Production technology, costs, and multiproduct industry structure: an application of the long-run profit function to the New England fishing industry

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Abstract. The long-run multiproduct profit function is developed to provide a more general procedure than the static minimum cost function to examine the technological and cost determinants of multiproduct industry structure and the likely form of any market equilibrium. In this approach outputs are endogenous and the long-run equilibrium levels of quasi-fixed factors are endogenously determined. The multiproduct structure of the multispecies New England fishing industry and the likely multiproduct form of any open-access equilibrium are examined.

Technologie de production, coûts, et structure industrielle à plusieurs produits: une application de la fonction de profit de longue période à l'industrie des pêches de la Nouvelle Angleterre. L'auteur développe la fonction de profit de longue période pour une industrie où les firmes produisent plusieurs produits afin de mettre en place un cadre d'analyse plus général que la fonction de coûts minima en statique. Cela lui permet d'examiner les déterminants (côté coûts et côté technologie) de la structure industrielle à plusieurs produits et la forme plausible de l'équilibre de marché susceptible de s'ensuivre. Dans cette approche, les niveaux de production sont endogènes et les niveaux de facteurs de production quasi-fixes en équilibre de longue période sont déterminés de façon endogène. L'auteur examine la structure à plusieurs produits de l'industrie des pêches de plusieurs espèces de la Nouvelle Angleterre et la forme multi-produits plausible que l'équilibre est susceptible de prendre quand l'accès est libre.

The multiproduct firm's structures of costs and technology are important determinants of multiproduct industry structure. In order to analyse this structure, Baumol, Panzar, and Willig (1982) recently established theoretical conditions for the existence of multiproduct cost advantages that can be achieved by specialized or diversified firms according to the scale and scope of their production. MacDonald and Slivinski (1985, 1987) further developed the

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analysis of multiproduct industry structure through a multiproduct generalization of Viner's (1952) procedure. In this approach costs are primarily distinguished between fixed and variable, upon which various forms of structure can be placed. The primary issue then becomes the existence of specialized and diversified firms in specialized, diversified, or mixed market equilibriums due to an advantage in either variable or fixed costs.

The theoretical treatments of MacDonald and Slivinski and Baumol, et al., do not necessarily require firms to produce the same exogenously specified set of goods; that is, a firm's product combinations can be endogenous although the overall industry level is exogenous. Yet, empirical analyses of multiproduct industry structure have typically used static minimum cost functions to examine these technological and cost determinants, and this approach implicitly assumes that each firm's outputs are exogenously determined and inputs are in full static equilibrium. (For recent examples, see Gillen and Owen, 1984; Mayo, 1984; and Kohli, 1981.) Both of these conditions are likely to be violated in practice, and any subsequent analyses of multiproduct industry structure and form of equilibrium are likely to be biased. Empirical analysis should therefore allow both for outputs to be decision variables to firms and for empirical determination of the long-run equilibrium levels of any quasi-fixed factors. A ready distinction between variable and fixed costs would also be more consistent with the theoretical treatments. The long-run multiproduct profit function offers just such a general approach to provide analyses consistent with theoretical conditions.

The long-run multiproduct profit function is developed in this article to analyse the firm-level technological and cost determinants of the multispecies New England otter trawl industry's structure and to determine the likely form of an open-access equilibrium.[1] Although Gordon (1954) first posited the general principles of an open-access equilibrium in fishing industries, its detailed multiproduct form at the level of the individual firm has been neglected.

The structures of the New England and many other coastal fishing industries have remained largely composed of single-vessel firms individually owned and operated. While many U.S. industries have become structurally concentrated through firm amalgamation, most of the fishing industries have displayed little vertical or horizontal integration. This structure has persisted despite the Magnuson Fisheries Conservation and Management Act (hereafter the Magnuson Act) of 1976 and the United Nations Third Law of the Sea Conference, which extended economic zones to 200 miles and severely curtailed the previously dominant fishing of foreign distant-water fleets. Rather than expanding to the larger scale but narrower scope of the foreign fleets, which might have allowed domination of the newly protected industries, the United

1 Otter trawling involves dragging a net at the stern or side of a vessel. After a period of time, the net is hauled in and its catch released onto the deck, where it is sorted, gutted, and packed in ice. The process is repeated throughout the fishing trip.

States and many other coastal nations have largely maintained their scope of production but with limited scale.

This paper thus develops the long-run multiproduct profit function and several long-run multiproduct cost concepts for the profit function to explain the persistent atomistic structure of the New England otter trawl industry, the prevalence of individual ownership and operation of single-vessel, multiproduct firms, the likely form of any open-access multiproduct equilibrium, and the failure of New England vessels to increase their scale of production to that of foreign distant-water fleets after the Magnuson Act. The paper is organized as follows. The next section discusses the long-run multiproduct profit function, while the third section develops the long-run multiproduct cost concepts. The fourth section provides an industry background, and the fifth section empirically implements the model. The sixth section provides the empirical results, and concluding remarks follow in the last section.

LONG-RUN PROFIT FUNCTION

The long-run multiproduct function is developed from the restricted (or variable) profit function. The restricted profit function HR may be defined as: $\text{HR}(P_M, P_N; K) = [\max_{Y,X} P'_M Y - P'_N X:(X, Y; K) \in Z]$, where HR is restricted profit (total revenue less variable costs), P_M is an $M \times 1$ vector of output prices, P_N is an $N \times 1$ vector of variable factor prices, $P = (P_M, P_N)$, $'$ is the transpose operator, Y is an $M \times 1$ vector of outputs, X is an $N \times 1$ vector of variable factors, K denotes the level of the quasi-fixed factor, capital, and Z represents the restricted production possibilities set for which a number of regularity conditions are assumed (McFadden, 1978). Given the assumptions on Z, HR is non-negative and well defined for all $P > 0$ and any K, HR is continuous, linearly homogeneous, and convex in P, HR is continuous, non-decreasing, and concave in K, and HR is non-decreasing (non-increasing) in $P_M(P_N)$ for every fixed K (McKay, et al.). Total profit, HT, at K can be specified as $\text{HT}(P, K) = \text{HR}(P; K) - P_K K$, where P_K is the market rental (service) price of capital.

The long-run multiproduct profit function, H, is obtained by application of the envelope condition (Samuelson, 1953). This condition states that in static equilibrium, the derivative of HR with respect to the quasi-fixed or fixed factor – that is, the shadow price – must equal the market rental price: $P_K = \text{HR}_K(P, K^*)$, where HR_K is the first partial derivative of the restricted equilibrium profit function with respect to K (or the shadow price of capital), and K^* is the optimal stock of capital. Optimal long-run levels of demand for K are obtained by solving $P_K = \text{HR}_K(P, K^*)$. Substitution of K^* into total profit provides the long-run multiproduct profit function in terms of P and K^*: $H(P, P_K) = \text{HR}[P, K^*(P, P_K)] - P_K K^*(P, P_K)$.

MULTIPRODUCT COST CONCEPTS

The restricted profit function embodies information not only on the firm's long-run technology, but also on the firm's cost structure.[2] This is easily shown by equivalently writing HR(·) as $HR(P_M, P_N; K) = [\max_Y P'_M Y - C(P_N, Y; K)]$, where $C(P_N, Y; K)$ is the firm's restricted cost function (Sakai, 1974). Hence firms initially minimize variable costs for each level of output conditional on the level of K and then maximize restricted profits conditional on K. Note that Y is a decision variable to firms. The long-run profit function, H, at K^* becomes $H(P, P_K) = HR[P, K^*(P, P_K)] - P_K K^*(P, P_K) = [P'_M Y^* - C(P_N, Y^*, K^*) - P_K K^*(P, P_K)]$, where Y^* is optimal Y. In contrast, the static minimum cost function is specified: $C(P_N, P_K; Y)$, where Y is exogenous. Evaluating the structure of long-run multiproduct costs from the long-run profit function rather than the static minimum cost function insures that evaluation is at optimal Y and K rather than the presumed K and an exogenous level and mix of Y which may or may not be optimal.

Economies of scope

Economies of scope are one of the most important elements of the multi-product cost structure and measure the effects of joint production upon costs. Economies of scope can arise from two cost sources: weak cost complementarity and fixed costs (Gormon, 1985). A twice differentiable multiproduct cost function C exhibits weak cost complementarities over the product set M, up to Y, if $C_{ij}(Y'') \leqq 0$, i not equal to j, for all Y'' with $0 \leqq Y'' \leqq Y$, with the inequality holding strictly over a set of non-zero measure, where C_{ij} is the second partial derivative of C with respect to products i and j. Thus the marginal cost of producing one product decreases (weakly) with increases in the quantities of all other products (Baumol, et al., 1982). In the absence of fixed costs, weak cost complementarities are a sufficient condition for economies of scope (Baumol, et al., 1982). In the absence of weak-cost complementarities, fixed costs can also generate scope economies. Fixed costs can also overcome weak-cost discomplementarities to generate economies of scope (Gormon, 1985).

The presence of weak-cost complementarities can be determined from the long-run multiproduct profit function by the results of Sakai and Lau (1976). Sakai indicates the following relationship between the Hessian matrix of C and the Hessian of the profit function H: $[C_{ij}] = [H_{ij}]^{-1}$, $i \neq j$, $i, j \in M$, where H_{ij} represents the second partial derivative of H with respect to the ith and jth product prices. Lau relates the derivatives of the long-run (H) and restricted (HR) profit functions, so that all terms entering $[H_{ij}]^{-1}$ can be derived from the

2 The cost or profit function summarizes all economically relevant information about the production technology of the firm but not about the firm's organizational technology. As Teece (1980) notes, to assert otherwise would involve assuming rather than deducing the condition for efficient multiproduct organization.

restricted profit function:

$$H_{ij} = \mathrm{HR}_{ij} - (\mathrm{HR}_{KK})^{-1}\mathrm{HR}_{iK}\mathrm{HR}_{jK}, \qquad i, j \in M. \qquad (1)$$

Product-specific returns to scale

Product-specific returns to scale measure the change in costs through variation in the output of one product while holding the quantities of other products constant. Firms with increasing product-specific returns to scale have a cost incentive to expand the scale of production of this product and may become specialized in its production. Following Baumol et al. (1982), define incremental cost of product i at Y as: $\mathrm{IC}_i(Y) = C(Y_i) - C(Y_{M-i})$, where Y_{M-i} is the output vector in which $Y_i = 0$. Average incremental costs at Y are $\mathrm{AIC}_i(Y) = \mathrm{IC}_i(Y)/Y_i$. Product-specific economies of scale at Y, $S_i(Y)$, are $S_i(Y) = \mathrm{IC}_i(Y)/Y_iC_i = \mathrm{AIC}_i(Y)/C_i$, where C_i is the marginal cost of C with respect to product i. S_i at Y are increasing, decreasing, or constant as $S_i(Y)$ is greater than, less than, or equal to unity, respectively.

The profit function cannot directly measure product-specific returns to scale, but a sufficient condition can be obtained by examining incremental marginal costs (Baumol, et al., 1982). The diagonal elements of the Hessian submatrix for outputs provide the measure of incremental marginal costs: $H_{ii}^{-1} = C_{ii}(P_N, P_K, Y^*)$. $H_{ij}^{-1}(Y^*) < 0$ implies decreasing marginal and average incremental costs, $S_i(Y^*) > 1$, and marginal costs from $i >$ revenue from i. Because the inverse marginal cost curves $C_i(P_N, P_K, Y^*)^{-1}$ equated to product prices are synonymous with the product supply curves at Y_i^* (Beattie and Taylor), a direct relationship exists between the firm's product supply and marginal cost curves with the profit function – in contrast to the minimum cost function.

Long-run multiproduct returns to scale

Long-run multiproduct or ray returns to scale for the profit function measure the behaviour of costs for proportional changes in total firm output and all variable and fixed inputs.[3] This is a straightforward extension of the concept of single-product scale economies, where the output composition remains fixed while its scale can vary. The degree of long-run ray returns to scale equals the ratio between long-run production costs and the revenues that occur with marginal cost pricing. The revenues exceed, are less than, or equal long-run costs as there are decreasing, increasing, or locally constant long-run ray returns to scale (Bailey and Friedlaender, 1982).

3 The single-product profit function is not well defined for increasing or constant returns to scale, but the multiproduct profit function does not suffer from this limitation. The structure of multiproduct costs is dependent upon both the scale and the composition of outputs. Increasing ray returns to scale implies only that the existing division of products among more than one firm would be more costly than monopoly production. Some other division of outputs among smaller, perhaps specialized, firms may provide an even less costly form of organization. Moreover, the profit function can still be estimated if firms are not price takers. (Diewert, 1982)

Cost subadditivity

The concept of cost subadditivity provides an additional measure by which to characterize the multiproduct cost structure. A cost function is said to be subadditive at an output vector, say Y, if and only if it is cheaper for a single firm to produce Y than to split it among more than one firm in any fashion. Formally, a cost function C is strictly subadditive at Y if $C(Y) < {}_i\Sigma_k C(Y_i)$ whenever ${}_i\Sigma_k Y_i = Y$ (Baumol et al., 1982).

The presence of cost subadditivity would suggest that some form of fishermen's monopoly is appropriate on private efficiency grounds. The monopoly could be private, could entail either complete government ownership and control as is found in the socialist block nations, could include extensive government co-ordination and regulation as is found in north-east Asia, or could consist of a set of single-product firms contracting among themselves.

Tests of cost subadditivity are difficult to devise, since one of the requirements is global knowledge of the cost function, while local knowledge in the neighbourhood of the point of approximation is usually the best that can be achieved. Acceptance of local subadditivity then provides a sufficient condition for global cost subadditivity (Evans and Heckman, 1984). Although Baumol et al. (1982) provide both necessary and sufficient conditions for cost subadditivity, the long-run multiproduct profit function (and cost function) allows only local sufficient conditions. Failure to establish cost subadditivity will then not preclude its existence. Previous tests of cost subadditivity specify all factors of production to be in full static equilibrium and outputs as exogenously fixed – specifications relaxed in this study.

In general, cost subadditivity requires economies from proportional expansion of the product vector along an output ray and economies arising from product combinations along a cross-sectional hyerplane (Baumol, et al., 1982). A necessary and sufficient condition for economies from proportional expansion of products along a ray is ray subadditivity.[4] Increasing multiproduct returns to scale up to Y in turn imply decreasing average costs along a product ray (ray average cost) up to Y, and therefore ray subadditivity at Y (Baumol, et al., 1982).[5]

Sufficient conditions for cross-sectional economies include the existence of cost convexity, weak cost complementarity throughout the product set, or transray convexity. Cost convexity and weak cost complementarity are sufficient conditions for transray convexity (Wang Chiang, 1981). Roughly speaking, a cost function is transray convex if, as a firm changes the composition of output while holding fixed the level of some aggregate measure for output, costs will be lower for diverse rather than specialized output mixes

4 A cost function C is strictly ray subadditive at Y if, for any set of two or more positive numbers v_i that sum to one, $C(v_i Y) > C(Y \Sigma v_i) = C(Y)$ (Baumol, et al., 1982)

5 Ray average costs (RAC) of producing the output vector Y are given by RAC $= C(kY)/k$, where Y is the vector of firm outputs, arbitrarily set equal to unity, and k is a positive constant. This defines the behaviour of costs along a ray emanating from the origin. RAC are said to be declining (increasing) as $C(k_1 Y)/k_1 < (>)\ C(k_2 Y)/k_2$ for $k_1 > k_2$ (Mayo, 1984).

(Bailey and Friedlaender, 1982).[6] Overall transray behaviour is difficult to test with either cost or profit functions, but testing for pairwise transray convexity is straightforward. If transray convexity does not exist among all product pairs, then transray convexity does not hold (Wang Chiang, 1981). Baumol et al. (1982) indicate that either one of the following conditions is sufficient for transray convexity between outputs i and j:

$$C_{ii} \geqq 0,\ C_{jj} \geqq 0,\ C_{ij} = C_{ji} \leqq 0,$$
$$C_{ii} \leqq 0,\ C_{jj} \leqq 0,\ C_{ij} = C_{ji} \leqq 0,\ C_{ij} \leqq -(C_{ii}C_{jj})^{1/2}. \quad (2)$$

Two sufficient conditions for cost subadditivity are testable with the long-run profit function. The first-sufficient condition is convexity in the cost function and ray subadditivity (Baumol, et al., Sharkey). This condition can be tested with the long-run profit function by examining for convexity the Hessian submatrix of costs with respect to outputs, $[H_{ij}]^{-1}\ \forall\ i, j \in M$. As noted above, increasing multiproduct returns to scale indicate declining ray average costs. A second-sufficient condition for cost subadditivity is transray convexity of the cost function and declining ray average costs (Baumol, et al., 1982; Sharkey, 1982). As before, increasing multiproduct returns to scale indicate declining ray average costs. Because weak cost complementarities among all product pairs are a sufficient condition for transray convexity, failure to establish the result provides evidence against transray convexity. The nature of transray convexity among all product pairs provides additional evidence on overall transray convexity at Y: failure to establish transray convexity among all product pairs indicates that overall transray convexity does not hold (Wang Chiang, 1981).

Market equilibrium

MacDonald and Slivinski (1985, 1987) show that multiproduct market equilibrium can take one of three forms: (1) pure specialization, in which no diversified or multiproduct firms operate; (2) pure diversification, in which no single-product firms operate; or (3) mixed equilibrium involving both diversified and specialized firms. The form of equilibrium depends upon the existence of an advantage in variable or fixed costs for either specialized or diversified firms.

INDUSTRY BACKGROUND

The multispecies New England otter trawl industry exploits some of the world's most valuable fishing grounds. The most important species harvested (in order of value) include cod, yellowtail and other flounders, haddock, redfish, and

6 Formally, a cost function C exhibits transray convexity along the hyperplane $\Sigma\, a_i Y_i = L$, $\forall\ a_i > 0$, if for any vector of products Y' and Y'' on L, $C(bY' + (1 - b)Y'') \leqq C(Y') + (1 - b)C(Y'')$, $0 < b < 1$. Thus the costs of producing a weighted sum of outputs jointly along any given transray cross section will be less than the weighted costs of individual production.

pollock. Firms are typically quite diversified in product mix although usually oriented toward particular product combinations. The aggregate demand for fresh and frozen fish is much larger than the quantity harvested by the fleet, and excess demand is satisfied by a substantial volume of imports. The harvested fish are marketed fresh in a variety of ways at the ex-vessel level. The ports of New Bedford and Boston contain important spot or auction markets, where fishermen sell their catches to the highest bidder. An important co-operative exists in Point Judith to which members are generally obliged to sell their harvests. In other ports the catch is sold directly to fish processors and brokers or by prior arrangement between individual vessels and fish processors (Wilson, 1980). Product prices vary by vessel.

Area can affect the production technology and cost structure through port effects on prices and institutional practices. Spatial variation in resource abundance is also important; cod is ubiquitously distributed, the flatfish are generally in central and southern waters, pollock and redfish tend to be in northern waters, and the underutilized miscellaneous species are generally in the warmer southern waters. Because of the inherent mobility of boats, all vessels can readily move up and down the coast but seldom to a great distance on any given trip. Boats can also primarily harvest in either offshore or inshore waters; the composition of fish stocks differs by these areas. Inshore vessels are more constrained by inclement weather and rough seas, often cannot harvest from offshore grounds, and make more frequent trips of less duration. Most fish species are harvested throughout the year. Seasonality is most important by virtue of its limiting smaller and inshore vessels in periods of rough weather and seas.

Few fishing firms are horizontally integrated to include two or more vessels, and individual owners operate most vessels. Vertical integration between shore-side processors and boats remains limited to the O'Hara Corporation of Rockland, Maine; instead, the trend over the past two decades is toward divestiture. The industry does not contain any vessels integrating the harvesting and processing functions, nor are mother ships employed.

EMPIRICAL IMPLEMENTATION

Translog profit function

Fishing vessels harvest multiple species with the levels and composition of catch as decision variables of the firms. Fuel, labour, and capital (in the form of the vessel, gear, and equipment) are organized to produce these multiple products. Fishing firms may be regarded as multiproduct firms producing a vector of endogenous outputs from a vector of endogenous inputs. The endogenous outputs and inputs suggest that a profit rather than cost or revenue function is the appropriate dual representation of the firm's production technology. In particular, the multiproduct profit function framework allows endogenous products without the econometric problems of simultaneous equations or the assumption of homothetic separability otherwise required for cost functions.

The translog multiproduct restricted profit function used for the empirical analysis is specified as a second-order Taylor's series approximation around the unit vector by scaling all variables by their arithmetic mean:

$$\begin{aligned}\ln \text{HR} = {} & A_0 + A_T T + A_{\text{IN}}\text{IN} + \Sigma_r A_r R_r + \Sigma_i A_i \ln P_i + A_K \ln K \\ & + \Sigma\Sigma_{ij} A_{ij} \ln P_i \ln P_j + A_{KK} \ln K \ln K + \Sigma_i A_{iT} \ln P_i T \\ & + \Sigma_i A_{i\text{IN}} \ln P_i \text{IN} + \Sigma\Sigma_{ir} A_{ir} \ln P_i R_r + \Sigma_i A_{iK} \ln P_i \ln K. \qquad (3)\end{aligned}$$

Variables are defined as above and in further discussion below. The revenue and cost share equations by Hotelling's Lemma are

$$\begin{aligned}\partial \ln \text{HR}/\partial \ln P_i = P_i Y_i/\text{HR} = U_i = {} & A_i + A_{iT}T + A_{i\text{IN}}\text{IN} + \Sigma_r A_{ir} R_r \\ & + \Sigma_j A_{ij} \ln P_j + A_{iK} \ln K, \qquad \forall\, i \in M, N, \qquad (4)\end{aligned}$$

which are negative for inputs and positive for outputs. Without loss of generality, symmetry requires $A_{ij} = A_{ji}$, $i \neq j$, i, $j \in M$, N, and linear homogeneity in the variable prices requires: $\Sigma_i A_i = 1$, $\Sigma\Sigma_{ij} A_{ij} = \Sigma_i A_{ij} = \Sigma_j A_{ij} = \Sigma_i A_{iK} = \Sigma_i A_{iT} = \Sigma_i A_{i\text{IN}} = \Sigma_i A_{ir} = 0$. These restrictions are directly imposed.

Resource abundance is specified as a technological constraint, since it is beyond the control of any individual firm but nevertheless affects the production environment within which the firm operates. Changes in resource abundance may then be viewed as shifts in the production technology that relates the generation of outputs from inputs (McFadden, 1978; Gordon, 1954). These changes are indexed by the 1981 dummy variable T, where the intercept is 1980.

Three dummy variables R_r designating vessels' home ports are specified to capture area affects: New Bedford, Rhode Island, and Maine. The intercept includes Gloucester, Boston, and other Massachussetts ports. A dummy variable IN for vessels averaging trips of less than two days duration indexes inshore vessels.

The restricted profit function (3) and revenue and cost share equations (4) have additive disturbances, owing to errors in optimization and the stochastic nature of fishing. The large number of harvesters and processors and the presence of auction markets assure exogenous product prices. Factor prices are exogenous because inputs are exchanged regionally and even nationally. Since the share equations sum to unity, the energy consumption equation is dropped and its parameters are identified through the linear homogeneity and symmetry restrictions. The system of equations (3)–(4) is estimated by maximum likelihood using TSP 4.0D, and the results are invariant to choice of deleted equation.

The expressions for long-run pairwise weak-cost complementarity and product-specific incremental marginal costs with the translog multiproduct profit function are derived in the same manner as the long-run factor demand elasticities presented in Brown and Christensen (1981) and Kulatilaka (1985), so that only their final forms are presented. Equation (1) with the translog form becomes

$$H_{ij} = (\text{HR}/P_iP_j)[(A_{ij} + U_iU_j) - (A_{iK} + U_iU_K)(A_{jK} + U_jU_K)/(A_{KK} + U_K^2 - U_K)]. \quad (5)$$

Equation (6) below with the translog form for an individual product provides the basis for the non-statistical test of product-specific incremental marginal costs.

$$H_{ii} = [(\text{HR}/P_i^2)(A_{ii} + U_i^2 - U_i) - (A_{iK} + U_iU_K)^2/(A_{KK} + U_K^2 - U_K)]. \quad (6)$$

The measure for multiproduct returns to scale with the long-run translog profit function is

$$({}_i\Sigma_N\, U_i + U_K)/({}_j\Sigma_M\, U_j). \quad (7)$$

Since measurement is taken along the expansion path, this is also a measure of long-run overall size economies.

The data

The balanced panel data set consists of annual observations for two years, 1980 and 1981, on forty-two full-time otter trawlers with home ports in all of the major and most minor New England ports. Three outputs are specified in the profit function (3) and share equations (4): roundfish (cod and haddock), flatfish (yellowtail and other flounders), and a residual, all others (pollock, redfish, miscellaneous species).[7] Two variable inputs are specified: labour (including captain) and energy (fuel and oil) consumption. The quasi-fixed input, capital, is represented by the vessel's gross registered tons (GRT). The return to labour is measured by its opportunity cost. The opportunity cost of labour per crew member is a Divisia index of the mean annual opportunity incomes of the crew (total manufacturing), the mechanic (maintenance mechanic, machinery), and captain (20 per cent higher than an ordinary seaman's), and varies by vessel and port. These data are from the U.S. Bureau of Labor Statistics and comparable state agencies. Most vessel acquisition prices are obtained from receipts and are measured without error; the remainder are from federal tax returns. Fuel prices are cash prices for number two diesel

7 The roundfish and flatfish species assemblages are Divisia indices, while the all others assemblage linearly aggregates over fifty different species. There are fifty-eight parameters to be estimated in the profit function and eighty-four observations. The limited number of observations precludes introducing fixed effects into the profit function, which would require estimation of forty-one additional parameters.

TABLE 1

Summary statistics of data

Variable	Mean	Minimum	Maximum
Price of roundfish	0.1961	0.1502	0.2630
Price of flatfish	0.2575	0.1694	0.3808
Price of all others	0.1494	0.0104	1.2841
Price of fuel	0.5812	0.5143	0.6611
Opportunity cost of labour per person	7801.1	6975.3	9715.7
Capital services price	42949	6100	155908
Pounds of roundfish	439623	2596	1268439
Pounds of flatfish	284993	26148	1091562
Pounds of all others	883201	4763	17925792
Crew size	5.29	2	10
Gross registered tons	120	22	314
Maine engine horsepower	514	225	1400
Days absent from port	167	85	249
Number of trips per year	57	14	257
Profit shares offshore vessels			
Roundfish	0.4033	0.0087	1.636
Flatfish	0.5163	0.0243	1.526
All others	0.7379	0.0283	1.706
Labour	0.3795	0.1043	1.508
Fuel	0.2780	0.0785	0.861
Capital	0.2819	0.0742	0.834
Profit shares inshore vessels			
Roundfish	0.8346	0.1310	1.845
Flatfish	0.5732	0.1159	1.075
All others	0.1983	0.0051	0.689
Labour	0.3267	0.1379	0.754
Fuel	0.2793	0.1058	0.937
Capital	0.2834	0.1464	0.750

NOTES
All values are in $1972 after deflation by GNP implicit price index.
All values are per vessel per year.
Data sources are described in text.

fuel from marine fuel docks. Fuel cost data are from federal income tax returns. Vessel-specific revenue and landings data and vessel and crew size are from the National Marine Fisheries Service's Weighout File. All values are deflated by the GNP implicit price index. Most data are confidential and proprietary. Table 1 provides a summary of the data set.

EMPIRICAL RESULTS

The estimated parameters of the translog multiproduct restricted profit function are reported in table 2.[8] The system's R^2 is 0.99, which is very close to

8 Each column in table 2 (except that labelled profit function) represents the parameter estimates corresponding to the ith revenue or input share equation. By assumption, the corre-

1, thereby indicating that the goodness-of-fit of the estimation is very good. The fitted share equations are consistent with monotonicity for all sample values. The restricted profit function is not convex in prices at the point of approximation, although this is not a statistical test.[9] The profit function is concave in the quasi-fixed factor.

Optimal capital stock

A numerical solution is required to solve for the optimal capital stock, $K^* = K^*(P, P_K)$, since a closed-form analytical solution is not possible with the translog form. Because the data are normalized to unity at the arithmetic sample mean, the parameter estimates in table 2 are employed to solve for the percentage deviation from the optimal long-run equilibrium stock of capital. Separate mean capital services prices per gross registered ton are used for inshore and offshore vessels at the point of approximation.

The divergence between estimated K^* and the observed K may simply reflect sampling error in the estimated optimal stock of capital, which can be tested under the null hypothesis: $K^* = K$. If the null hypothesis is not rejected, then the multiproduct cost structure can be evaluated at the observed level of K; otherwise the estimated K^* is employed. Following Kulatilaka, the delta method is used to derive a first-order Taylor's series approximation for the variance of K^*. A t-test is then constructed for the difference between the ratio K^*/K and unity: $t = [(K^*/K) - 1]/[V(K^*)]^{1/2}$, which is t-distributed, where $V(K^*) = K_A{}^*(A)K_A{}^{*\prime}$, A is the vector of estimated parameters and thus is a random variable, $K_A{}^*$ is a vector of partial derivatives of K^* with respect to A, and $K_A{}^* = -(\text{HR}_{KK})^{-1}\text{HR}_{KA}$ evaluated at K^*. Because the use of fitted profit shares in calculating $V(K^*)$ may not provide a normally distributed test statistic with the translog form (Anderson and Thursby 1986), the test statistic is evaluated at the point of approximation using both fitted and mean actual profit shares for 1980.

The ratio of optimal GRT to observed mean GRT for offshore vessels in 1980 is 0.902 (= 106.23 GRT*/117.81 GRT) and for inshore vessels is 0.655 (= 81.92

sponding parameter estimates of the profit and share equations are equal. Thus the parameter estimates corresponding to equations (3) and (4) are A_i for the intercept, A_{ii} for the own price, A_{ij} for cross-price interaction terms, and A_{iK} for the interaction between the own price and capital. The profit equation column reports parameter estimates unique to the profit equation itself, so that the intercept term refers to A_0 in equation (3), A_T refers to the 1981 intercept term, A_{IN} refers to the inshore dummy variable, R_r refers to the three area dummy variables, A_K refers to the first-order capital variable, and A_{KK} refers to the squared capital variable.

9 The generalized R^2 is computed as $1 - \exp(2(l_0 - L_1)/N)$, where $L_0(L_1)$ is the sample maximum of log-likelihood when all slope coefficients are zero (unconstrained) and N is sample size (Baxter and Cragg, 1970). A test of convexity cannot be interpreted as strictly a test of profit maximization, because convexity can be violated for a number of other reasons. For example, Wales (1977) shows that the estimates of a flexible functional form may violate convexity even if the data come from a perfectly well-behaved technology. Linear aggregation of over fifty species into the all others assemblage can also cause the apparent failure of convexity.

TABLE 2

Parameter estimates of translog restricted profit function

Exogeneous variables	Product shares			Factor shares		Profit function
	Roundfish	Flatfish	All others	Labour	Fuel[a]	
Intercept	0.875 (0.084)	0.262 (0.070)	0.490 (0.085)	−0.325 (0.061)	−0.303 (0.047)	0.086 (0.142)
1981 dummy	−0.052 (0.070)	0.101 (0.060)	0.092 (0.074)	−0.122 (0.064)	−0.020 (0.042)	−0.142 (0.132)
Inshore	0.066 (0.096)	0.006 (0.078)	−0.251 (0.108)	0.157 (0.084)	0.023 (0.056)	0.191 (0.178)
New Bedford dummy	−0.197 (0.104)	0.456 (0.085)	−0.281 (0.120)	−0.034 (0.093)	0.056 (0.062)	−0.072 (0.197)
Rhode Island dummy	−0.616 (0.106)	0.088 (0.085)	0.212 (0.105)	0.085 (0.951)	0.231 (0.938)	0.303 (0.188)
Maine dummy	−0.510 (0.106)	0.157 (0.080)	0.319 (0.098)	0.105 (0.940)	−0.070 (0.939)	−0.049 (0.165)
Roundfish price	−0.400 (0.255)	0.175 (0.164)	−0.153 (0.055)	0.261 (0.149)	0.117 (0.101)	
Flatfish price		−0.381 (0.167)	−0.144 (0.044)	0.334 (0.113)	0.016 (0.071)	
All others price			−0.060 (0.038)	0.215 (0.036)	0.142 (0.022)	
Opportunity cost of labour				−0.811 (0.179)	−0.001 (0.208)	
Fuel price					−0.276 (0.362)	
Capital	0.292 (0.068)	−0.384 (0.056)	0.229 (0.072)	−0.008 (0.060)	−0.130 (0.039)	0.664 (0.140)
Capital squared						0.114 (0.072)

a Parameter estimates are derived from the constraints implied by linear homogeneity in prices and symmetry.

NOTE: Linearized standard errors are in parentheses.

GRT*/125.00 GRT). The estimated t for offshore vessels with actual (fitted) shares is −0.04 (−0.02) and for inshore vessels is −0.16 (−0.15), implying no statistically significant difference between optimal and observed capital stocks for either sector at conventional levels of significance. The test result may reflect a robust level of optimal long-run capital stock in an industry in which fishermen make long-run investment decisions with expectations of important cyclical and stochastic fluctuations in resource abundance over both time and space. Moreover, since a vessel of a certain size and design is required to fish in the stormy north-west Atlantic and to reach the fishing grounds, optimal capital stock is likely to be quite robust.

TABLE 3

Multiproduct Cost Structure

	Weak cost complementarity			
	Roundfish	Flatfish	All others	Incremental marginal costs
Inshore				
Roundfish		−0.771	0.301	0.138
Flatfish			−1.235	−5.260
All others				0.883
Offshore				
Roundfish		−0.789	0.213	0.155
Flatfish			−0.927	−5.780
All others				0.399

NOTES

Evaluated at arithmetic sample mean for all Massachusetts ports in 1980 except New Bedford.
Evaluated using fitted shares calculated with optimal capital.
Weak cost complementarity values calculated using equation (5).
Incremental marginal cost values calculated using equation (6).

Multiproduct cost structure

Table 3 presents the estimated 1980 structure of long-run multiproduct costs evaluated at the optimum (equals observed) capital stock for both inshore and offshore vessels. The results are calculated using fitted shares evaluated at the point of normalization and optimal (here equals observed) capital stock. The empirical results calculated using 1980 arithmetic mean values of actual profit shares provide the same qualitative results. Table 1 provides these actual shares.

The results for long-run pairwise cost complementarities indicate that product-specific economies of scope exist between flatfish and the two other products, roundfish and all others, for both inshore and offshore vessels. Flatfish are a pivotal species because cost savings accrue to vessels harvesting flatfish with roundfish and all others. The most important factor contributing to scope economies may be the spatial distribution of different species assemblages among different fishing grounds and latitudes along with the inherent mobility of vessels. The variations in species composition of the resource by latitude and distance from shore tend to impose both upper and lower limits to the extent of scope economies. Seasonality is of minimal importance because important species groups are harvested throughout the year. Fishing skill and experience also contribute. The usual contributors toward economies of scope in multiproduct industries, such as risk minimization and the quasi-public nature of capital, may also be important (cf. Bailey and Friedlaender, 1982; Baumol, et al., 1982; Sharkey, 1982). The similarity of factor proportions for different products may also contribute (MacDonald and Slivinski, 1985).

The incremental marginal costs results for both inshore and offshore vessels suggest the presence of declining product-specific marginal and average incremental cost curves and increasing product-specific returns to scale for flatfish but decreasing product-specific returns to scale for roundfish and all others. Declining flatfish stocks that are placed under excessive harvesting pressure can cause excess flatfish harvesting capacity, and therefore the declining product-specific cost curves. None the less, even though product-specific returns to scale for flatfish are increasing, specialized flatfish vessels are unlikely because economies of scope are realized by jointly harvesting flatfish with other species.

The 1980 estimate of long-run multiproduct returns to scale using fitted shares is 0.79 for offshore vessels and 0.77 for inshore vessels, indicating decreasing overall returns to scale for both sectors. Cost or profit advantages do not accrue from increasing production in fixed output proportions holding prices and resource abundance constant. As the scale of production expands for a given level and mix of resource abundance, vessels fish in more marginal grounds, further deplete the resource stocks in existing areas, fish in more adverse weather, and so forth. The decreasing product-specific returns to scale and limits to economies of scope contribute toward the decreasing ray returns.

The two sufficient conditions for cost subadditivity are not satisfied by the empirical results. The evidence of decreasing overall returns to scale indicates that ray subadditivity is unlikely. Cross-sectional economies are also limited, since only limited pairwise weak-cost complementarities and no pairwise transray convexities are found. Moreover, evaluation of the Hessian submatrix of outputs pertaining to the cost function indicates the absence of uniformly positive-definite diagonal elements and principal minors which are not all positive semi-definite. The cost surface is not convex with respect to outputs. Some form of fishermen's monopoly does not provide the most efficient method by which to organize production.[10]

Multiproduct industry structure

The multiproduct cost structure indicates that New England fishing firms under open-access resource conditions face definite limits to the private cost savings they could enjoy from expanding the scale and narrowing the scope of their production. Vessel orientation remains coastal, and does not emulate the large vessels of the foreign distant-water fleets. Large vessels of that magnitude require enormous levels of resource abundance, such as that realized by harvesting in a world scale. This factor and the high search costs of locating

10 Monopoly organization which optimizes the amount of social fishing effort over time might be socially efficient by mitigating market failure from congestion and stock externalities. The procedure developed in this study does not consider any extant external costs and benefits, and is static in the population dynamics.

fish contribute toward the constant movement and pulse fishing of distant-water fleets.[11] The relatively high opportunity cost of labour and the relatively low opportunity cost of animal protein in the United States further increase the costs of operating large distant-water fleet vessels by New England fishermen. In contrast, distant-water fleets composed of large catcher-processors tend to be successfully operated by nations with a sufficiently advanced industrial base and higher opportunity costs of protein production from agriculture and / or lower opportunity costs of labour, such as the socialist bloc nations, the countries of north-east Asia, and several western European nations.

Specialized firms are limited, because both the fixed and variable costs should be lower for diversified firms than for specialized firms. The increasing product-specific returns to scale occurs with the same species assemblage, flatfish, which realizes economies of scope with both the other outputs. Although under current open-access resource conditions flatfish revenues alone are insufficient to cover the incremental costs of its production, sufficient cost savings are generated because of the scope economies to insure continued flatfish harvesting. That is, the economies of scope sufficiently outweigh product-specific scale effects for flatfish. Variable costs of diversified firms are therefore less than those that would occur with specialized firms.

The structure of fixed costs further contributes to the absence of specialized firms. The absence of cost subadditivity, presence of decreasing ray returns to scale, and capital at its optimum level suggest definite limits to the magnitude of fixed costs arising from the production technology. That is, these fixed costs are relatively small, particularly in comparison to the overall level of industry output, which MacDonald and Slivinski (1985) indicate favours a diversified equilibrium.

Costs arising from the organizational technology also limit firm specialization. Intangible assets such as technological knowhow, management, and information can be divided into a pure public input of overall knowledge of fishing and seamanship and into product-specific knowledge about different species and grounds. Because up to some point product-specific knowledge can be acquired at minimal additional costs through the general process of fishing, the incremental fixed knowhow and informational costs of producing additional species are comparatively small, which allows all fixed costs to be spread among more outputs. This spreading of fixed costs and sharing of intangible assets among additional outputs, in turn, generates scope economies (Baumol, et al., 1982; Gormon, 1985; Teece, 1980, 1982), and further favours diversified over specialized firms.

Prohibitive transactions and information costs are perhaps the most limiting constraint to firm amalgamation of these multiproduct firms. Coase (1937) argues that activities are collected in a firm when the transactions costs

11 Pulse fishing refers to the practice of heavily exploiting a given area and then moving on to a new area.

incurred using the price mechanism of a market exceed the costs of organizing the activities through direct managerial controls. The firm will expand until the marginal value of an additional transaction internal to the firm equals the cost at the margin of increasing the size of the firm. These costs, or diseconomies of scale to firm size, are in turn related to the fixed supply of entrepreneurial input and the high costs of obtaining information as well as organizational and strategic impediments to its market transfer (Williamson, 1979; Teece, 1980, 1982; Sharkey, 1982).

Fishing is particularly sensitive to entrepreneurial and managerial ability, especially at the vessel level, because it is a semi-systematic, spatially dispersed hunting process. Information on location and availability of fish is therefore important. Since the plant dimension is the vessel, which is an indivisible and lumpy asset, and the vessel is very mobile and spatially dispersed from other vessels, transferring information from one vessel to another is costly and difficult. Moreover, attracting and retaining competent skippers with high skill levels in multivessel firms is difficult. Because vessel acquisition prices are sufficiently small, a skilled captain can easily aspire to vessel ownership, and capable skippers have high opportunity costs to vessel operatorship without ownership.[12]

Successful multivessel firms instead tend to be owned and operated only under circumstances substantially reducing transactions and information costs between vessels. The most common occurrences are ownership by an extended family employing family members as skippers, which removes transactions costs from market valuation, and ownership by very experienced fishermen intimately involved in operating their vessels. The latter can also attract competent crews and skippers and captain vessels when necessary. Thus, other than under exceptional circumstances, organizational diseconomies limit horizontal integration of these multiproduct but single-vessel firms.

The cost structure also inhibits vertical integration of the processing and harvesting sectors. Following Williamson, the criterion for organizing commercial transactions is assumed to be cost minimization. Vertical integration entails removing transactions from the market and organizing them internally

12 Although the economic returns to solely vessel ownership may be limited (unless for tax shelter purposes), ownership in conjunction with the captain's share, any efficiency rents due to skill, and non-pecuniary returns from this way of life then lead to an attractive overall return.

Monopoly reasons for merger also do not exist, nor are there advantages to obtaining vessels cheaper through merger than through purchase. Economies of networking and materials procurement are also not factors. Some capital-raising or other similar pecuniary economies probably exist, but they are not dominant factors.

The structure of transactions costs also favours diversified (but single-vessel) firms. Technology and fishing skill transfer opportunities among different species groups are recurrent rather than occasional (because of the indivisible and spatially dispersed vessel as a quasi-public input), and the application specialized rather than non-specialized. Intrafirm production of multiple products therefore lowers transactions costs more than two specialized firms contracting among themselves in order to enjoy economies of joint production (Teece 1980, 1982).

within the firm. Vertical integration of harvesting and processing in this industry necessarily implies horizontal integration of vessels or a large expansion in the scale of production. Costs are instead lowered by procuring fish supplies through the market rather than organizing production internally to the firm, since the cost structure typically precludes multivessel firms or expanding the scale of production. Stable and adequate supplies are also available to processors from the large number of individual vessels or fish brokers, thereby reinforcing the more efficient cost structure attained by separating the ownership of harvesting and processing with a more limited scale of production. Backward integration into production by processors is instead more likely if resources are scarce and supplies uncertain. Production risks are also retained by producers, particularly the crew, because of the share of labour remuneration system. The relationship between processors and harvestors remains predominantly a bilateral governance structure, in which the autonomy of the parties is maintained (Wilson, 1980).

CONCLUDING REMARKS

The structure of long-run multiproduct costs indicates that industry structure is likely to remain atomistic, displaying minimal vertical and horizontal integration of firms. Individual owner-operatorship of single-vessel, multiproduct firms remains the norm. Evidence is not provided for private efficiency gains from industry concentration or centralization through expanding the scale or scope of production, horizontal integration, or a fishermen's monopoly. Family ownership and operation remain feasible, and the possibility exists of purchasing smaller boats and moving up in scale as experience and savings are accumulated. Any open-access multiproduct equilibrium that might exist is likely to be diversified, because both variable and fixed costs should be lower for diversified firms than for specialized firms.

The long-run multiproduct profit function offers a convenient framework to analyse the technological and cost determinants of multiproduct industry structure and the likely form of equilibrium. The levels and mixes of outputs are decision variables to firms, the long-run equilibrium levels of any quasi-fixed factors are endogenously determined, and a ready distinction is made between variable and fixed costs.

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