Input prices were calculated using labor compensation costs, capital costs, and intermediate material costs divided by employment, capital inputs, and intermediate inputs from the BLS database (BLS, 2022), respectively. Table 1 reports the descriptive statistics for this study. The trend variable (t) denotes years, spanning 1 to 33 (33 years: 1987 – 2019).

Table 4. Descriptive Statistics

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
GDP deflator	2015 = 100, quarterly, seasonally adjusted	81	15	54	108
US population (POP)	Thousands, monthly	288726	26491	241857	329314
US beef consumption (Y)	Millions of Pounds, monthly	2100	171	1677	2512
US beef price (p)	Cents per pound, retail weight equivalent, monthly	478	65	380	641
US pork price (p_{pork})	Cents per pound, retail weight equivalent, monthly	346	24	292	424
US broiler composite price ($p_{broiler}$)	Cents per pound, retail weight equivalent, monthly	206	19	173	271
US personal consumption expenditures for meat ($PMCE$)	Millions of dollars, monthly, seasonally adjusted	110	12	94	135
Capital input (x_K)	2007 = 100, annually	93	16	65	123
Intermediate input (x_M)	2007 = 100, annually	100	7	84	112
Labor input (x_L)	2007 = 100, annually	95	7	78	104
Capital price (w_K)	2007 = 100, annually	66	36	5	122
Intermediate price (w_M)	2007 = 100, annually	104	11	84	133
Labor price (w_L)	2007 = 100, annually	97	7	84	113

Note: The number of observations is 396 for monthly variables, 132 for quarterly and 33 for annual variables.

In the empirical procedure of this study, all price variables are deflated by the GDP deflator and then normalized by mean of each variable to impose the local concavity condition on the indirect cost function. The Bayesian estimation is conducted by month, so the number of observation in the result is 396.

Results

The results of the non-hierarchical and Bayesian hierarchical models are reported in Table 5 and 6. All non-hierarchical models converged, as evidenced by the $\hat{R}$ values and effective sample sizes (Appendix I and II). For the consumer side, estimated beef demand elasticities (η) are all negative. The parameters of substitutes for beef (pork: λ_1 and broiler: λ_2), US meat expenditure (λ_3) and US population (τ_1) are expected to have positive signs, but only the models imposing the homogeneity condition report positive signs appropriately.

Table 5. Posterior Means and Standard Deviations (Non-Hierarchical Model)

Para-meter	No Restriction		Homogeneity in Output Demand		Concavity in Output Cost		Homogeneity and Concavity	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.	Mean	S.D.
b_{KK}	-0.002	0.001	0.002	0.001	-0.003	0.001	-0.002	0.001
b_{LK}	0.025	0.007	0.048	0.006	0.012	0.003	0.011	0.003
b_{MK}	-0.023	0.007	-0.049	0.006	-0.010	0.003	-0.010	0.002
b_{LL}	-0.051	0.027	-0.028	0.025	-0.078	0.022	-0.082	0.021
b_{ML}	0.025	0.030	-0.020	0.026	0.066	0.021	0.070	0.020
b_{MM}	-0.002	0.034	0.069	0.028	-0.056	0.020	-0.061	0.018
b_K	0.147	0.038	0.253	0.038	0.127	0.037	0.170	0.038
b_L	-0.214	0.073	-0.036	0.071	-0.252	0.070	-0.140	0.073
b_M	-0.159	0.081	-0.309	0.093	-0.098	0.073	-0.173	0.084
b_{Kt}	-0.004	0.002	-0.006	0.002	-0.005	0.002	-0.008	0.002
b_{Lt}	-0.040	0.021	-0.044	0.019	-0.017	0.017	0.008	0.015
b_{Mt}	0.010	0.016	0.024	0.014	-0.009	0.012	-0.023	0.012
α_K	0.224	0.006	0.229	0.006	0.227	0.006	0.235	0.006
α_L	0.071	0.013	0.076	0.012	0.066	0.012	0.069	0.011

α_M	-0.018	0.011	-0.012	0.012	-0.013	0.011	-0.004	0.011
β_K	4.17E-04	3.92E-04	4.50E-04	4.18E-04	3.50E-04	3.38E-04	2.77E-04	2.67E-04
β_L	0.043	0.009	0.036	0.008	0.034	0.007	0.018	0.006
β_M	0.014	0.004	0.017	0.005	0.018	0.004	0.027	0.004
γ_K	0.018	0.002	0.019	0.002	0.017	0.002	0.018	0.002
γ_L	-0.016	0.006	-0.014	0.005	-0.023	0.005	-0.029	0.005
γ_M	0.015	0.005	0.009	0.005	0.021	0.005	0.023	0.005
δ_K	0.609	0.041	0.500	0.041	0.628	0.040	0.580	0.041
δ_L	1.168	0.078	0.993	0.076	1.204	0.075	1.088	0.078
δ_M	1.133	0.087	1.268	0.101	1.076	0.080	1.145	0.092
η	-0.342	0.026	-0.504	0.040	-0.343	0.026	-0.513	0.040
λ_1	-0.010	0.014	0.047	0.020	-0.014	0.013	0.051	0.020
λ_2	0.003	0.018	0.080	0.026	4.60E-04	0.017	0.081	0.026
τ_1	-0.306	0.126	1.009	0.160	-0.340	0.124	0.960	0.161
λ_3	-0.262	0.043	- [b]	-	-0.266	0.042	-	-
τ_2	0.230	0.027	-0.067	0.029	0.236	0.026	-0.060	0.030
τ_0	-0.238	0.027	0.069	0.030	-0.244	0.027	0.062	0.031
WAIC	-8777		-8484		-8778		-8450	

Note: See Appendix I for convergence statistics. The number of observations is 396.

[a] Standard deviations.

[b] Means and standard deviations of λ_3 are omitted because λ_3 is restricted by the homogeneity condition of the output demand function. λ_3 can be recovered by $[\lambda_3 = -(\eta + \lambda_1 + \lambda_2)]$.

Table 6. Posterior Means and Standard Deviations (Bayesian Hierarchical Model)

Para-meter	No Restriction		Homogeneity in Output Demand		Concavity in Output Cost		Homogeneity and Concavity	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.	Mean	S.D.
b_{KK}	-0.002	0.001	0.002	0.001	-0.003	0.001	-0.002	0.001
b_{LK}	0.025	0.007	0.047	0.006	0.012	0.003	0.011	0.003
b_{MK}	-0.023	0.007	-0.049	0.006	-0.010	0.003	-0.009	0.002
b_{LL}	-0.051	0.027	-0.028	0.025	-0.078	0.022	-0.081	0.021
b_{ML}	0.026	0.029	-0.020	0.026	0.066	0.021	0.069	0.019
b_{MM}	-0.003	0.033	0.069	0.029	-0.056	0.020	-0.060	0.018
b_K	0.150	0.038	0.255	0.038	0.130	0.035	0.172	0.038
b_L	-0.208	0.071	-0.034	0.072	-0.247	0.067	-0.137	0.073
b_M	-0.154	0.082	-0.301	0.093	-0.093	0.073	-0.168	0.085
b_{Kt}	-0.005	0.002	-0.006	0.002	-0.005	0.002	-0.008	0.002
b_{Lt}	-0.039	0.021	-0.044	0.019	-0.017	0.017	0.008	0.016

b_{Mt}	0.009	0.016	0.024	0.014	-0.009	0.013	-0.023	0.012
α_K	0.225	0.007	0.229	0.006	0.228	0.006	0.235	0.006
α_L	0.071	0.013	0.076	0.012	0.066	0.012	0.069	0.011
α_M	-0.017	0.011	-0.012	0.012	-0.012	0.010	-0.004	0.011
β_K	4.20E-04	3.90E-04	4.49E-04	4.25E-04	3.49E-04	3.24E-04	2.77E-04	2.64E-04
β_L	0.042	0.009	0.036	0.008	0.034	0.007	0.018	0.006
β_M	0.014	0.004	0.017	0.005	0.018	0.004	0.027	0.004
γ_K	0.018	0.002	0.019	0.002	0.017	0.002	0.018	0.002
γ_L	-0.017	0.006	-0.014	0.006	-0.023	0.005	-0.029	0.005
γ_M	0.015	0.005	0.009	0.005	0.021	0.005	0.023	0.005
δ_K	0.605	0.041	0.498	0.040	0.624	0.039	0.578	0.041
δ_L	1.161	0.075	0.991	0.076	1.199	0.072	1.085	0.079
δ_M	1.128	0.088	1.260	0.101	1.070	0.079	1.140	0.092
η	-0.346	0.026	-0.507	0.040	-0.347	0.026	-0.516	0.039
λ_1	-0.010	0.014	0.048	0.021	-0.013	0.014	0.051	0.021
λ_2	0.003	0.018	0.081	0.027	0.000	0.017	0.081	0.026
τ_1	-0.315	0.124	1.012	0.161	-0.344	0.122	0.959	0.160
λ_3	-0.261	0.043	- [b]	-	-0.265	0.043	-	-
τ_2	0.232	0.026	-0.068	0.029	0.237	0.026	-0.060	0.030
τ_0	-0.240	0.027	0.070	0.030	-0.245	0.027	0.061	0.030
WAIC	-8776		-8484		-8729		-8450	

Note: See Appendix II for convergence statistics. The number of observations is 396.

[a] Standard deviations.

[b] Means and standard deviations of λ_3 are omitted because λ_3 is restricted by the homogeneity condition of the output demand function. λ_3 can be recovered by $[\lambda_3 = -(\eta + \lambda_1 + \lambda_2)]$.

For the estimation results of the indirect cost function, it is necessary to check the violation of concavity condition at each observation by inspecting b_{jh}. For all observations, the curvature of the indirect cost function is only valid for the model where concavity was imposed (Table 7). The models that did not impose concavity violate concavity at some or all data points. Thus, the input price parameters (b_{jh}) are consistent with cost minimizing behavior.

Table 7. Number of Observations that Violate the Concavity Condition

Model	Number of Concavity Violations
Non-Hierarchical Model	
No Restriction	66
Homogeneity in Output Demand	369
Concavity in Output Cost	0
Homogeneity and Concavity	0
Bayesian Hierarchical Model	
No Restriction	369
Homogeneity in Output Demand	369
Concavity in Output Cost	0
Homogeneity and Concavity	0

Note: The number of observations is 396.

US beef demand and supply elasticities, market power, and welfare loss rate are reported in Table 8. The demand elasticity (η) and market power (θ) are largely influenced by imposition of the homogeneity condition in beef demand, but not by the concavity condition. The demand elasticities and market power estimates of the models with homogeneity imposed are larger than the estimates from the models that did not impose homogeneity. Social welfare loss ($\dot{L}$) is also affected by the imposition of homogeneity in prices and expenditures for demand. On the contrary, the supply elasticity (ε) is lower when concavity is imposed. Imposing concavity increased the market power parameter and the social welfare loss estimate. When both homogeneity and concavity are imposed, market power and social welfare decrease significantly.

A comparison of the Bayesian hierarchical and non-hierarchical estimates does not reveal many distinct differences in parameter estimates. The Bayesian hierarchical model is expected to be a better model because the model also uses information from previous literature regarding the US beef demand and supply elasticities. However, the widely applicable information criterion

(WAIC) also does not provide significant differences between the hierarchical and the non-hierarchical models.

Compared to other NEIO studies that used Applebaum's (1982) model and Bhuyan and Lopez's (1995) method to measure social welfare loss, the demand elasticity imposed by the homogeneity of this study is in the range of other NEIO studies (Table 8) and previous literature that estimated US beef demand elasticities (Table 2). Compared with other NEIO studies (Table 8) that measured supply elasticity, the supply elasticity of this study is relatively lower than other studies but it is much closer to reported supply elasticities from previous literature (Table 3). The market power and social welfare loss estimated in this study are larger than the other NEIO studies that used the same model. Without the theoretical restrictions, the market power and social welfare loss measures are similar to Arnade, Pick and Gopinath (1998). However, when imposing theoretical restrictions, market power and social welfare loss rate are larger than other studies. This result is weak evidence that previous NEIO studies may have underestimated market power and social welfare loss because homogeneity in US beef (meat) demand and concavity in US beef (meat) packing cost conditions were not imposed. These results are expected because output demand and supply elasticities are closely related to market power and ensuing loss in social welfare. The period of analysis may be an explanation of why market power estimates are higher. Previous NEIO studies used industry aggregated data from 1960 to 1980, but this study uses data from 1987 to 2019. According to MacDonald (2018), the largest four firm shares (CR4) of the US steer and heifer slaughter industry changed from 36% to 85% during 36 years (1977 – 2012). The US beef packing industry has become more concentrated. Nevertheless, the larger valued estimates of market power and social welfare loss rate reported here should be interpreted carefully. For example, this study did not consider the cost efficiency effects of concentrated market structures.

Table 8. Posterior Means and Standard Deviation for Major Parameters and Comparison with Other Studies

Model	Demand Elasticity (η)		Supply Elasticity (ε)		Market Power (θ)		Welfare Loss Rate ($\dot{L}$)	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.	Mean	S.D.
Non-Hierarchical Model								
No Restriction	-0.342	0.026	0.932	0.016	0.305	0.025	0.230	0.027
Homogeneity in Output Demand	-0.504	0.040	0.975	0.019	0.451	0.039	0.348	0.044
Concavity in Output Cost	-0.343	0.026	0.930	0.016	0.310	0.025	0.242	0.026
Homogeneity and Concavity	-0.513	0.040	0.962	0.018	0.469	0.038	0.389	0.043
Bayesian Hierarchical Model								
No Restriction	-0.347	0.026	0.932	0.016	0.310	0.025	0.234	0.027
Homogeneity in Output Demand	-0.507	0.040	0.974	0.019	0.454	0.037	0.351	0.042
Concavity in Output Cost	-0.347	0.026	0.930	0.016	0.314	0.025	0.245	0.026
Homogeneity and Concavity	-0.516	0.039	0.961	0.019	0.472	0.037	0.392	0.043
Other NEIO Studies								
Schroeter (1988): US beef	-0.527	0.064	1.689	0.145	0.014 – 0.042	0.013 – 0.006	-	-
Bhuyan and Lopez (1995): US meat	-[b]	-	-	-	-	-	0.014	-
Bhuyan and Lopez (1997): US meat	-0.528	-	1.585	-	0.219	-	-	-
Bhuyan and Lopez (1998): US meat	-0.528	0.051	-4.167	0.145	0.219	0.024	0.050	-
Arnade, Pick and Gopinath (1998): US meat	-0.230	0.091	< 1	-	0.260	0.105	0.205	-

Note: See Appendix I, and II for convergence statistics. The number of observations is 396.

[a] Standard deviations for this study (Bayesian) and standard errors for other NEIO studies (frequentist).

[b] Values that were not reported or not applicable.

Conclusions

This study estimated market power and social welfare loss in the US beef packing industry. Imposition of zero-degree homogeneity of output demand and the concave curvature of indirect cost are important to identify the NEIO model properly. However, due to practical reasons with respect to estimation procedures, these theoretical restrictions have been generally ignored. Unlike other NEIO studies, this study imposed the zero-degree homogeneity on US beef demand and the concave curvature on indirect cost of US beef production at the industry level.

The results show that the homogeneity and the concavity condition affect the US beef elasticities of demand and supply. The result also confirms that the market power and the social welfare loss are influenced by the theoretical restrictions. When both restrictions of homogeneity and concavity are imposed, the market power and the social welfare loss deteriorate more than imposing either theoretical restriction individually. Compared with other NEIO studies, the estimated market power and social welfare loss from this study are significantly higher due to the theoretical restrictions. For the comparison of Bayesian hierarchical and non-hierarchical models, this study cannot find a significant difference between the two models.

The purpose of this study is to confirm the effect of imposing the theoretical restriction under the simple NEIO model. This study uses Appelbaum (1982)'s classic NEIO model, thus the limitations of this study are detailed by other NEIO models that expand Appelbaum (1982). First, this study does not consider the cost efficiency effects of market concentration, oligopsony power, and flexible proportion technology of the cost function. These issues were already covered by other NEIO studies (Azzam and Pagoulatos 1990; Azzam 1997; Raper, Love and Shumway 2000; Park, Chung and Raper 2017). Marketing channels from beef packers to individual consumers were also ignored in this study. There may be oligopsony power between packers in procuring slaughter cattle and selling processed beef, and beef wholesaling retailers.

Due to the data availability, different beef cuts and qualities were aggregated into one identical beef product for the NEIO model. In addition, there are data discrepancies between demanded beef quantity, meat retail prices, and meat expenditure. The meat retail prices and expenditure data for US beef demand function represent US individual consumers. Food service sectors representing outside of household are excluded from the price and expenditure data set. While the demanded beef quantity covers all sectors including household and outside of household sectors. These aggregated data and data discrepancies may lead to biased and inaccurate estimates for market power and social welfare change.

Lastly, comparisons of market power and social welfare from other NEIO studies should be conducted on the same data within the same period. But there were difficulties to get the used data to replicate the previous literature. These previous studies used the unique data set provided by the authors. The hypothesis tests for statistical comparison with the measures from previous studies are also required.

For future studies, a more extended NEIO model should impose the homogeneity of output demand and curvature conditions of cost, production, or profit function to get appropriate results.

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CHAPTER III

MEASURING MARKET COMPETITIVENESS: AN APPLICATION EXAMINING AN INTERNATIONAL BEEF MARKET

Abstract

This paper proposes a method for measuring the degree of rivalry in contested markets. Quantifying market competitiveness is important for distributional and legal reasons. From the perspective of consumers in importing countries, an exporter's ability to influence market prices by controlling the supply of intermediate goods for food processors, or final products for retail markets, affects consumer welfare. Exporters compete with each other differently by marking up export good price level, or manipulating quantity level, while considering their rivals' conjectural behaviors. The proposed rivalry index is bounded between '0' to '1' indicating the market is perfectly competitive or perfectly collusive (cartel). Development of the index follows from a comparative static analysis of rivalry best response functions under Cournot and Stackelberg leader-follower assumptions in the case of quantity competition, and Bertrand and Stackelberg leader-follower assumptions under price competition. An empirical example estimates the degree of rivalry between the United States and Australia in the imported beef markets of South Korea and Japan. The results suggest that the preferred models for the Korean and the Japanese markets are quantity and price cartels, respectively. However, the rivalry index does not provide evidence of collusion between the United States and Australia. Trade barriers including high rated tariffs and safeguards and competition with importing country's domestic beef suppliers may hinder the collusive behaviors of the US and Australia.

Introduction

Determining the degree of market power is important for gauging how far a market is from one of perfect competition, and concomitantly the impacts of market power on social welfare. Policies and regulations designed to mitigate collusive behavior between firms or exporters benefit from knowing the degree of collusion between rivals and how collusion occurs[1]. This paper extends New Empirical Industrial Organization (NEIO) results to develop a rivalry index. The index measures the degree of competitiveness between firms or exporters in contested markets. The proposed index complements existing NEIO market-competitive measures. The rivalry index characterizes the intensity of competition under Bertrand, Cournot, cartel, and Stackelberg (BCCS) price and quantity assumptions. The proposed index is developed from a comparative static analysis of the exporters' profit functions under BCCS assumptions and the concomitant best response functions.

The index complements previous NEIO methods used to gauge market competitiveness by quantifying the intensity of collusion between rivals. Similar to conjectural elasticities derived under NEIO an assumption, the rivalry index is bounded between '0' and '1', with '1' indicating the market is perfectly competitive and '0' indicating a cartel structure. Intermediate values correspond with oligopolistic behavior. One advantage of the rivalry index, and the approach used to estimate it, is the relative ease at which it is calculated. The index can also be used to calculate the degree of collusion between rivals using the published results of previous studies. A proof-of-concept application concludes, which uses a Bayesian approach to determine the degree to which United States (US) and Australian beef exports to South Korea and Japan can be characterized as a BCCS market structure.

[1] Firms and exporters are used interchangeably.

Literature Review

There are three approaches for determining how competitive markets are (Reimer and Stiegert 2006). All of these approaches stem from the exporter's first order conditions for profit maximization. The first approach is the pricing-to-market method (Krugman 1987; Knetter 1989). This procedure determines if exporters price-discriminate. Price discrimination occurs when exporters make pricing decisions that affect bilateral exchange rates, which is an indicator of market power. A drawback of the pricing-to-market approach is that it cannot discern the degree, or intensity, of rivalry or a market power structure, for example, Bertrand, Cournot, or Stackelberg.

The second method is the conjectural variation (CV) approach developed by Karp and Perloff (1989, 1993) and Buschena and Perloff (1991). CV measures the degree of market competitiveness. The CV approach assumes that a single homogeneous good is traded and that exporters compete by setting profit-maximizing output quantities. Goldberg and Knetter (1999) modified this method by introducing an elasticity of residual demand into the formulation. The residual demand elasticity has a non-zero value when exporters wield significant market power. A non-zero value for this elasticity indicates that the demand curve is steeper, which corresponds with a supplier's ability to exercise market power. Goldberg and Knetter (1999) applied their version of the CV approach to German beer and US linerboard paper markets. Their results were consistent with other market competition indicators, including firm market share and the number of firms in a market. Reed and Saghaian (2004) used Goldberg and Knetter (1999)'s residual elasticity analysis method to measure market power in the Japanese beef import market. They estimated residual demands of four major beef exporters: the US, Canada, Australia, and New Zealand. They found that US beef exporters commanded the highest degree of market power, while the market power of Australia and New Zealand beef exporters was moderate and Canada's limited.

The third method is Carter and MacLaren (1997)'s 'menu approach' of determining the structure of export markets, which extended Gasmi et al. (1992)'s approach. Carter and MacLaren's study focused on Japanese beef imports from the United States and Australia. Their approach nested Bertrand, Cournot, and Stackelberg models under one of perfect competition. Applying each imperfectly competitive market model, comparative statics analysis was used to capture exporter's profit maximizing behavior derived from the first order condition. Collusion parameters equal zero under the null hypothesis of perfect competition. Carter and MacLaren's method also allows for product differentiation among exporters. Their application included separate demand functions for US grain-fed beef and Australian grass-fed beef products. Market structure was verified with a series of nested hypotheses and tested with Vuong (1989)'s likelihood ratio (LR) statistic. Among the Bertrand, Cournot, and Stackelberg market structures, Carter and MacLaren concluded that Australia was a Stackelberg price-setting leader. Asgari and Saghaian (2013) applied Carter and MacLaren (1997)'s nested model approach to analyze pistachio imports by Japan. They found that the import market for pistachios was Stackelberg, with the US setting export quantities.

This research extends Carter and MacLaren's nested model approach to characterize international market structures under Bertrand, Cournot, cartel, and Stackelberg (BCCS) assumptions. The rivalry index proposed here extends Carter and MacLaren's econometric model of potential market structures. Comparative statics results from the first order conditions derived profit maximization are used to formulate the rivalry index. Carter and MacLaren (1997)'s model is limited because, while it can identify imperfectly competitive market structure, it cannot measure the degree or intensity of collusive behavior. This study supplements Carter and MacLaren (1997) by suggesting a new method to measure the degree of collusion.

The empirical application examines beef exports from the US and Australia to Japanese and South Korean import markets. South Korea and Japan rank in the top six and four beef importing countries respectively worldwide. The nature and extent of competition between the

US and Australia beef exports into South Korean and Japanese markets are changing. Beef products from the US but Australia are differentiated and are potential substitutes. The 2018 share of US beef exports accounted for 52% and 44% of South Korea and Japan's imported beef markets, respectively. Australia accounted for 44% and 49% of South Korea and Japan's beef imports, respectively. In the same year, the value of beef imported into South Korea and Japan from the world was 513,324 and 744,038 thousand US dollars, respectively. Australia's beef exports to the world decreased after a severe and prolonged drought from 2018 through 2020 (USDA-FAS 2019; MLA 2019; MLA 2021a). From 2019 to 2020, Australian beef exports declined by 17 percent (USDA-FAS 2020). During this time, the US expanded its market share in Korean and Japanese beef import markets (MLA 2022).

US beef exports command a premium over Australia's beef exports in South Korean and Japanese markets. The US-Australia price difference has widened gradually since 2015, even though Australia enjoys lower tariff rates on the beef it exports to Japan as compared to tariffs applied to US beef imports (Quilty 2019). The exact reasons for this gap in export prices are difficult to discern. One explanation may be that there are quality differences in the US and Australian beef products. US beef products are generally more expensive than Australian beef products in Korean and Japanese markets. This is because US beef products are predominantly grain-fed, which results in a higher fat content and is an attribute preferred by South Korean and Japanese consumers (Lee and Kennedy 2009; Obara, Mcconnell and Dyck 2010). Changes in exchange rates, transportation costs, the severe drought in Australia since 2018, and Chinese restrictions on Australian beef imports may have also contributed to widening of the price gap (USDA-FAS 2019; Quilty 2019).

Another possible reason for the increase in the US-Australia price gap is that both countries influence Korean and Japanese beef prices through their ability to exercise market power. Reed and Saghaian (2004) found that exporting countries resembled oligopolies in their ability to mark up the price of imported beef in the Japanese imported beef market. That is not to say Australian and US beef exporters are *de facto* price conspirators. Rather, market power, in whatever form it manifests in this context, may simply be an unintended consequence that results from the comparative advantages Australia and the US have with respect to beef production, along with the institutional structures that evolved to facilitate or regulate trade and commerce with Japan and South Korea. Intentional or otherwise, the NEIO literature offers several approaches for quantifying the structure and degree of market competitiveness. This study proposes an additional measure of market power derived under NEIO assumptions called a rivalry index.

Methods and Procedures

The rivalry index is derived from the first order conditions of profit-maximizing firms or exporters under Bertrand, Cournot, cartel, or Stackelberg (BCCS) assumptions. The approach is extendable to price or quantity competition with multiple traded goods, firms, or exporters. The index is developed first under price competition assumptions, followed by quantity competition assumptions. Similar to Carter and McClaren's econometric model of BCCS contested markets, both the price and quantity models subsume Cournot, Bertrand, Stackelberg, and cartel cases under the null assumption of perfect competition. The difference between the approach introduced here and Carter and MacClaren's procedure is that the proposed measure indicates which type of BCCS structure most likely characterizes a market, but also the intensity at which competitors interact. Price competition models are discussed first followed by quantity competition models.

Price Competition Models: Bertrand and Stackelberg

Profit-maximizing firms or exporters set prices as strategic variables under the assumption of price competition. Export quantities are determined subsequently by the exporter's own price, its rival's price, and other factors affecting demand. When goods are homogenous, then the Bertrand price model devolves into the Bertrand paradox. The Bertrand paradox states that a Bertrand-contested market converges toward one of perfect competition when goods are perfect substitutes. However, the Bertrand paradox fails when firms or exporters offer differentiated products (Tirole, 1988). This study assumes that an exporter's tradable goods (beef) are differentiated and discriminated by consumers in importing countries.

Let $(i, j) \in \{1, 2\}$ index two exporters for the simplicity of deriving key relationships. Under the assumption of price competition, importer demand for ith exporting country's beef is:

$$q_i = \alpha_i + \beta_{ii} \cdot p_i + \beta_{ji} \cdot p_j \tag{1}$$

where j indexes i's potential exporting rival, q_i is exporter i's demanded quantity, α_i is an intercept, and p_i is exporter i's beef price with slopes $\beta_{ii} \leq 0$. The slope $\beta_{ji} \geq 0$ because rival j's beef is a potential substitute for exporter i's product.

Exporter i's profit is:

$$\pi_i(p_i) = (p_i - c_i) \cdot q_i \tag{2}$$

with c_i a per unit variable cost of production that is a marginal cost derived from $\frac{\partial tc(q)}{\partial q} = c$ where $tc(q)$ is total production cost that includes the cost of exporting. Under Bertrand (BE) and Price-Stackelberg (PL: Price Leader; PF: Price Follower) assumptions, the comparative statics results of the first order conditions (FOC) for profit-maximizing exporters are, respectively:

Bertrand:
$$\frac{\partial \pi_i^{BE}}{\partial p_i} = q_i + (p_i - c_i) \cdot \frac{\partial q_i(p_i, p_j)}{\partial p_i} = 0 \tag{3.1}$$

Stackelberg Price Leader:
$$\frac{\partial \pi_i^{PL}}{\partial p_i} = q_i + (p_i - c_i) \cdot \frac{\partial q_i\left(p_i, p_j(p_i)\right)}{\partial p_i} = 0 \tag{3.2}$$

Stackelberg Price Follower:
$$\frac{\partial \pi_i^{PF}}{\partial p_i} = q_i + (p_i - c_i) \cdot \frac{\partial q_i(p_i, p_j)}{\partial p_i} = 0 \tag{3.3}$$

where $p_j\ (p_i)$ is the Stackelberg price setting leader i's reaction to follower j's pricing strategy.

On the other hand, the Bertrand competitor's and Stackelberg price-setting follower's FOCs do not include the rival's reaction function. This means that followers do not consider their rivals' pricing behavior, and therefore $\frac{\partial p_j}{\partial p_i} = 0$. Followers only react to the leader's price setting behavior when followers set their prices. Bertrand competitors and Stackelberg price followers have the same FOCs because they do not consider their rival's price setting calculus. From each exporter's FOC and in terms of price, a Nash equilibrium obtains under Bertrand (p_i^{BE}, p_j^{BE}) and Stackelberg (p_i^{PL}, p_j^{PF}) when exporter i is a pricing leader.

Exporter i's corresponding best response (BR) function derived from the FOCs above are, respectively:

Bertrand:
$$p_i^{BE} = \frac{-\beta_{ji} \cdot p_j + \frac{\partial q_i}{\partial p_i} \cdot c_i - \alpha_i}{\frac{\partial q_i}{\partial p_i} + \beta_{ii}} = \frac{-\beta_{ji} \cdot p_j + \beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{4.1}$$

Stackelberg Price Leader:
$$p_i^{PL} = \frac{-\beta_{ji} \cdot p_j + \left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j} \cdot \frac{\partial p_j}{\partial p_i}\right) \cdot c_i - \alpha_i}{\left(\frac{\partial q_i}{\partial p_i} + \frac{\partial q_i}{\partial p_j} \cdot \frac{\partial p_j}{\partial p_i}\right) + \beta_{ii}}$$

$$= \frac{-\beta_{ji} \cdot p_j + \left(\beta_{ii} + \beta_{ji} \cdot \frac{-\beta_{ij}}{2 \cdot \beta_{jj}}\right) \cdot c_i - \alpha_i}{\left(\beta_{ii} + \beta_{ji} \cdot \frac{-\beta_{ij}}{2 \cdot \beta_{jj}}\right) + \beta_{ii}} \tag{4.2}$$

Stackelberg Price Follower:
$$p_i^{PF} = \frac{-\beta_{ji} \cdot p_j + \frac{\partial q_i}{\partial p_i} \cdot c_i - \alpha_i}{\frac{\partial q_i}{\partial p_i} + \beta_{ii}} = \frac{-\beta_{ji} \cdot p_j + \beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{4.3}$$

where the price-setting leader knows its follower's best response as indicated by $\frac{\partial p_j}{\partial p_i} = \frac{-\beta_{ij}}{2 \cdot \beta_{jj}}$, and $\frac{\partial p_j}{\partial p_i} = 0$ for Bertrand and Stackelberg follower's cases.

The best response functions for Bertrand competitors and Stackelberg price followers are the same because their FOC are identical. Differentiating each of the best response functions above with respect to price, the degree (or friction) of bilateral price-responsiveness under Bertrand and Stackelberg assumptions is:

$$\frac{\partial p_j}{\partial p_i} = \begin{cases} \dfrac{-\beta_{ij}}{2 \cdot \beta_{jj}} \text{ (Bertrand)} \\ \dfrac{-2 \cdot \beta_{ii} \cdot \beta_{ij}}{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}} \text{ (Stackelberg Price Leader)} \\ \dfrac{-\beta_{ij}}{2 \cdot \beta_{jj}} \text{ (Stackelberg Price Follower)} \end{cases} \quad \forall\, i \neq j, \frac{\partial p_i}{\partial p_i} = 1 \qquad (5)$$

The slope of the jth best response function is the price response of the jth exporter to the ith exporter's price-setting behavior, that is, $\frac{\partial p_j}{\partial p_i}$. In the Bertrand and Stackelberg-follower cases, the slopes of their best response functions are positive $\left(\frac{\partial p_j}{\partial p_i} > 0\right)$ because $\beta_{ij} \geq 0$ and $\beta_{ii} \leq 0$. However, the slope of the Stackelberg leader is unrestricted because the denominator of the price response $\left(4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}\right)$ can be positive or negative and depends on the magnitude of the exporters' cross-elasticities $\left(\beta_{ij} \cdot \beta_{ji}\right)$. When the price responses of exporters approach zero $\left(\frac{\partial p_j}{\partial p_i} \approx 0\right)$, the market tends toward perfect competition because the jth exporter does not make any price adjustments after its rival chooses a price. Multilateral price-responsiveness is therefore a proxy for a conjectural elasticity in price competition space.

A Nash equilibrium exists under Bertrand and Stackelberg assumptions when the slope of the leader's best response function is positive (Figure 1). Exporters in price-competitive markets adjust prices downward when prices exceed the Nash equilibrium price (p_i^*). Figure 1 demonstrates the recursive process of reaching a Nash equilibrium (NE). When exporter i sets its price to p_i^A, then exporter j adjust its price to p_j^A following jth best response. In response to exporter j's price adjustment, exporter i in turn adjust its price to p_i^B from its best response function, and in return exporter i adjusts again its price to p_j^B. The superscripts, A and B, indicate time sequence to adjusting exporter's price considering its rival's response. This process continues until both competitors' prices converge to the Nash prices (p_i^*, p_j^*). Prices converge at the Nash equilibrium because if one exporter sets its price above the equilibrium price, the exporter faces a decrease in demand (or zero demand if tradeable goods by all exporter are identical) and profits fall (Tirole, 1988). A price reduction by one exporter affects all other exporter prices, and also its own price. Eventually, exporter profit falls and approaches zero if the tradeable goods across the exporters are identical or similar. All exporters eventually adjust their prices towards a Nash equilibrium (NE) (Figure 1).

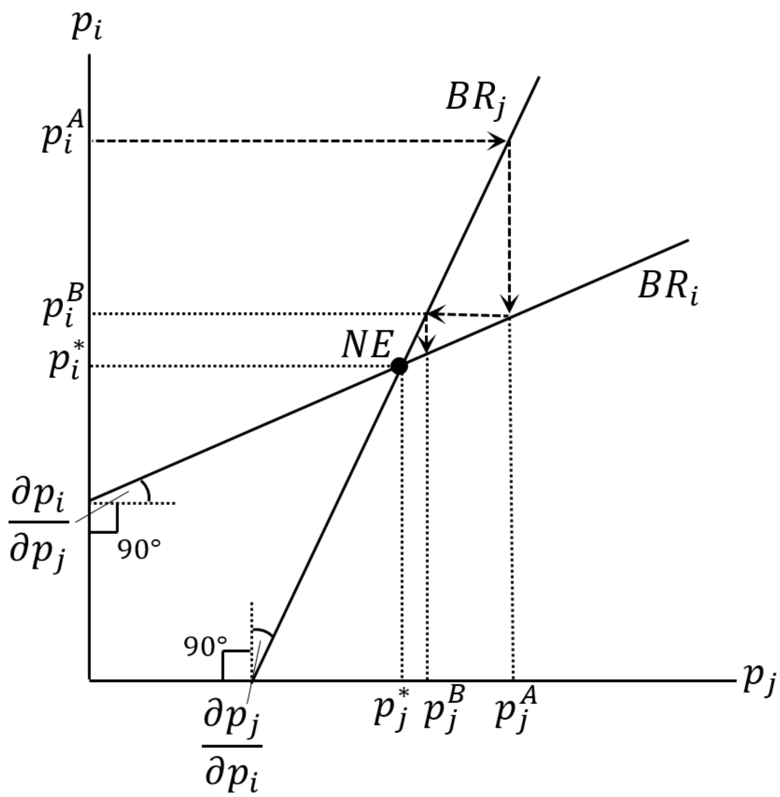

Figure 1. Price Competition for Two Competitors

Note: NE is the Nash equilibrium; p_i is the price of ith exporter that converges to the Nash equilibrium price (p_i^*); BR_i are best response functions; and $\partial p_i/\partial p_j$ is the slope of ith best response function.

Rivalry Index for the Price Competition Models

The rivalry index is derived from the comparative statistic results derived above. The index measures the degree, or intensity, of rivalry between competitors. Rivalry intensity characterizes exporter responsiveness to each other's pricing decisions. The system of equations developed below is similar to Sheldon (2021)'s contested market model, which computes quantity equilibrium for domestic firms and foreign competitors. The procedure used here departs from Sheldon's approach because it computes an equilibrium for export prices and quantities among multiple competitors.

Solving simultaneously for exporter best response functions results in a Nash equilibrium. Under the assumption of price competition, for example, a price-setting exporter's reaction function is:

$$p_i = \frac{\partial p_i}{\partial p_j} \cdot p_j + \mathrm{I}_i \tag{6}$$

where $\frac{\partial p_i}{\partial p_j}$ is the slope of the ith best response function and I_i is a term that consists of behavioral terms whose form depends on the market structure assumption. For example,

$$\mathrm{I}_i = \begin{cases} \dfrac{\beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}} \text{ (Bertrand)} \\ \dfrac{\left(\dfrac{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}}{2 \cdot \beta_{jj}}\right) \cdot c_i - \alpha_i}{\left(\dfrac{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}}{2 \cdot \beta_{jj}}\right)} \text{ (Stackelberg Price Leader)} \\ \dfrac{\beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}} \text{ (Stackelberg Price Follower)} \end{cases} \tag{7}$$

Equation (6) can be rewritten as a linear system of equations[2]:

$$\begin{bmatrix} 1 & -\dfrac{\partial p_i}{\partial p_j} \\ -\dfrac{\partial p_j}{\partial p_i} & 1 \end{bmatrix} \begin{bmatrix} p_i \\ p_j \end{bmatrix} = \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \forall\, i \neq j \tag{8}$$

which solves for the Nash equilibrium in price space. The Jacobian matrix, which includes $\partial p_i / \partial p_i$ (=1) and $-\partial p_i / \partial p_j$, embodies all the information required to measure rivalry intensity. Denote the Jacobian matrix by **R**. The vector of equilibrium prices for the exporters solves as:

$$\begin{bmatrix} p_i \\ p_j \end{bmatrix} = \frac{\mathrm{adj}(\mathbf{R})}{\det(\mathbf{R})} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{9}$$

[2] See Appendix VII for the derivations of the best response function (Equation (6)) and the system of equation (Equation (8)) in price competition case.

where 'adj' and 'det' are adjoint and determinant matrix operators, respectively, and $\frac{\mathrm{adj}(\boldsymbol{R})}{\det(\boldsymbol{R})}$ is the matrix inverse of **R**.

Figure 2 depicts the Nash equilibriums for different best response function slopes, with each evaluated at the same level of $\det(\mathbf{R})$ under price competition and holding the exporter's own price parameter (β_{ii}) fixed. The Nash equilibriums NE^A, NE^B, and NE^C occur at the intersection of the exporters' best response functions: $\{BR_i^A, BR_j^A\}$, $\{BR_i^B, BR_j^B\}$, and $\{BR_i^C, BR_j^C\}$. Figure 2 assumes that the best response functions all share the same I_i term because β_{ii} is fixed. The pair of ith and jth best response functions is denoted by a superscript (A, B, C), and the determinant of each pair is also held constant. The thick line in Figure 2 is an iso-determinant curve that maps the trajectory of Nash equilibriums while holding $\det(\mathbf{R})$ constant. The iso-determinant curve follows from the determinant expression, $\det(\mathbf{R}) = 1 - \left(\frac{\partial p_i}{\partial p_j}\right) \cdot \left(\frac{\partial p_j}{\partial p_i}\right)$ while holding the determinant constant and changing $\frac{\partial p_i}{\partial p_j}$ and $\frac{\partial p_j}{\partial p_i}$. The term $\left(\frac{\partial p_i}{\partial p_j}\right) \cdot \left(\frac{\partial p_j}{\partial p_i}\right)$ in the determinant equation is obtained by solving Equation (9) for the exporter's price responses $\frac{\partial p_i}{\partial p_j}$ and $\frac{\partial p_j}{\partial p_i}$.

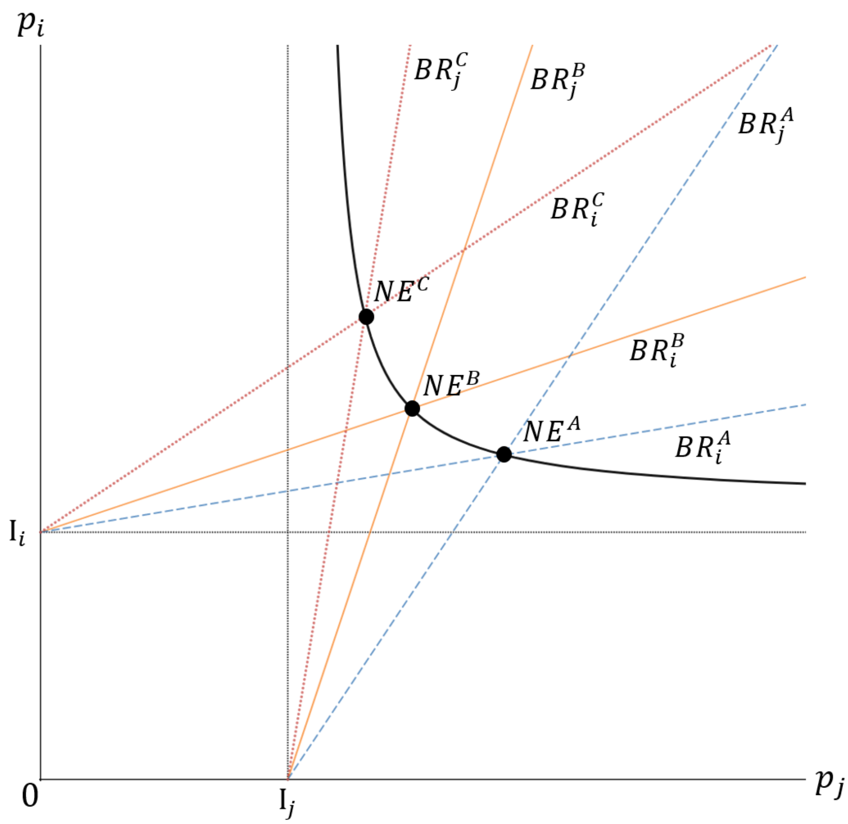

Figure 2. Nash Equilibriums at the Same Level of $det(\boldsymbol{R})$ under Price Competition

Note: NE^A is the Nash equilibrium for the Ath pair of ith and jth best response functions $\{BR_i^A, BR_j^A\}$; I_i is the intercept of ith best response function. Each best response pair have the same determinant ($\det(\mathbf{R})$) and the same intercepts. The iso-determinant curve is the thicker line connecting the Nash equilibriums.

Determinant $\det(\mathbf{R})$ embodies the degree, or intensity, of competition between i and j. The determinant is bounded between zero and one. Negative equilibrium prices or unobtainable Nash equilibrium result when the determinant falls outside this condition. Matrix **R** is non-invertible when $\det(\mathbf{R})$ is zero. When this happens, exporter responsiveness to its rivals is equivalent for all exporters. Geometrically, this means all exporter reaction functions are parallel or overlapping. In this case, exporters are in cartel relationship because all exporters change their prices in an identical way. On the other hand, when $\det(\mathbf{R})$ approaches one, then all exporter responses to rivals are zero. This means exporters do not collude with each other in setting prices and the market is perfectly competitive. As $\det(\mathbf{R})$ approaches zero, exporters increase their prices close to the cartel price level. On the other hand, as $\det(\mathbf{R})$ approaches one, exporters decrease their prices to levels approaching a perfectly competitive market price. Figure 3 shows iso-determinant curves for different determinant values. Higher determinant values of indicate a lower degree of collusion between exporters as both exporters increase their price levels together. Conversely, lower determinant values indicate a higher degree of collusion.

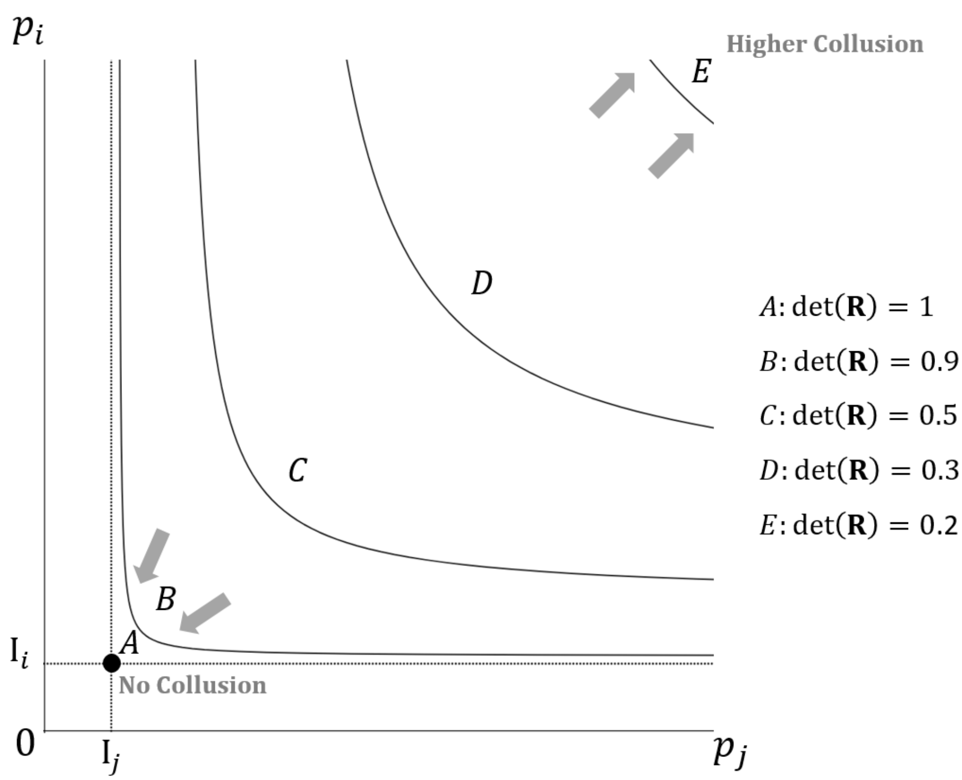

Figure 3. Combinations of Nash Equilibriums under Price Competition with Two Competitors

Note: $\{A, B, C, D, E\}$ is the iso-determinant curve under different determinant ($\det(\mathbf{R})$); I_i is the intercept of ith best response function; The closer to A indicates lower collusion between exporters, whereas the further from A indicates higher collusion.

Quantity Competition Models: Cournot and Stackelberg

In this scenario, exporters set quantities as strategic variables under quantity competition. Similar to the price competition models, prices of the exporters' tradable goods are determined by the quantity they choose, their rival's chosen quantity, and demand shifting factors. Under quantity competition, import demand for the ith exporter's beef is:

$$p_i = \alpha_i + \beta_{ii} \cdot q_i + \beta_{ji} \cdot q_j \tag{10}$$

Following Tirole (1988)'s Cournot model of quantity competition, it is assumed that while q_i and q_j are differentiated goods, they can be aggregated to account for total demand for imported beef: $Q = q_i + q_j$. In this case, q_i and q_j are potential substitutes, which implies that $(\beta_{ii}, \beta_{ij}) \leq 0$. As exporter i and j compete with each other, increasing q_j increases aggregate output Q. Consequently, prices decrease.

An exporter's profit function is:

$$\pi_i(q_i) = (p_i - c_i) \cdot q_i \tag{11}$$

Under Cournot (CN) and Quantity Stackelberg (QL: Quantity Leader; QF: Quantity Follower) assumptions, the comparative static results of the first order conditions (FOC) for exporter profits are, respectively:

Cournot: $$\frac{\partial \pi_i^{CN}}{\partial q_i} = \frac{\partial p_i(q_i, q_j)}{\partial q_i} \cdot q_i + (p_i - c_i) = 0 \tag{12.1}$$

Stackelberg Quantity Leader: $$\frac{\partial \pi_i^{QL}}{\partial q_i} = \frac{\partial p_i\left(q_i, q_j(q_i)\right)}{\partial q_i} \cdot q_i + (p_i - c_i) = 0 \tag{12.2}$$

Stackelberg Quantity Follower: $$\frac{\partial \pi_i^{QF}}{\partial q} = \frac{\partial p_i(q_i, q_j)}{\partial q_i} \cdot q_i + (p_i - c_i) = 0 \tag{12.3}$$

where $q_j\ (q_i)$ is the Stackelberg quantity-setting leader i's reaction to follower j's quantity-setting strategy. Similar to the price competition assumption, the FOC of Cournot competitors and Stackelberg quantity-followers are identical. Cournot competitors and Stackelberg quantity-followers FOC do not include their rival's reaction to setting quantities. This implies that followers simply react to the leader's quantity-setting behavior. Followers do not consider their rivals' quantity setting behavior, which implies $\frac{\partial q_j}{\partial q_i} = 0$ in the follower's best response function.

The best response functions derived from the FOCs are, respectively:

Cournot: $$q_i^{CN} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{\frac{\partial p_i}{\partial q_i} + \beta_{ii}} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{2 \cdot \beta_{ii}} \quad (13.1)$$

Stackelberg Quantity Leader: $$q_i^{QL} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{\left(\frac{\partial p_i}{\partial q_i} + \frac{\partial p_i}{\partial q_j} \cdot \frac{\partial q_j}{\partial q_i}\right) + \beta_{ii}} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{\left(\beta_{ii} + \beta_{ji} \cdot \frac{-\beta_{ij}}{2 \cdot \beta_{jj}}\right) + \beta_{ii}} \quad (13.2)$$

Stackelberg Quantity Follower: $$q_i^{QF} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{\frac{\partial p_i}{\partial q_i} + \beta_{ii}} = \frac{-\beta_{ji} \cdot q_j + c_i - \alpha_i}{2 \cdot \beta_{ii}} \quad (13.3)$$

where the quantity-setting leader i considers its follower's best response $\left(\frac{\partial q_j}{\partial q_i}\right)$ to be $\frac{-\beta_{ij}}{2 \cdot \beta_{jj}}$.

Cournot competitors and Stackelberg quantity-followers have identical best response functions because their FOCs are the same.

The degree (or friction) of bilateral quantity responses under each assumption are measured as:

$$\frac{\partial q_j}{\partial q_i} = \begin{cases} \frac{-\beta_{ij}}{2 \cdot \beta_{jj}} \text{ (Cournot)} \\ \frac{-2 \cdot \beta_{ij} \cdot \beta_{ii}}{4 \cdot \beta_{jj} \cdot \beta_{ii} - \beta_{ij} \cdot \beta_{ji}} \text{(Stackelberg Quantity Leader)} \\ \frac{-\beta_{ij}}{2 \cdot \beta_{jj}} \text{ (Stackelberg Quantity Follower)} \end{cases}, \qquad \forall\, i \neq j, \qquad \frac{\partial q_i}{\partial q_i} = 1 \quad (14)$$

The structure of the best response functions for quantity setting exporters differs from those under price competition, but the structure of bilateral responses is the same. Under the same logic governing price competition assumptions, the slope of the jth best response function (BR_j) is the quantity response of the jth exporter to the ith exporter's quantity setting behavior $\left(\frac{\partial q_j}{\partial q_i}\right)$. The slope of the best response function for Cournot competitor and Stackelberg follower is negative because $\beta_{ij} \leq 0$ and $\beta_{ii} \leq 0$. The sign of the slope for the Stackelberg leader depends on the exporters' own and cross-price elasticities, that is, $4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}$. The market tends toward one that is perfectly competitive as the quantity responses of exporters approach zero that is, $\frac{\partial q_j}{\partial q_i} \approx 0$.

Figure 4 depicts the Nash equilibrium under Cournot and Stackelberg conditions. Similar to the price competition case, exporters in quantity-competitive markets adjust quantities in response to their rival's quantity choices. When exporter i sets its quantity to q_i^A, then exporter j adjust its price to q_j^A following jth best response function (BR_j) replying q_i^A. The recursive adjustment process eventually converges to the Nash equilibrium (NE) quantity (q_i^*, q_j^*).

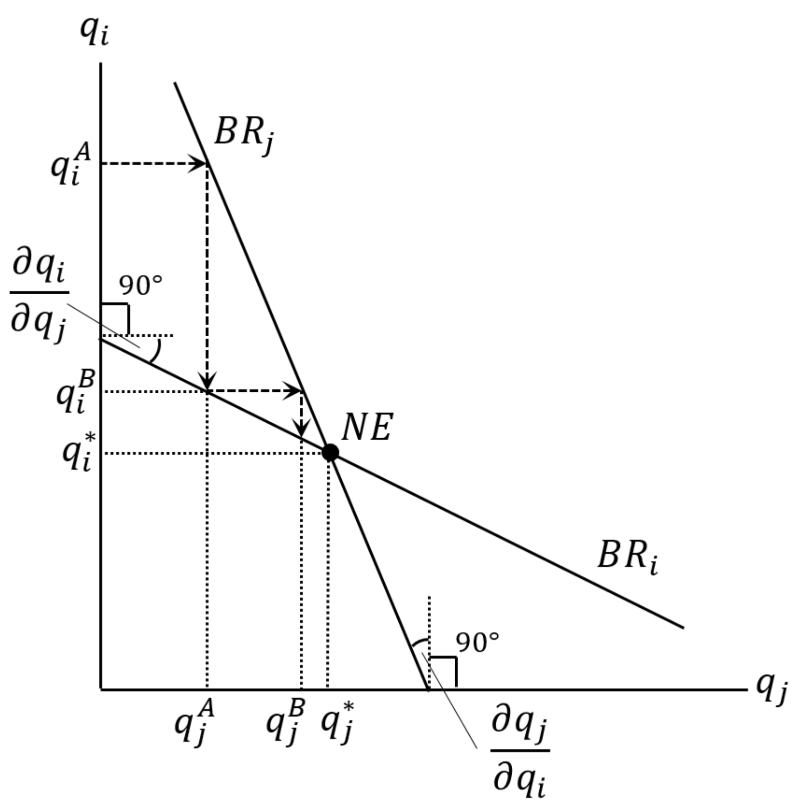

Figure 4. Quantity Competition for Two Exporters

Note: NE is the Nash equilibrium; q_i is the quantity of the ith exporter; q_i^* is the Nash equilibrium quantity; BR_i is a best response function; and $\partial q_i/\partial q_j$ is the slope of a best response function.

Quantity Competition: Cartel Case

Under the quantity-setting cartel assumption (QT), the corresponding FOC with respect to q_i is:

$$\frac{\partial \pi^{QT}}{\partial q_i} = \frac{\partial p_i(q_i, q_j)}{\partial q_i} \cdot q_i + (p_i - c_i) + \frac{\partial p_j(q_i, q_j)}{\partial q_i} \cdot q_j = 0 \tag{15}$$

The cartel's FOC condition is more complicated compared to the previous FOC because it includes all cartel members' profit functions. A cartel member's reaction function derived from the FOCs under quantity-setting assumptions is:

$$q_i^{QT} = \frac{-\beta_{ji} \cdot q_j - \frac{\partial p_j}{\partial q_i} \cdot q_j + c_i - \alpha_i}{\frac{\partial p_i}{\partial q_i} + \beta_{ii}} = \frac{-\beta_{ji} \cdot q_j - \beta_{ij} \cdot q_j + c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{16}$$

A cartel member's best response function includes the other members' quantity and marginal cost terms. The degree of bilateral quantity responsiveness under the quantity-setting cartel assumption is:

$$\frac{\partial q_j}{\partial q_i} = -\frac{\beta_{ij} + \beta_{ji}}{2 \cdot \beta_{jj}} \ \forall \ i \neq j, \frac{\partial q_i}{\partial q_i} = 1 \tag{17}$$

with the same interpretations from the quantity competition cases holding. The slope of the jth best response function is the quantity response of the jth cartel member's quantity setting behavior $\frac{\partial q_j}{\partial q_i}$. The slope of a cartel member's best response function is negative ($\beta_{ij} \leq 0$) with $\beta_{ii} \leq 0$. If the slope $\frac{\partial q_j}{\partial q_i}$ is zero, then the quantity responses of exporters approach zero, meaning that the cartel members do not collude with each other at all (i.e., the cartel dissolves).

Rivalry Index for the Quantity Competition Models

The rivalry index for the quantity competition models follows the same logic of the price competition case. The quantity-setting exporter's reaction function is:

$$q_i = \frac{\partial q_i}{\partial q_j} \cdot q_j + \mathrm{I}_i \tag{18}$$

where $\frac{\partial q_j}{\partial q_i}$ is the slope of the ith best response function and I_i is a function of parameters and costs:

$$\mathrm{I}_i = \begin{cases} \dfrac{c_i - \alpha_i}{2 \cdot \beta_{ii}} \text{ (Cournot)} \\ \dfrac{c_i - \alpha_i}{4 \cdot \beta_{jj} \cdot \beta_{ii} - \beta_{ij} \cdot \beta_{ji}} \text{ (Stackelberg Quantity Leader)} \\ \dfrac{c_i - \alpha_i}{2 \cdot \beta_{ii}} \text{ (Stackelberg Quantity Follower)} \\ \dfrac{c_i - \alpha_i}{2 \cdot \beta_{ii}} \text{(Quantity Setting Cartel)} \end{cases} \tag{19}$$

The comparative statics on equilibrium can be expressed by the system of equations[3] that solves for the Nash equilibrium under quantity competition:

$$\begin{bmatrix} 1 & -\dfrac{\partial q_i}{\partial q_j} \\ -\dfrac{\partial q_j}{\partial q_i} & 1 \end{bmatrix} \begin{bmatrix} q_i \\ q_j \end{bmatrix} = \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \forall\, i \neq j \tag{20}$$

Exporter responsiveness is measured by the matrix determinant of the Jacobian that includes $\frac{\partial q_i}{\partial q_i}$ (= 1) and $-\frac{\partial q_j}{\partial q_i}$. The vector of export quantities at the Nash equilibrium is:

$$\begin{bmatrix} q_i \\ q_j \end{bmatrix} = \frac{\mathrm{adj}(\boldsymbol{R})}{\det(\boldsymbol{R})} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{21}$$

Like the price competition rivalry index, the determinant $\det(\mathbf{R})$ can be interpreted as the degree of competitiveness.

Figure 5 depicts an iso-determinant curve that consists of the Nash equilibriums (NE^A, NE^B, NE^C). As with the price competition case (Figure 2), these Nash equilibriums occur at intersections of the best response functions: $\{BR_i^A, BR_j^A\}$, $\{BR_i^B, BR_j^B\}$, and $\{BR_i^C, BR_j^C\}$. Each pair of best response functions has the same determinant ($\det(\mathbf{R})$) and I_i terms, which are arrived at by holding the exporter's own quantity parameter (β_{ii}) fixed. Under the same logic for price

[3] See Appendix VIII for the derivations of the best response function (Equation (18)) and the system of equation (Equation (20)) in quantity competition case.

competition, the iso-determinant curve under quantity competition is derived from the determinant equation and the solution to Equation (21).

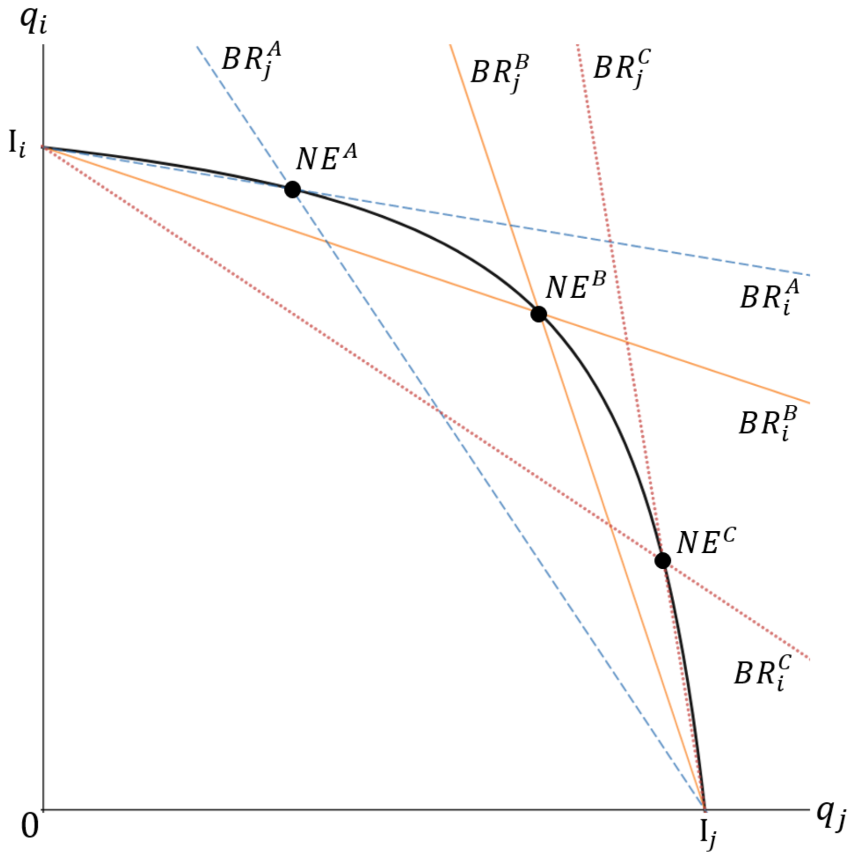

Figure 5. Nash Equilibriums at the Same Level of $det(\boldsymbol{R})$ under Quantity Competition

Note: NE^A is the Nash equilibrium of Ath pair of ith and jth best response functions $\{BR_i^A, BR_j^A\}$; I_i is the intercept of ith best response function. Each best response pair has the same determinant ($\det(\mathbf{R})$) and the same intercepts. The iso-determinant curve is the thick line connecting the Nash equilibriums.

Under quantity competition, $\det(\mathbf{R})$ is also bounded between zero and one. When $\det(\mathbf{R})$ equals one, the off-diagonal elements of the quantity responsiveness matrix are zero, which means that the exporters do not collude in setting quantities. As $\det(\mathbf{R})$ approaches zero, quantity levels approach a cartel equilibrium. One the contrary, when $\det(\mathbf{R})$ approaches one, exporters set their quantities closer to levels that would be observed under perfect competition.

Figure 6 shows iso-determinant curves evaluated at different determinants. Higher determinant values indicate lower levels of collusion between exporters as both exporter reduce their exporting quantities together. Conversely, lower determinant values indicate higher levels of collusion. Determinants outside the (0, 1)-interval result in unstable equilibrium scenarios.

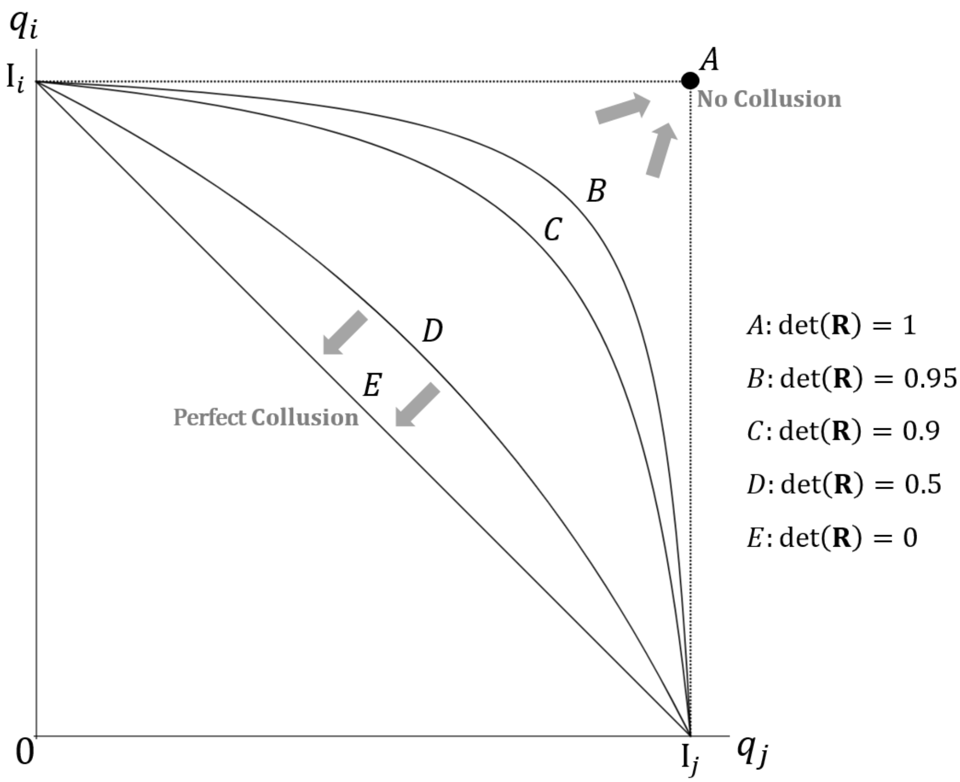

Figure 6. Combination of Nash Equilibrium under Quantity Competition with Two Exporters

Note: $\{A, B, C, D, E\}$ is the iso-determinant curve under different determinants ($\det(\mathbf{R})$); I_i is the intercept of ith best response function. Movement toward A indicates lower collusion between exporters. Movement away from A indicates higher collusion.

Empirical Procedures

Carter and MacLaren (1997)'s nested model procedure is used to estimate each of the models above. Estimated parameters are used to calculate the rivalry indexes. Carter and MacLaren used four linear, simultaneous equations in their analysis, which were derived from the importing market's demand function for exporter's traded good and the FOC's of exporters' profit-maximizing decisions. Carter and MacLaren (1997) estimated the system's parameters simultaneously using full-information maximum-likelihood under Bertrand, Cournot, and Stackelberg assumptions. Bayesian estimation procedures are used here due to the ease at which theoretical restrictions on parameters can be imposed.

The system of equations is:

$$\mathbf{Y} \sim MVN\big(\boldsymbol{\mu}, \mathrm{diag}(\boldsymbol{\sigma})\boldsymbol{\Omega}\mathrm{diag}(\boldsymbol{\sigma})\big) \tag{22}$$

$$\mathbf{Y}_{Price} = \begin{bmatrix} q_i \\ q_j \\ p_i^{BEST} \\ p_j^{BEST} \end{bmatrix}, \mathbf{Y}_{Quantity} = \begin{bmatrix} p_i \\ p_j \\ q_i^{BEST} \\ q_j^{BEST} \end{bmatrix} \tag{23}$$

where **Y** is a vector of demands and the best response functions ('BEST') and $\boldsymbol{\mu}$ is mean vector including exporters' demand functions and best response functions. for the price competition models ($\mathbf{Y}_{Price}$), $\boldsymbol{\mu}$ is the right-hand side of Equations 1 and 6. Similarly, for the quantity competition models ($\mathbf{Y}_{Quantity}$), $\boldsymbol{\mu}$ is the right-hand side of Equations 10 and 18. The vector $\boldsymbol{\sigma}$ is a conformable matrix of scalar (error standard deviation) terms, and $\boldsymbol{\Omega}$ is a correlation matrix that follows the Lewandowski-Kurowicka-Joe (LKJ) prior distribution (Lewandowski, Kurowicka, and Joe 2009). Pre- and post-multiplying the vector of scalars with the correlation matrix yields a positive-semidefinite covariance matrix.

In the empirical estimation procedure, the demand intercept term, α_i includes demand shifting variables:

$$\alpha_i = \lambda_i + \gamma_i \cdot GDP + \delta_i \cdot TARIFF_i + \kappa_i \cdot BSE$$

where GDP is the importing country's GDP per capita, $TARIFF$ is tariff rate for imported beef from exporting the county, BSE is a dummy variable identifying when the outbreak of bovine spongiform encephalopathy (BSE) affected South Korea and Japan, and λ_i, γ_i, δ_i, and κ_i are parameters. The exporter's marginal cost (cost per unit of production), c_i is a function of:

$$c_i = \eta_i \cdot DISTANCE_i + \tau_i \cdot MAIZEP_i + \upsilon_i \cdot IRATE_i$$

where $DISTANCE$ is exporter distance to an importing country, $MAIZEP$ is exporter's domestic maize price, $IRATE$ is exporter's real interest rates, and η_i, τ_i, and υ_i are parameters.

Based on BCCS assumptions, the priors for the parameters are:

$$(\lambda_i, \delta_i, \kappa_i) \sim N(0, 10),\ \beta_{ii} \sim N_{-\infty}^{0}(0, 10),\ (\gamma, \eta_i, \tau_i, \upsilon_i) \sim N_0^{\infty}(0, 10),$$

$$\beta_{ij} \sim \begin{cases} N_0^{\infty}(0, 10) \text{ (for price competition case)}, \\ N_{-\infty}^{0}(0, 10) \text{ (for quantity competition case)} \end{cases}$$

$$\boldsymbol{\sigma} \sim \text{Exponential}(1),\ \boldsymbol{\Omega} \sim \text{LKJcorr}(2)$$

All parameters are distributed under the normal distribution with zero mean and 10 standard deviation except $\boldsymbol{\sigma}$ and $\boldsymbol{\Omega}$. The priors for β_{ii} and β_{ij} are truncated positive or negative, depending on BCCS assumptions. McElreath (2020) suggests using an exponential distribution as a prior for the scale parameters. The exponential prior carries no more information than an average standard deviation from a mean when the rate parameter is set to one (McElreath, 2020). Following Carter and MacLaren (1997), this paper assumes that the GDP per capita (GDP) will be positively correlated with import quantities or prices. Distance between exporters and importers ($DISTANCE_i$), maize prices ($MAIZEP_i$), and the real interest ($IRATE_i$) are hypothesized to increase exporter marginal costs. Thus, the priors for γ_i, η_i, τ_i, and υ_i are hypothesized to be positive and are therefore truncated above zero.

R-Stan's Hamiltonian Monte Carlo No U-turn Sampler (HMC-NUTS) (Stan Development Team 2022) is used to generate posterior distributions of the model parameters. The HMC-NUTS performance is superior to Gibbs or Metropolis-Hastings samplers in terms of the number of iterations required for convergence (Gelman et al. 2013). Four chains were used, each with 20,000 iterations and 10,000 warm-up samples for the adaptation phase. The thinning, maximum tree depth, and target acceptance (adaptation) rate were set to 10, 15 and 0.95, respectively. Therefore, there are 4 × 1,000 posterior samples used to calcite the means and standard deviations of the posterior distributions.

Model Comparison

Two criteria are used to compare the performance of each BCCS model. The widely applicable information criterion (WAIC) is the first criterion, which is calculated with a model's log-posterior density (McElreath 2020). A probability weight is calculated for each model using the ensemble of computed WAIC. The probability weight is the likelihood a model is preferred amongst competing models. Higher weights indicate a better fitting model.

The other model comparison method uses the Bayes factor (BF). The BF are also used as a pairwise model comparison and are based on each model's marginal likelihood (Gelman et al. 2013). When the BF exceed '1', then the interpretation is that there is evidence to prefer a competing model (H_1) over a reference model (H_0). According to Jeffreys (1961)'s rubric for interpreting BF, which was revised by Lee and Wagenmakers (2014), 10 < BF is strong evidence for favoring Bertrand over the price cartel specification and vice versa (BF < 1/10 for favoring price cartel over Bertrand).

Data

Annual data on beef exports to Japan and South Korea from the US and Australia were collected for the period 1995 to 2018 (Table 9). International trade data for bovine animal meat is from the BACI (Base pour l'Analyse du Commerce International) database curated by the French research center, CEPII (Centre d'Etudes Prospectives et d'Informations Internationales) (CEPII 2021). The BACI database includes export quantities of US and Australian beef, and the prices by importing countries. The international beef trade data for South Korea and Japan were used separately for two beef import markets. Therefore, there is one demand function per exporter in two importing markets for South Korea and Japan.

Gross Domestic Product (GDP), normalized by population, tariff rate to exporting country, and dummy variable for the outbreak of BSE in US are used as demand-shifting variables. South Korea and Japan's GDP per capita and tariff rate were obtained from the World

Bank's Data Bank (World Bank, 2021) and MLA reports for overseas market (MLA 2022) respectively. The BSE dummy variable indicating the period 2004 to 2009 ($BSE = 1$) was set by the year after of the ban of the imported beef from the US by South Korea and Japan (2003) and the year after the reopening to importing US beef (2008). Cost-shifting variables affecting the marginal costs of exporting beef are based on Carter and MacLaren (1997)'s specification for marginal costs. Carter and MacLaren used each exporting country's corn price and interest rate as cost shifters. Interest rates are also from the Data Bank (World Bank 2021). Real domestic maize prices are from the Food and Agriculture Organization's Food Price Monitoring and Analysis data (FAO 2021). Distance (kilometers) between exporters and importers are from DistanceFromTo (DistanceFromTo 2022).

Table 9. Descriptive Statistics

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
US GDP Deflator	2015=100	86.204	11.434	105.417	68.688
US Real Interest Rate ($IRATE_1$)	%	3.608	2.039	7.148	1.137
US Domestic Maize Price ($MAIZEP_1$)	US Dollars /ton	223.143	90.504	464.57	123.43
Australia Real Interest Rate ($IRATE_2$)	%	4.328	1.867	8.057	0.97
Australia Domestic Maize Price ($MAIZEP_2$)	US Dollars /ton	247.268	85.683	361.19	83.58
The Korean Beef Importing Market					
US Unit Price (p_1)	Thousands current USD /metric tons	105993	68619	76	267473
US Quantity (q_1)	Metric tons	4.621	1.497	2.501	7.294
Tariff Rate to US ($TARIFF_1$)	%	37.708	6.22	21.3	43.6
Distance to US ($DISTANCE_1$)	Kilometer	10743	-	-	-
Australia Unit Price (p_2)	Thousands current USD /metric tons	123771	47079	38948	196376
Australia Quantity (q_2)	Metric tons	3.482	1.353	1.637	5.512
Tariff Rate to Australia ($TARIFF_2$)	%	39.154	4.241	26.6	43.6
Distance to Australia ($DISTANCE_2$)	Kilometer	6832	-	-	-

GDP per capita (GDP)	US dollars per capita	20181	7364	8282	33423
The Japanese Beef Importing Market					
US Unit Price (p_1)	Thousands current USD /metric tons	207958	133088	816	483050
US Quantity (q_1)	Metric tons	4.873	1.039	2.951	6.425
Tariff Rate to US ($TARIFF_1$)	%	40.202	3.804	38.5	50
Distance to US ($DISTANCE_1$)	Kilometer	10173			
Australia Unit Price (p_2)	Thousands current USD /metric tons	334689	50703	246054	439067
Australia Quantity (q_2)	Metric tons	3.968	0.968	2.534	5.866
Tariff Rate to Australia ($TARIFF_2$)	%	38.745	5.5	28.55	50
Distance to Australia ($DISTANCE_2$)	Kilometer	6852	-	-	-
GDP per capita (GDP)	US dollars per capita	38400	4292	31916	48633

Note: The number of observations is 24. The dummy variable indicating BSE (BSE) is ‘1’ for 2004 – 2009. Stand deviation, minimum, and maximum of distance variables are omitted because the distance is fixed.

Results

Equation 26 was estimated under each BCCS quantity and price assumption separately for the South Korean and the Japanese markets. Three of the eight models converged. The Cournot and Stackelberg models did not converge as evidenced by the $\hat{R}$, which were all greater than 1.01 (Appendix III to V). The effective sample sizes were also relatively small (Appendix IV to VI). The Bertrand and cartel models converged, with the largest $\hat{R}$ less than 1.01 and the smallest effective sample size of 3,379. Discussion focuses on the converged models.

The proposed procedure requires that the signs of estimated coefficients are consistent with their theoretical expectations. For all models, all own quantity and price parameters (β_{ii}) are negative, which is consistent with their expected direction (Table 10 and 11). The cross price parameters (β_{ji}) are less than zero for the quantity competition models and positive for the price competition models, which is consistent with their theoretical expectations.

All parameters of the marginal cost function ($\eta_i, \tau_i, \upsilon_i$) and GDP per capita ($\gamma_i$) are positive, which is also consistent with their hypothesized relationships (Table 2 and 3). All parameters on tariff rates (δ_i) are negative, meaning that tariff rates decrease exporting prices and demand. Lastly, all parameters of BSE dummy (κ_i) are negative for US and positive for Australia. The estimated sign of BSE dummy implies that the outbreak of BSE in US had negative effects on the US beef export price and quantity, whereas Australia was benefitted from the BSE outbreak with higher export prices and demand.

Table 10. Posterior Means and Standard Deviations (South Korea)

Parameter (1 = US, 2 = Australia)	**Bertrand**		**Price Cartel**		**Quantity Cartel**	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.
λ_1	0.172	9.921	0.312	9.994	4.805	1.776
β_{11}	-139.544	6.026	-139.343	6.079	-5.24E-05	1.08E-06
β_{21}	7.625	5.828	9.211	6.610	-1.46E-07	1.21E-07
γ_1	4.405	0.047	4.407	0.047	1.10E-04	3.24E-05
δ_1	-18.627	8.874	-19.617	8.842	-0.050	0.030
κ_1	-1.888	9.919	-1.887	9.800	-0.443	0.313
η_1	0.001	0.001	0.001	0.001	9.78E-05	9.58E-05
τ_1	0.599	0.230	0.602	0.237	0.003	0.003
υ_1	1.74E-04	1.74E-04	1.62E-04	1.64E-04	6.57E-07	6.57E-07
λ_2	-1.418	10.017	-1.050	10.109	0.001	1.251
β_{22}	-151.972	5.996	-151.967	6.082	-2.50E-05	2.53E-07
β_{12}	6.311	5.094	5.648	4.687	-7.85E-07	6.92E-07
γ_2	5.706	0.025	5.704	0.025	1.83E-04	1.73E-05
δ_2	-63.220	9.515	-62.120	9.407	-0.007	0.023
κ_2	0.861	9.971	0.889	10.060	0.150	0.174
η_2	0.004	0.003	0.004	0.003	0.001	1.25E-04
τ_2	0.198	0.156	0.194	0.153	0.036	0.006
υ_2	0.002	0.001	0.002	0.001	5.42E-05	7.65E-06
$\det(\mathbf{R})$	0.999	0.001	0.997	0.004	0.999	4.64E-04

r_{11}	1	0[b]	1	0	1	0
r_{12}	-0.021	0.017	-0.049	0.027	0.019	0.014
r_{21}	-0.027	0.021	-0.053	0.029	0.009	0.007
r_{22}	1	0	1	0	1	0
WAIC	9560		9595		9285	

Note: See Appendix III and IV for convergence statistics. The number of observations is 24. r_{ii} is the diagonal element of the Jacobian matrix (**R**) and ith own responsiveness of price or quantity, which is fixed to one.
[a] Standard deviations.
[b] Standard deviations of r_{ii} is zero because r_{ii} is fixed to one.

Table 11. Posterior Means and Standard Deviations (Japan)

Parameter (1 = US, 2 = Australia)	**Bertrand**		**Price Cartel**		**Quantity Cartel**	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.
λ_1	0.191	9.973	0.351	9.988	0.711	1.732
β_{11}	-162.445	5.915	-162.429	5.808	-1.38E-05	3.44E-07
β_{21}	8.404	6.237	9.675	6.754	-3.16E-08	3.11E-08
γ_1	4.588	0.034	4.587	0.034	7.28E-05	1.85E-05
δ_1	18.020	8.077	18.011	7.924	0.049	0.036
κ_1	-1.883	10.043	-1.778	9.909	-0.834	0.577
η_1	0.007	0.004	0.007	0.004	0.006	2.43E-04
τ_1	0.597	0.204	0.604	0.203	2.22E-04	2.17E-04
υ_1	4.32E-04	3.21E-04	4.24E-04	3.19E-04	2.83E-07	2.78E-07
λ_2	0.661	10.095	0.979	9.983	4.578	0.583
β_{22}	-190.904	6.037	-191.036	6.009	-1.11E-05	1.20E-07
β_{12}	7.422	5.680	7.510	5.802	-4.05E-06	2.75E-07
γ_2	7.295	0.022	7.295	0.022	2.47E-05	8.44E-06
δ_2	17.603	8.616	17.454	8.915	-0.027	0.014
κ_2	2.122	10.125	1.795	10.042	-0.123	0.255
η_2	0.002	0.002	0.002	0.002	0.003	1.21E-04
τ_2	0.134	0.123	0.140	0.127	0.025	0.005
υ_2	4.88E-04	4.41E-04	4.84E-04	4.39E-04	2.67E-07	2.67E-07
$\det(\mathbf{R})$	0.999	0.001	0.997	0.003	0.973	0.004

r_{11}	1	0[b]	1	0	1	0
r_{12}	-0.019	0.015	-0.045	0.023	0.183	0.013
r_{21}	-0.026	0.019	-0.053	0.028	0.148	0.013
r_{22}	1	0	1	0	1	0
WAIC	14857		14801		16048	

Note: See Appendix V and VI for convergence statistics. The number of observations is 24. r_{ii} is the diagonal element of the Jacobian matrix (**R**) and ith own responsiveness of price or quantity, which is fixed to one.

[a] Standard deviations.

[b] Standard deviations of r_{ii} is zero because r_{ii} is fixed to one.

According to the WAIC criterion, the quantity cartel model fits the data comparatively better fit than the other models in terms of characterizing the structure of South Korean imports of US and Australian beef products (Table 12). The probability weights of the other competing models are effectively zero, meaning their fit is comparatively worse than that of the quantity cartel model. In the case of the Japanese market (Table 13), the price cartel model is also the best fitting model as the probability weights of the other models are zero.

Table 12. Widely Applicable Information Criterion (WAIC) and Model Probability Weights (South Korea)

Model	WAIC	se(WAIC)	ΔWAIC	se(ΔWAIC)	*weight*
Quantity Cartel	9285	2065.5	0	-	1
Bertrand	9560	1803.7	276	849	0
Price Cartel	9595	1816.7	310	844	0

Note: $\mathrm{se}(\mathrm{WAIC})$ is the standard error of WAIC; subscription i denotes model; $\Delta\mathrm{WAIC}$ is $[\mathrm{WAIC}_i - \min(\mathrm{WAIC})]$; and $\mathrm{se}(\Delta\mathrm{WAIC})$ is the standard error of $\Delta\mathrm{WAIC}$. A higher weight indicates a better fitting model.

Table 13. Widely Applicable Information Criterion (WAIC) and Model Probability Weights (Japan)

Model	WAIC	se(WAIC)	ΔWAIC	se(ΔWAIC)	*weight*
Price Cartel	14801	2108	0	-	1
Bertrand	14857	2118	56	35	0
Quantity Cartel	16048	3191	1246	2576	0

Note: se(WAIC) is the standard error of WAIC; subscription i denotes model; ΔWAIC is $[\mathrm{WAIC}_i - \min(\mathrm{WAIC})]$; and se(ΔWAIC) is the standard error of ΔWAIC. A higher weight indicates a better fitting model.

Table 14 and 15 compare each model using Bayes factors (BF). For the South Korean market, the BF comparison suggests that the quantity cartel is most preferred. BF for the Japanese market reports that Bertrand and the price cartel are preferred compared to the other model, the quantity cartel model. Comparing the Bertrand (H_1) over price cartel model (H_0), the corresponding BF is 4.67, which is an inconclusive result. Thus, the BF comparisons are consistent with the WAIC findings. Results suggest that the structure of the South Korean and Japanese import market for beef from the US and Australia are most similar to the quantity cartel and the price cartel model respectively.

Table 14. Model Comparison: Bayes Factor (BF)[a] (South Korea)

H_0 \ H_1	Bertrand	Price Cartel	Quantity Cartel
Bertrand	1	1.616	> 999
Price Cartel	0.619	1	> 999
Quantity Cartel	< 0.001	< 0.001	1

[a] The column entries are numerators and row entries is the denominator for calculating a Bayes factors, $BF = p(y|H_1)/p(y|H_0)$. A BF > 1 indicates H_1 is preferred to H_0.

Table 15. Model Comparison: Bayes Factor (BF)[a] (Japan)

H_0 \ H_1	Bertrand	Price Cartel	Quantity Cartel
Bertrand	1	0.214	< 0.001
Price Cartel	4.665	1	< 0.001
Quantity Cartel	> 999	> 999	1

[a] The column entries are numerators and row entries is the denominator for calculating a Bayes factors, $BF = p(y|H_1)/p(y|H_0)$. A BF > 1 indicates H_1 is preferred to H_0.

This result is unexpected because in the international beef market, different qualities of beef, tariff rates, regulations, and trade agreements by exporting countries make collusion difficult for major exporters. There is also limited information on the interaction between the US and Australian beef exporters. There are national trade associations supporting beef export such as the US Meat Export Federation (USMEF) and Meat & Livestock Australia (MLA), but it is an absurd statement to claim that the USMEF and MLA intentionally collude because these associations are made up of atomistic beef exporters.

Rivalry Indexes

The purpose of the rivalry index is to gauge the level of collusion, or intensity of competition, between price- or quantity-competing firms or exporters. The rivalry matrix for each model was recovered from the posteriors of the model parameters (Table 10and 11, calculated from Equation 5 and 11). The posterior means of the matrix determinant test under Bertrand, price cartel, and quantity cartel are, respectively, 0.999, 0.997, and 0.999 for the Korean market (Figure 7), and 0.999, 0.997, and 0.973 for the Japanese market (Figure 8). In contrast to the selected models of cartel, the rivalry index indicates that there is effectively no quantity or price collusion between Australian-US beef exporters to the South Korean and the Japanese markets thus the exporters are neither Bertrand competitors nor cartel. Thus, the proposed index also serves as an *ex post* “litmus test” which confirms or refutes the model selection results, in this case, cartel.

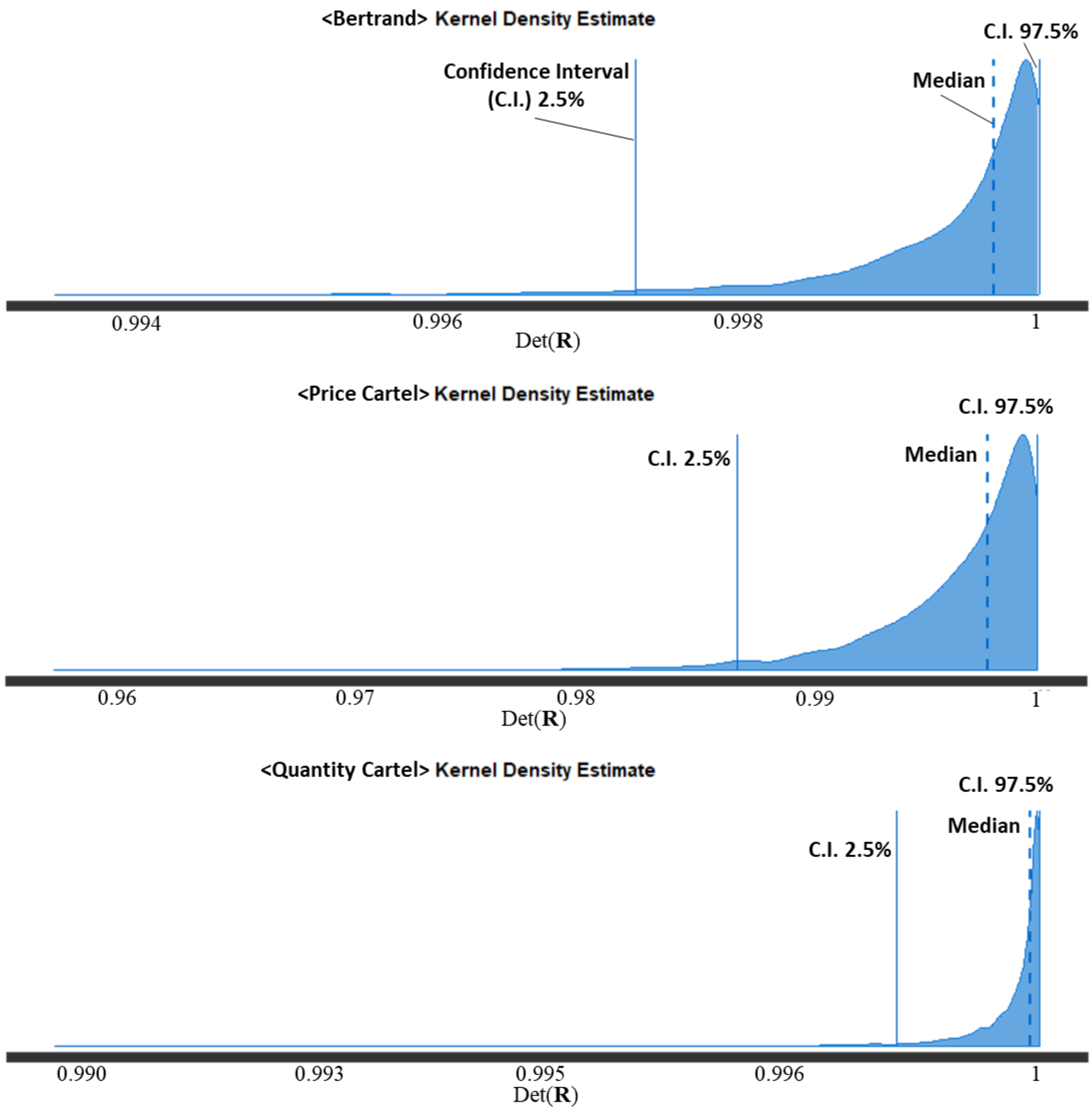

Figure 7. Posterior Distribution Plot of $det(R)$ in Price Competition (South Korea)

Note: The vertical lines are lower and upper bounds of a 95% confidence interval. The vertical dotted line is the median point of the Kernel density estimation.

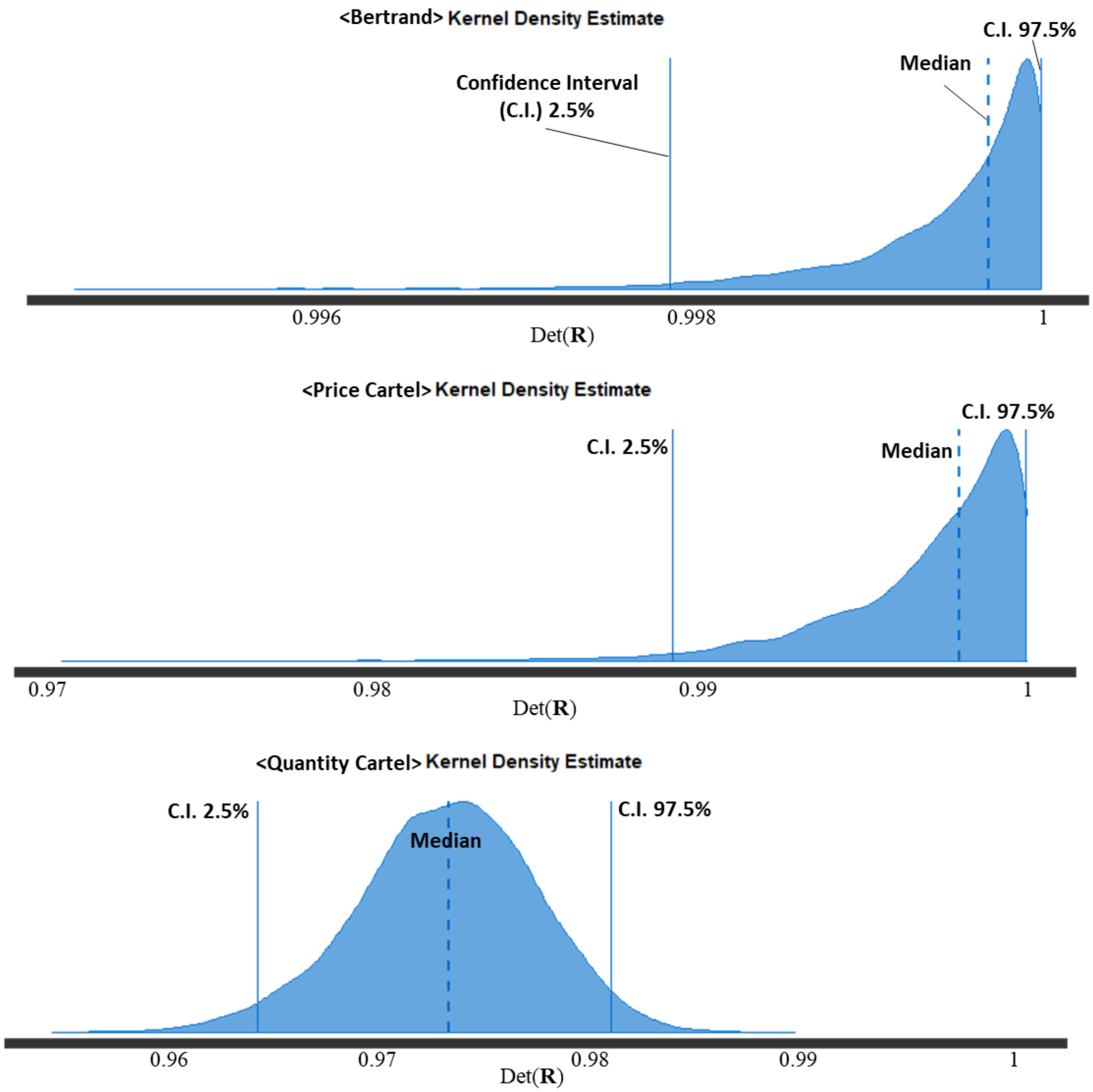

Figure 8. Posterior Distribution Plot of $\det(\mathbf{R})$ in Quantity Competition (Japan)
Note: The vertical lines are lower and upper bounds of a 95% confidence interval. The vertical dotted line is the median point of the Kernel density estimation.

That the rivalry index points toward a perfectly competitive market is unsurprising. Beef exports into South Korea and Japan are strictly regulated. For example, tariff rate quotas (TRQ) have been used by importing countries to regulate imported goods (Gorter and Kliauga 2005). Safeguards and sanitary regulations also affect beef imports. Once these regulations are implemented, exporters are compelled to restrict quantities sent to importing countries. Safeguards were triggered several times for beef imported from the US and Australia by Japan.

For example, Japan triggered a safeguard on frozen beef from the US, August 2017. The measure resulted in a 50% tariff rate increase for US beef, which was increased from 38.5% (MLA 2017). In March 2021, In March 2021, Japan triggered safeguard measures on US beef again, increasing tariff rates from 25.8% to 38.5% (USDA-FAS 2021a). Australia is also affected by safeguard. The USDA-FAS (2021b) reported that Australia is expected to be more price-competitive in South Korea's beef market because Australia is obliged to meet South Korea's safeguard levels. The Agricultural Safeguard clause in the Korea-Australia Free Trade Agreement subjects beef imported from Australian to a 30% tariff rate (revised from a previous rate of 16%) once imports exceed 181,120 metric tons. Both examples show that a high tariff rate significantly weakens the competitiveness of beef imported.

In addition to strict trade barriers, these exporters also compete with an importing country's domestic beef suppliers. There is a significant statistical relationship between Korean domestic beef and imported beef from Australia and US (Moon and Seok 2021; Kim and Mark 2017). Under the burden of higher tariff and restrictive amount of exporting quantity, there is a faint possibility of cooperating to collude in price and quantity setting. Even if Australia and the US colluded with each other and behaved as if they were a single exporter and set prices higher, still, there are higher tariff rates in South Korea and Japan for imported beef products, and increased prices due to collusion would degrade the exporting country's competitiveness rather than increase its profits.

Another reason for the indeterminate collusion finding between the exporters relates to the oligopsony power of beef importers. In South Korea, only a few buyers hold exclusive rights to supply imported beef to the Korean beef market. There were 10 imported beef buyers permitted by Korean government in 2000 (Kim and Veeman, 2001). The Bertrand and Cournot models used here are unable to detect market power when its structure is oligopsonistic.

The findings reported here contradict Carter and MacLaren (1997)'s earlier results. They characterize the Japanese import market for beef from the US and Australian as Stackelberg. Using the Japanese beef import data from 1973 to 1990, Carter and MacLaren concluded that the best fitting model is a Stackelberg model with Australia a price leader. However, this result cannot be confirmed because they did not measure rivalry. The rivalry index of the Australian Stackelberg price leader model calculated from their study is 0.571. But, considering each t-statistic of exporter's own and cross price parameters, the rivalry index would be effectively '0', meaning no collusion between Australia and the US in the Japanese beef importing market.

Conclusions

A new method was developed to characterize the degree, or intensity, of competition between exporters and to measure the degree of the rivalry of the exporters under Bertrand, Cournot, cartel, and Stackelberg assumptions. The rivalry index is a matrix determinant test that measures the degree of collusion between price- or quantity-competitors. An empirical example focused on two major beef exporters; the United States and Australia; and two importers, South Korea and Japan (1995 to 2018).

Findings suggest that the US and Australia beef export markets to South Korean and Japan are quantity cartel and price cartel respectively. However, results from the rivalry index were indeterminate, indicating that the degree of collusion between competitive interactions between them is anemic and that export price strongly lean towards those one would expect in a perfectly competitive situation. The implementation of beef import regulations by South Korea and Japan may explain this result.

There are caveats to this research. This paper assumes that exporter's beef product are identical so quality and specific beef cuts are did not considered. As Carter and MacLaren (1997) and Chung, Boyer and Han (2009) mentioned, US and Australian beef products are heterogeneous products in that US beef are usually treated as grain-fed and Australian beef are treated as grass-fed. Different quality of beef product may be a major factor in high valued rivalry index because US and Australian beef products may have low rate of substitution. To bypass this beef quality issue, further study should measure the rivalry index under the similar beef quality such as the same grain-fed beef.

This paper used centroid distance between exporting and importing countries as a cost-shifting variable. Generally, beef products are exported by shipment, so the distance between major ports should be an appropriate measure to estimate the marginal cost to export beef. Due to the limited information on exporting country's cost to export, the exporter's cost function is simplified as a linear functional form. This cost function does not reflect returns to scale property and input markets to produce beef to export. Lastly, this paper did not provide statistical methods to test the rivalry index. A statistical method to test the null hypothesis of no collusion may provide a clearer characterization of rivalry. One issue to test the null hypothesis is that the null hypothesis statistic is '1', but the upper bound of the test statistic is '1' as well. To test this truncated statistic parametrically, a test method including truncated distribution such as exponential distribution is necessary.

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CHAPTER IV

CONCLUSION

Four hypotheses was tested in this dissertation. The first and second hypotheses are about measurement of market power and social welfare loss with the concavity condition of the indirect cost function and the homogeneity condition of the out demand in the US beef packing industry. Both hypotheses were tested in the first essay. The first hypotheses was rejected in that the first essay detected significant market power and social welfare loss in the US beef packing industry. The second hypotheses was also rejected as the elasticities of output demand and supply, market power, and social welfare loss are effectively influenced by the concavity and homogeneity conditions. These theoretical restrictions make the market power and the social welfare loss even worse. The third and fourth hypotheses are deal with the competition and collusion of the US and Australia in the South Korean and Japanese imported beef markets. These third and fourth hypotheses were tested in the second essay. The test result for the third hypotheses was inconclusive. Because the model comparison result from the second essay suggests that the best fitting models for the South Korean and the Japanese markets are quantity and price cartel models. On the other hand, the fourth hypotheses was rejected as the rivalry index of both markets are effectively zero, meaning no collusion between the US and Australia in the international beef market.

There are still many works to do regarding the correlation between market power and merger and acquisition in an industry. The NEIO model of first essay can be extended using other NEIO models that supplements Applebaum's classic NEIO model. The rivalry index is also need to develop to measure social welfare change under the collusion of exporters or firms. For further study, one of the limitations of the NEIO approach is that the model itself only measures market power within an industry. Many NEIO studies have dealt with market power focusing on horizontal and vertical integration, or an industry's upstream and downstream marketing channels, but few studies analyzed the effect of market power across industries. Like the case of the M&A between Tyson and IBP, significant market power in one industry could affect other industries and intensify global market power across multiple industries. The effects of increasing market power of one industry on others are rarely known. In light of this limitation, additional research to expand the NEIO model to analyze merger and acquisition activity in the context of market power and social welfare change.

Appendix I. Posterior Effective Sample Size and Convergence criteria, $\hat{R}$ (Non-Hierarchical Model)

Para-meter	No Restriction		Homogeneity in Output Demand		Concavity in Output Cost		Homogeneity and Concavity	
	ESS [a]	$\hat{R}$	ESS	$\hat{R}$	ESS	$\hat{R}$	ESS	$\hat{R}$
b_{KK}	4019	1.000	4225	1.001	4004	0.999	3899	1.000
b_{LK}	3736	1.001	4148	0.999	3881	1.000	3953	0.999
b_{MK}	3684	1.001	4158	0.999	3880	1.000	3853	1.000
b_{LL}	3896	1.001	3786	1.000	3833	0.999	3738	1.001
b_{ML}	3923	1.001	3749	1.000	3808	1.000	3730	1.001
b_{MM}	3952	1.001	3990	1.000	3799	1.000	3736	1.001
b_K	4175	1.000	3965	1.000	3758	1.000	3813	1.000
b_L	4074	1.000	3783	1.000	3886	1.000	3683	0.999
b_M	4035	1.000	3380	1.000	3894	0.999	3909	1.000
b_{Kt}	3973	1.000	3917	0.999	3791	1.000	3829	1.001
b_{Lt}	4167	1.000	3890	1.000	3813	0.999	3706	1.000
b_{Mt}	4229	1.000	4023	1.000	3897	0.999	3709	1.000
α_K	4057	1.000	4057	1.000	3786	1.000	3676	1.001
α_L	3855	1.000	3706	1.000	4108	1.000	3930	0.999

α_M	4101	1.000	4109	1.000	3834	0.999	3988	1.001
β_K	3985	1.000	3897	1.000	3818	1.001	3720	0.999
β_L	4111	1.000	3763	1.000	3633	0.999	3750	1.000
β_M	4151	1.000	4114	0.999	4191	0.999	3584	1.000
γ_K	4146	1.000	4061	1.000	3675	1.000	3369	1.001
γ_L	4238	1.000	4007	0.999	3958	1.000	3671	1.000
γ_M	4266	0.999	4154	0.999	3999	0.999	3815	1.001
δ_K	4161	1.000	3966	1.000	3752	1.000	3808	1.000
δ_L	4069	1.000	3732	1.000	3889	1.000	3687	0.999
δ_M	4044	1.000	3370	1.000	3910	0.999	3910	1.000
η	3990	0.999	3544	1.001	3767	1.000	3831	1.000
λ_1	3777	0.999	3869	1.000	4168	1.000	3914	1.000
λ_2	4028	0.999	4074	0.999	3462	1.001	3997	1.000
τ_1	4159	1.000	3903	1.000	3819	1.001	3958	1.000
λ_3	3887	1.000	- [b]	-	3774	1.001	-	-
τ_2	4073	1.000	3865	1.000	3798	1.002	4004	1.000
τ_0	4089	1.000	3819	1.000	3880	1.001	4004	1.000
θ	4049	0.999	3603	1.000	3758	1.000	3781	1.000
ε	4108	1.000	4000	1.000	4007	1.000	3664	1.001
$\dot{L}$	4086	1.000	3832	1.000	3675	1.000	3636	1.000

Note: $\hat{R} < 1.01$ is indicator of convergence. Larger effective sample sizes are evidence in favor of model convergence.

[a] Effective sample size.

[b] Effective sample size and $\hat{R}$ of λ_3 are omitted because λ_3 is restricted by the homogeneity condition of the output demand function.

Appendix II. Posterior Effective Sample Size and Convergence criteria, $\hat{R}$ (Bayesian Hierarchical Model)

Para-meter	**No Restriction**		**Homogeneity in Output Demand**		**Concavity in Output Cost**		**Homogeneity and Concavity**	
	ESS [a]	$\hat{R}$	ESS	$\hat{R}$	ESS	$\hat{R}$	ESS	$\hat{R}$
b_{KK}	3887	0.999	3836	1.000	3872	1.000	3666	1.000
b_{LK}	3845	0.999	3992	1.000	4037	0.999	3898	1.000
b_{MK}	3844	0.999	4048	1.000	4071	1.000	3994	0.999

b_{LL}	3885	0.999	3999	1.001	3903	1.001	4128	0.999
b_{ML}	3826	0.999	3918	1.001	3885	1.001	4130	0.999
b_{MM}	3797	0.999	3862	1.000	3873	1.001	4133	0.999
b_K	3409	1.001	3874	1.001	3837	1.000	3508	1.000
b_L	3562	1.001	3574	1.002	3944	1.000	3540	1.000
b_M	3330	1.001	4001	1.000	4083	0.999	3759	1.000
b_{Kt}	3739	1.000	3841	0.999	4054	1.000	3979	0.999
b_{Lt}	3764	1.000	3997	1.000	3409	1.000	3973	1.001
b_{Mt}	3724	1.000	3979	1.000	3596	1.000	4125	1.001
α_K	3711	1.000	3872	1.000	3802	1.000	3777	1.000
α_L	3943	1.000	3627	1.001	4004	1.000	3695	1.001
α_M	3719	1.000	3940	1.000	3851	1.000	3727	1.000
β_K	3875	1.000	4117	1.001	4031	1.001	3957	1.000
β_L	3806	1.000	3903	1.000	3445	1.000	3862	1.001
β_M	3806	1.000	4107	1.000	3989	1.000	3741	1.000
γ_K	3731	0.999	3968	0.999	3861	1.000	3846	1.001
γ_L	3746	1.000	3951	1.000	3488	1.000	4161	1.000
γ_M	3709	1.000	3879	1.000	3680	1.000	4169	1.000
δ_K	3483	1.001	3862	1.001	3810	1.000	3553	1.000
δ_L	3701	1.001	3527	1.002	3945	1.000	3547	1.000
δ_M	3418	1.001	4029	1.000	4065	0.999	3811	1.000
η	3548	1.000	3394	1.000	4010	1.000	3840	1.000
λ_1	3596	0.999	3864	1.001	4146	1.000	4095	1.000
λ_2	4044	0.999	3950	1.000	3923	1.001	3728	1.000
τ_1	3699	1.001	3857	1.000	3783	1.000	3604	0.999
λ_3	4084	1.000	- [b]	-	3963	1.000	-	-
τ_2	3612	1.002	3935	1.000	3564	1.000	3615	0.999
τ_0	3632	1.002	4013	1.000	3632	1.000	3624	0.999
θ	3602	1.000	3502	1.000	3935	1.000	3840	1.000
ε	4029	1.000	3769	1.000	3666	1.000	3849	1.000
$\dot{L}$	3812	1.000	3818	1.000	3789	1.000	3815	1.001

Note: $\hat{R} < 1.01$ is indicator of convergence. Larger effective sample sizes are evidence in favor of model convergence.

[a] Effective sample size.

[b] Effective sample size and $\hat{R}$ of λ_3 are omitted because λ_3 is restricted by the homogeneity condition of the output demand function.

Appendix III. Convergence criteria, $\hat{R}$ (South Korea)

Para-meter (1 = US, 2 = Au.)	**Price Competition**				**Quantity Competition**			
	Bertrand	Price Cartel	Australia Price Leader	US Price Leader	Cournot	Quantity Cartel	Australia Quantity Leader	US Quantity Leader
α_1	1.000	1.000	0.999	0.999	205.111	1.000	1.179	4.316
β_{11}	1.001	1.000	2.838	17.053	63.707	1.000	10.209	4.020
β_{21}	1.000	1.001	11.008	10.939	98.508	1.000	2.018	59.659
γ_1	1.000	1.000	1.562	1.272	39.891	1.000	2.078	19.980
δ_1	1.000	1.001	1.804	2.233	1.003	1.000	1.170	3.403
ε_1	0.999	1.000	1.000	1.000	94.731	1.000	1.223	1.535
η_1	1.000	1.000	1.196	2.653	74.489	1.001	2.015	147.816
τ_1	1.000	1.000	1.032	1.144	33.480	1.000	11.213	42.168
υ_1	1.000	0.999	1.041	7.495	98.091	1.000	4.591	135.305
α_2	1.000	1.000	1.000	1.000	188.121	1.000	1.025	2.087
β_{22}	1.000	1.000	19.321	3.019	79.428	1.000	1.034	185.649
β_{12}	1.000	1.000	11.805	11.557	147.817	1.000	1.015	6.819
γ_2	1.000	0.999	1.335	1.135	124.472	1.000	1.062	10.942
δ_2	1.000	0.999	1.073	1.235	1.022	1.000	1.038	2.008
ε_2	1.000	0.999	1.000	1.000	65.341	1.000	1.029	3.284
η_2	1.000	1.000	4.354	1.111	4.682	1.000	2.455	18.076
τ_2	1.000	0.999	1.373	1.146	112.075	1.000	1.259	40.552
υ_2	1.000	1.001	6.366	1.573	19.070	0.999	2.361	30.490
$\det(\mathbf{R})$	1.000	1.000	64.706	60.967	42.958	1.001	1.000	94.497
r_{11}	-[a]	-	-	-	-	-	-	-
r_{12}	1.000	1.001	12.023	10.840	214.681	1.000	1.000	1.958
r_{21}	1.000	1.001	10.355	12.362	28.774	1.000	1.058	1.369
r_{22}	-	-	-	-	-	-	-	-

Note: $\hat{R} < 1.01$ is indicator of convergence.

[a] r_{ii} has no value (-) because r_{ii} is fixed to one.

Appendix IV. Posterior Effective Sample Size (South Korea)

Parameter	**Price Competition**				**Quantity Competition**			
(1 = US, 2 = Au.)	Bertrand	Price Cartel	Australia Price Leader	US Price Leader	Cournot	Quantity Cartel	Australia Quantity Leader	US Quantity Leader
α_1	4386	3982	3932	3873	2	3898	8	2
β_{11}	3670	4036	2	2	2	3911	2	2
β_{21}	4031	4240	2	2	2	3618	3	2
γ_1	4002	3882	3	5	2	3832	3	2
δ_1	4292	4068	3	2	3942	3921	9	2
ε_1	3682	4119	4034	4161	2	4014	25	6
η_1	4084	3930	7	2	2	3689	3	2
τ_1	3671	3899	79	9	2	4006	2	2
υ_1	4079	3936	54	2	2	3855	2	2
α_2	4061	4058	4139	3640	2	3670	502	6
β_{22}	3858	3967	2	2	2	3912	102	2
β_{12}	3886	3418	2	2	2	4176	1859	2
γ_2	3938	4049	4	9	2	3676	30	2
δ_2	3980	4059	18	6	344	3764	100	7
ε_2	3909	4015	4039	4043	2	3952	193	2
η_2	3896	3682	2	12	2	3625	2	2
τ_2	4018	4035	4	9	2	3878	5	2
υ_2	3999	3960	2	3	2	4158	2	2
$\det(\mathbf{R})$	3736	4073	2	2	2	4091	4010	2
r_{11}	-[a]	-	-	-	-	-	-	-
r_{12}	3881	4178	2	2	2	4149	4016	4
r_{21}	4028	4133	2	2	2	4155	24	7
r_{22}	-	-	-	-	-	-	-	-

Note: Larger effective sample sizes are evidence in favor of model convergence.

[a] r_{ii} has no value (-) because r_{ii} is fixed to one.

Appendix V. Convergence criteria, $\hat{R}$ (Japan)

Parameter (1 = US, 2 = Au.)	Price Competition				Quantity Competition			
	Bertrand	Price Cartel	Australia Price Leader	US Price Leader	Cournot	Quantity Cartel	Australia Quantity Leader	US Quantity Leader
α_1	1.000	1.001	1.000	1.000	467.351	1.000	3.707	3.194
β_{11}	1.000	1.001	2.293	20.720	144.282	1.000	1.593	4.267
β_{21}	1.000	1.000	12.017	12.135	44.526	1.000	6.897	54.508
γ_1	1.000	1.000	1.236	1.001	31.245	1.000	1.112	5.117
δ_1	1.000	1.000	1.060	1.034	1.044	1.001	1.100	4.192
ε_1	1.000	1.002	1.000	1.000	211.308	1.000	1.722	6.293
η_1	1.000	0.999	1.068	1.312	63.456	1.000	1.014	85.841
τ_1	1.000	0.999	1.052	4.134	53.930	1.000	1.012	231.907
υ_1	1.000	0.999	1.004	11.190	82.353	1.000	1.073	393.196
α_2	1.000	1.000	1.000	1.000	586.997	0.999	1.996	4.534
β_{22}	1.000	1.000	24.210	2.786	44.320	0.999	1.000	80.174
β_{12}	1.000	0.999	12.451	12.618	269.321	1.000	6.417	36.147
γ_2	1.000	1.000	1.084	1.241	47.248	1.000	1.081	24.540
δ_2	1.000	1.000	1.014	1.016	1.176	0.999	2.387	6.679
ε_2	1.000	1.000	1.000	1.000	290.836	1.000	1.680	14.295
η_2	1.000	1.000	1.277	1.192	150.514	0.999	69.200	144.888
τ_2	1.000	0.999	1.434	1.201	54.309	1.000	1.024	10.193
υ_2	1.000	1.000	12.115	1.004	32.373	1.000	1.306	221.454
$\det(\mathbf{R})$	1.000	0.999	71.483	78.923	155.195	1.000	1.000	18291.0
r_{11}	-[a]	-	-	-	-	-	-	-
r_{12}	1.000	0.999	13.563	12.406	371.879	1.000	1.003	8.324
r_{21}	1.000	0.999	11.212	14.953	182.433	1.000	7.165	7.989
r_{22}	-	-	-	-	-	-	-	-

Note: $\hat{R} < 1.01$ is indicator of convergence.

[a] r_{ii} has no value (-) because r_{ii} is fixed to one.

Appendix VI. Posterior Effective Sample Size (Japan)

Para-meter (1 = US, 2 = Au.)	**Price Competition**				**Quantity Competition**			
	Bertrand	Price Cartel	Australia Price Leader	US Price Leader	Cournot	Quantity Cartel	Australia Quantity Leader	US Quantity Leader
α_1	4051	3717	3764	3966	2	3686	2	3
β_{11}	3857	4116	2	2	2	3767	3	2
β_{21}	3963	3887	2	2	2	3884	2	2
γ_1	3781	4084	6	3817	2	3881	11	2
δ_1	3511	3767	24	60	91	3745	13	2
ε_1	3932	3379	3897	3734	2	3891	3	2
η_1	3653	3677	21	5	2	3840	1793	2
τ_1	3978	3836	32	2	2	3983	2552	2
υ_1	3871	3669	3096	2	2	3707	19	2
α_2	3788	3595	3546	3977	2	3912	3	2
β_{22}	3951	3941	2	2	2	3996	3954	2
β_{12}	3929	4065	2	2	2	3795	2	2
γ_2	3947	3721	15	6	2	3840	16	2
δ_2	3716	4115	517	425	14	4010	2	2
ε_2	3966	3667	4028	3651	2	4120	3	2
η_2	3955	3903	5	7	2	4023	2	2
τ_2	3926	4073	4	7	2	3906	142	2
υ_2	4194	3968	2	3873	2	3905	5	2
$\det(\mathbf{R})$	3746	4144	2	2	2	3828	4011	2
r_{11}	-[a]	-	-	-	-	-	-	-
r_{12}	3935	4081	2	2	2	3819	3124	2
r_{21}	3972	4094	2	2	2	3831	2	2
r_{22}	-	-	-	-	-	-	-	-

Note: Larger effective sample sizes are evidence in favor of model convergence.

[a] r_{ii} has no value (-) because r_{ii} is fixed to one.

Appendix VII. Derivations for the Best Response Function and the System of Equations in Price Competition Case

From the ith exporter's best response functions (Equation 4.1 – 4.3 of Essay 2), the best response functions can be arranged by:

Bertrand:
$$p_i^{BE} = \underbrace{\frac{-\beta_{ji}}{2 \cdot \beta_{ii}}}_{\text{Slope } \left(\frac{\partial q_j}{\partial q_i}\right)} \cdot p_j + \underbrace{\frac{\beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}}}_{\text{Intercept } (\mathrm{I}_i)} \tag{1.1}$$

Stackelberg Price Leader:
$$p_i^{PL} = \frac{-2 \cdot \beta_{ji}}{\left(\frac{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}}{2 \cdot \beta_{jj}}\right)} \cdot p_j + \frac{\left(\frac{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}}{2 \cdot \beta_{jj}}\right) \cdot c_i - \alpha_i}{\left(\frac{4 \cdot \beta_{ii} \cdot \beta_{jj} - \beta_{ij} \cdot \beta_{ji}}{2 \cdot \beta_{jj}}\right)} \tag{1.2}$$

Stackelberg Price Follower:
$$p_i^{PF} = \frac{-\beta_{ji}}{2 \cdot \beta_{ii}} \cdot p_j + \frac{\beta_{ii} \cdot c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{1.3}$$

where the term above the rival's price (p_j) is the slope $\left(\frac{\partial q_j}{\partial q_i}\right)$ of the ith best response function, and the term after p_j is the intercept (I_i) of the best response function.

The system of equation can be derive from the following steps. Assuming there are two exporters, i and j, their best response function can be arranged by:

$$p_i = \frac{\partial p_i}{\partial p_j} \cdot p_j + \mathrm{I}_i$$

$$p_j = \frac{\partial p_j}{\partial p_i} \cdot p_i + \mathrm{I}_j \tag{2.1}$$

By rearranging these function as:

$$p_i - \frac{\partial p_i}{\partial p_j} \cdot p_j = \mathrm{I}_i$$

$$p_j - \frac{\partial p_j}{\partial p_i} \cdot p_i = \mathrm{I}_j \tag{2.2}$$

Finally, the matrix expression of Equation (2.2) is:

$$\begin{bmatrix} 1 & -\frac{\partial p_i}{\partial p_j} \\ -\frac{\partial p_j}{\partial p_i} & 1 \end{bmatrix} \begin{bmatrix} p_i \\ p_j \end{bmatrix} = \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \forall\, i \neq j \tag{2.3}$$

that is Equation (8) in the Essay 2. By solving for the Nash equilibrium in exporter's price, Equation (2.3) can be expressed as:

$$\begin{bmatrix} p_i \\ p_j \end{bmatrix} = \begin{bmatrix} 1 & -\frac{\partial p_i}{\partial p_j} \\ -\frac{\partial p_j}{\partial p_i} & 1 \end{bmatrix}^{-1} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{2.4}$$

where the exporter's Nash equilibrium price vector is at the left-hand side. The inverse matrix of the Jacobian matrix including exporter's bilateral conjectural elasticities can be solved by:

$$\begin{bmatrix} p_i \\ p_j \end{bmatrix} = \frac{\mathrm{adj}(\mathbf{R})}{\det(\mathbf{R})} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{2.5}$$

that is Equation (9) in the Essay 2.

Appendix VIII. Derivations for the Best Response Function and the System of Equations in Quantity Competition Case

By the same logic of the price competition case, the ith exporter's best response functions (Equation 13.1 – 13.3 of Essay 2) can be arranged by:

Cournot:

$$q_i^{CN} = \frac{-\beta_{ji}}{2 \cdot \beta_{ii}} \cdot q_j + \frac{c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{3.1}$$

Stackelberg Quantity Leader:

$$q_i^{QL} = \frac{-2 \cdot \beta_{ij} \cdot \beta_{ii}}{4 \cdot \beta_{jj} \cdot \beta_{ii} - \beta_{ij} \cdot \beta_{ji}} \cdot q_j + \frac{c_i - \alpha_i}{4 \cdot \beta_{jj} \cdot \beta_{ii} - \beta_{ij} \cdot \beta_{ji}} \tag{3.2}$$

Stackelberg Quantity Follower:

$$q_i^{QF} = \frac{-\beta_{ji}}{2 \cdot \beta_{ii}} \cdot q_j + \frac{c_i - \alpha_i}{2 \cdot \beta_{ii}} \tag{3.3}$$

where the term above the rival's price (q_j) is the slope $\left(\frac{\partial q_j}{\partial q_i}\right)$ of the ith best response function, and the term after q_j is the intercept (I_i) of the best response function.

Like the price competition, the system of equation can be derive from the following steps. Assuming there are two exporters, i and j, their best response function can be arranged by:

$$q_i = \frac{\partial q_i}{\partial q_j} \cdot q_j + \mathrm{I}_i$$

$$q_j = \frac{\partial q_j}{\partial q_i} \cdot q_i + \mathrm{I}_j \tag{4.1}$$

By rearranging these function as:

$$q_i - \frac{\partial q_i}{\partial q_j} \cdot p_j = \mathrm{I}_i$$

$$q_j - \frac{\partial q_j}{\partial q_i} \cdot p_i = \mathrm{I}_j \tag{4.2}$$

Finally, the matrix expression of Equation (4.2) is:

$$\begin{bmatrix} 1 & -\frac{\partial q_i}{\partial q_j} \\ -\frac{\partial q_j}{\partial q_i} & 1 \end{bmatrix} \begin{bmatrix} q_i \\ q_j \end{bmatrix} = \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \forall\, i \neq j \tag{4.3}$$

that is Equation (20) in the Essay 2. By solving for the Nash equilibrium in exporter’s quantity, Equation (4.3) can be expressed as:

$$\begin{bmatrix} q_i \\ q_j \end{bmatrix} = \begin{bmatrix} 1 & -\frac{\partial q_i}{\partial q_j} \\ -\frac{\partial q_j}{\partial q_i} & 1 \end{bmatrix}^{-1} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{4.4}$$

where the exporter’s Nash equilibrium quantity vector is at the left-hand side. The inverse matrix of the Jacobian matrix including exporter’s bilateral conjectural elasticities can be solved by:

$$\begin{bmatrix} q_i \\ q_j \end{bmatrix} = \frac{\mathrm{adj}(\mathbf{R})}{\det(\mathbf{R})} \begin{bmatrix} \mathrm{I}_i \\ \mathrm{I}_j \end{bmatrix} \tag{4.5}$$

that is Equation (21) in the Essay 2.

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