Marine Resource Economics, Volume 22, pp. 1–14
Printed in the U.S.A. All rights reserved
0738-1360/00 $3.00 + .00

Optimal Vessel Quotas and Capacity of a Danish Trawler Fleet Segment: A Dual Approach

AYOE HOFF
HANS FROST
University of Copenhagen

Abstract *In the period of investigation, 1995–2000, the Danish fishery for species meant for human consumption was managed by individual non-transferable vessel quotas, while the fishery for species meant for fishmeal and fish oil was subject to a total quota. The revenues of the fishermen targeting species for human consumption are therefore fixed on the assumption that they are price takers, and that they will maximize profits by minimizing their costs. To model the economic behaviour of the fishermen in terms of the optimal quota size per vessel and optimal fleet size, a dual cost-function approach is an appropriate choice. This method is applied using a generalized Leontief cost function to model the behaviour of the Danish fleet of trawlers below 50 GRT, targeting species for human consumption solely. The estimated cost function is used to determine the optimal quotas yielding: (i) minimum average cost and (ii) maximum profit.*

The results of the estimations show that the optimal quotas per vessel should be increased by more than 2.5 times and consequently that the fleet should be reduced by more than 60%. As this has not been the case, a probable explanation is that non-transferable quotas leave the fishermen with the option of quitting the fishery only if a decommissioning programme is in place. There is no option to transfer the quota to another vessel.

Key words Cost function, dual approach, economic behaviour, Leontief cost function, long-run equilibrium, maximum profit, minimum average cost.

JEL Classification Codes B41, C13, C61, C67.

Introduction

The Danish fishery is generally managed by a combination of quota regulation and capacity regulation. The latter is managed by a permit issued to the given vessel, which in turn must be registered in the Danish register for fishing vessels. The permit is an exclusive licence to fish, incorporating certain capacity specifications in relation to tonnage and engine power. Changes in capacity are limited by a set of rules imposed by the Danish development programme for capacity limits to the Danish fishing fleet, subject to the Common Fisheries Policy of the European Union (Lindebo 2000).

Ayoe Hoff is a research fellow and Hans Frost is an associate professor. Both are at the Institute of Food and Resource Economics, Fisheries Economics and Management Division Faculty of Life Sciences, University of Copenhagen, Rolighedsvej 25, 1958 Frederiksberg C, DK- Denmark, email: ah@foi.dk and hf@foi.dk, respectively.
We received helpful comments from two anonymous referees, which are greatly appreciated. We are indebted to Helle Gjeding Jorgensen who has carried out a linguistic check of the article.

The actual fishery is regulated through a combination of different quota systems for different species. The Danish fishery has most commonly been managed by quotas based on the TACs (total allowable catch) allocated by the European Union to Denmark in a given year. On top of the exclusive vessel licence, permits are granted to the fishermen as non-transferable quotas of the target species according to vessel length. The individual vessel quotas are normally allocated sequentially for periods of less than a year; for example, on a monthly basis. The fishery for demersal species, such as cod, haddock, saithe, plaice, and lobster, has been managed by individual non-transferable vessel quotas since 1993. The demersal fishery is mainly conducted by vessels less than 20 metres in length (approximately 50 GRT[1]). For pelagic species, non-transferable quotas have also been applied since 1993, while the Danish fishery for herring has been subject to individual transferable quotas (ITQs) since 2003 based on historical rights. The herring fishery is mainly executed by large vessels with a length of 40 metres and over (above 300 GRT). The vessel group between these two has mostly been targeting species meant for fishmeal and fish oil (industrial species), which are managed by general quotas. Nearly the entire Danish fishery will be managed by ITQs subject to the TAC allocated to Denmark by the European Union by 2007.

As such, output regulation is the dominating factor in the management of the Danish fishing fleet. When output is regulated solely through TACs, the fishery is dominated by a 'race to fish.' In this case, each fisherman is a revenue maximiser. It could be argued that this is the case for the segment of the Danish fleet targeting industrial species. When output is regulated through individual quotas (IQs), however, the gross revenue of the individual fisherman is fixed, assuming exogenous fish prices, and it is expected that he will maximise his profits by adjusting costs. As noted by Jensen (2002), "Cost minimization is a relevant option for describing firms that vary their input compositions, while output supply functions are restricted and vertical." Thus, the appropriate approach to model the economic behaviour of the Danish vessels with IQs is a dual cost-function approach.

The Danish fleet of trawlers below 50 GRT targeting codfish, flatfish, and lobster falls in this category; *i.e.*, it is regulated through individual non-transferable quotas. The average profit realized by this fleet was approximately zero, indicating profit dissipation due to overcapacity (FOI 2001). The aim of this paper is to assess to what extent a reallocation of the individual non-transferable vessel quotas, followed by a fleet-capacity reduction, will improve the economic situation of the fleet. The generalized Leontief cost function is applied to model the cost relationship for the fleet, and the resulting cost function will be used to determine the economically optimal quota structure of the fleet. In this connection, three optimal quota structures are considered: (*i*) quotas yielding minimum average short-run costs, (*ii*) quotas yielding maximum profits for the average vessel in the fleet, and (*iii*) quotas yielding maximum long-run profit. Further, in each case it is assessed how much the fleet must be reduced, on average, to compensate for the increased IQs, *i.e.*, how much overcapacity the fleet is operating with at present.

The paper is introduced with a presentation of the dataset used in the present application. Secondly, the properties of cost functions are discussed, and the generalized Leontief cost function is presented. This is followed by a discussion of optimal economic behaviour estimated through cost functions. The paper concludes with a presentation of the estimation results for the fleet of Danish trawlers below 50 GRT, followed by a summary and discussion of the results.

---

[1] A good fit is provided by the formula: $GRT = 0.0298^{*}length^{2.4968}$, $R^2 = 0.958$.

The Danish Trawler Fleet below 50 GRT

The selected fleet segment, the Danish fleet of trawlers below 50 GRT operating in all Danish fishing grounds, is one of five fleet segments for which account statistics have been published (FOI 1995). It is one of the most important segments of the Danish fleet, and is constituted by 505 vessels, falling to 469 in the period 1995–2000. This is 27% and 31%, respectively, of the total number of vessels in the Danish fleet.[2]

The account statistics are based on a sample of 82 vessels in 1995 and 98 vessels in 2000, a total of 561 observations are available for the whole period. Data is aggregated on a yearly level for each vessel included in the dataset. Of the vessels in the sample, only those for which the catch weight of cod, flatfish, and lobster constitutes more than two-thirds of the total catch weight are included. This implies that vessels targeting industrial species, which are not subject to IQs, are left out. This leaves 253 observations. Of the remaining observations, 77 indicate very low fishing costs relative to catches per fishing days compared to the average of the total sample, and have been omitted from the final dataset. The omitted observations could have been caused by faulty recordings, odd fishing patterns, "lucky catches," particularly skilled skippers, *etc*. The inclusion of these observations would have entailed continuously decreasing average costs, and hence the optimal capacity in terms of vessels would decrease towards zero. This leaves 176 observations (vessels) in total that with a high degree of certainty are subject to restrictions in terms of individual non-transferable quotas. Table 1 presents average catch revenues and catch weights of the target species. It is seen that cod is the most important species regarding catch weight, as well as revenue.

Extensive data are available concerning the expenses of the fleet in question, comprising disaggregated information on maintenance, sale costs, running costs, depreciation, *etc*. In the present study, three aggregated cost variables have been constructed for each observation: wage per crewman, overall running costs per days at sea, and capital costs per gross tonnage.[3] The wage per crewman is estimated as the recorded wage expense paid by the owner/skipper of the vessel to the crew, plus the calculated return to the owner/skipper divided by number of crewmen. The measure of capital costs for the vessel has been estimated at 0.12 times the total assets of the vessel at the end of the year, divided by the vessel tonnage. Determination of

Table 1
Average Catch Revenue (1000 ¤[*]) and Weight (tonnes) per Vessel for the Danish Trawler Fleet Targeting Cod, Lobster, and Flatfish (1995–2000)

	Total	Cod	Lobster	Flatfish	Other
Revenue	173 (91)	68 (61)	61 (69)	39 (30)	5 (6)
Weight	81 (48)	49 (45)	8 (9)	20 (14)	4 (4)

[*] The exchange rate between DKK and ¤ is 7.44 to 1.
Note: Numbers in the parentheses are the standard deviations.

[2] Actually, the figures are for companies. However, very few companies own more than one vessel.
[3] The authors are aware that some input cost separability is hereby implicitly assumed. This has not been tested, but care has been taken to add costs relating to the same inputs.

capital costs is subject to some discussion in the literature. The choice of 12% covers interest, depreciation, and a risk premium. Sensitivity analyses regarding alternative capital costs are performed to investigate the impact on the results. Finally, the measure of running costs per fishing day has been estimated as the sum of the expenses for fuel, maintenance, ice, stores, and landing costs, divided by the number of days at sea. The variable short-run costs are the total variable expenses for each observation, including running costs and wages, but excluding capital costs. The total short-run costs are the sum of the variable costs and capital expenses. Table 2 shows the averages and standard deviations for the three cost variables and the total short-run costs for the fleet. Moreover, the average number of crewmen, the average number of days at sea, and the average vessel tonnage are shown.

Table 2
Averages and Standard Deviations of Cost- and Capacity-variables for the Danish Trawler Fleet (<50 GRT) Targeting Cod, Lobster, and Flatfish (1995–2000)

Total Short-run Costs (1000 ¤*)	Wage (1000 ¤*)	Crew	Running Costs (1000 ¤*)	Days at Sea	Capital Costs (1000 ¤*)	Tonnage (GRT)
180 (84)	40 (12)	2 (1)	0.4 (0.3)	165 (37)	1.2 (0.7)	21 (12)

* The exchange rate between DKK and ¤ is 7.44 to 1.
Note 1: Wages are per crewman, running costs per days at sea, and capital costs per GRT.
Note 2: Numbers in the parentheses are standard deviations.

The Generalized Leontief Cost Function

A fishing vessel is characterised by the output catch (production) of a number of different species ($y_1,\ldots,y_M$) obtained using a number of inputs ($x_1,\ldots,x_N$); *e.g.*, fishing days, engine power, crew size, capital, *etc*. For any given combination of input prices and output values, a vector of inputs can be found that: (*i*) can produce the given outputs and (*ii*) minimizes the cost, C, of doing so. The long-run cost function is defined as the minimum cost of production, given the levels of outputs and (exogenous) input prices ($w_1,\ldots,w_N$) (Heathfield and Wibe 1987; Chambers 1988):

$$C(y_1, ..., y_M, w_1, ..., w_N) = \min_{x_1,...,x_N} \left\{ \sum_{n=1}^{N} w_n \cdot x_n \middle| (y_1, ..., y_M) \right\}. \tag{1}$$

In the short run, some of the input factors; *e.g.*, the capital, k, may be fixed. In this case, the restricted short-run cost function is given by (Segerson and Squires 1990):

$$\begin{aligned} C_{SR}(y_1, ..., y_M, w_1, ..., w_V, k, w_k) &= \min_{x_1,...,x_V} \left\{ \sum_{i=1}^{V} w_n \cdot x_n \middle| (y_1, ..., y_M) \right\} + w_k \cdot k \\ &\equiv VC(y_1, ..., y_M, w_1, ..., w_V, k) + w_k \cdot k, \end{aligned} \tag{2}$$

where $(x_1,\ldots,x_V)$ are the inputs that are variable in the short run, *VC* is the short-run variable cost function, and w_k is the price of the fixed capital, *k*.

A cost function should, as a rule, fulfil the following regularity conditions, be: (*i*) positive, (*ii*) non-decreasing as a function of the input prices, (*iii*) non-decreasing in the outputs (monotonicity), (*iv*) concave and continuous in the input prices, and (*v*) homogeneous of degree one in the input prices (Chambers 1988). Furthermore, when the cost function is differentiable in input prices, *w*, it fulfils Shepard's lemma for the demand of the inputs:

$$\frac{\partial C}{\partial w_n} = x_n . \tag{3}$$

The own- and cross-price elasticities of the input factors, which measure the change in the demand of input *i* when the price of input *j* varies, are defined as (Heathfield and Wibe 1987):

$$\varepsilon_{ij} = \frac{\partial x_i}{\partial w_j}\frac{w_j}{x_i} = \frac{w_j}{\left(\frac{\partial C}{\partial w_i}\right)}\frac{\partial^2 C}{\partial w_j \partial w_i} . \tag{4}$$

The overall multi-product returns to scale are defined as (Kumbhakar 1994):[4]

$$ORTS = \left[\sum_{m=1}^{M}\frac{\partial \ln C}{\partial \ln y_m}\right]^{-1} = \frac{C}{\sum_{m=1}^{M} y_m \frac{\partial C}{\partial y_m}} . \tag{5}$$

The firm is said to have economies of scale when ORTS > 1; *i.e.*, when the percentage change in total costs is less than a percentage increase in outputs along a ray. Or said in another way, when increasing production leads to decreasing overall average costs.

The specific form of the cost functions is most often unknown and must, therefore, be approximated by a flexible continuous, twice differentiable functional form. Often encountered flexible forms are the translog and the generalized Leontief cost functions.[5]

The translog function has the weakness that it cannot include zero output values, which is in itself a disadvantage when the catch of some species is zero. It also makes it difficult to calculate economies of scale (Kumbhakar 1994). The generalized Leontief function has been used in the present context. Including *M* outputs, *N* variable inputs, and one fixed input *k*, this is defined as (Diewert and Wales 1987; Kumbhakar 1994; Larsson 2003):

$$C_L^M(y_1, ..., y_M, w_1, ..., w_N, w_k, k, t) \tag{6}$$

---

[4] A straightforward extension of the well-known measure of returns to scale for a single output firm.
[5] The generalized McFadden cost function (Kumbhakar 1994) is yet another possible flexible form, which is, by construction, concave in the input prices.

$$= \left(\sum_{r=1}^{M}\delta_r y_r\right)\left[\sum_{i=1}^{N}\sum_{j=i}^{N} b_{ij} w_i^{1/2} w_j^{1/2} + t\sum_{i=1}^{N} b_{it} w_i + t^2 \sum_{i=1}^{N} b_{itt} w_i + k\sum_{i=1}^{N} b_{ik} w_i + k^2 \sum_{i=1}^{N} b_{ikk} w_i\right]$$

$$+ \sum_{i=1}^{N} a_i w_i + t\sum_{i=1}^{N} a_{it} w_i + k\sum_{i=1}^{N} a_{ik} w_i + \sum_{i=1}^{N}\sum_{r=1}^{M}\sum_{s=r}^{M} \beta_{irs} w_i y_r y_s + w_k \cdot k$$

$$\equiv VC_L^M(y_1, ..., y_M, w_1, ..., w_N, t) + w_k \cdot k,$$

where VC_L^M is the variable cost, and C_L^M is the total cost of production. One disadvantage of using a flexible functional form is that it will seldom fulfil the regularity conditions (see above) required for the cost function. As stated by Diewert and Wales (1987), “One of the most vexing problems applied economists have encountered in estimating flexible functional forms in the production or consumer context is that the theoretical curvature conditions that are implied by economic theory are frequently not satisfied by the estimated cost (…) function.” It is thus necessary to restrict the shape of the flexible function in such a way that it will comply, either locally or globally, with the regularity conditions. Imposing regularity conditions through parametric restrictions on the flexible functional forms has been widely applied in dual theory (see Diewert and Wales 1987 for a detailed discussion of the subject).

In the present context, the function (6) is by construction homogeneous of degree one in the input prices. Furthermore, it will be increasing and globally concave in the input prices if $\delta_r \cdot b_{ij} \geq 0$ for all r, i and j.[6] If this constraint is introduced, it will rule out the possibility of complementarity between the inputs (cf. Diewert and Wales 1987), which is why it is not included in the present case. Instead, the authors have chosen to test for local concavity in the observation points included in the estimations. Finally, the function (6) is not automatically increasing in the outputs. Inspection of the function shows that it is a second-order polynomial in the outputs, formulated by:

$$f(y_1, ..., y_M) \equiv \sum_{i=1}^{N}\sum_{r=1}^{M} w_i \beta_{irr} y_r^2 + \sum_{i=1}^{N}\sum_{\substack{r,s=1 \\ r \neq s}}^{M} w_i \beta_{irs} y_r y_s + A\sum_{r=1}^{M} \delta_r y_r + B, \tag{7}$$

where A and B are functions of input prices, time, and capital. For this function to be globally increasing for all $y > 0$, its corresponding parabola must firstly open upwards, and secondly, the parabola minimum must be attained for $y_r \leq 0$ for all r. These conditions are ensured by restricting $\beta_{irs} \geq 0$ for all i, r, s.

The input demand equations for the variable inputs are derived from equation (6) by Shepard’s lemma (equation 3):

$$x_n = \frac{\partial VC_L^M}{\partial w_n} \tag{8}$$

[6] This rule is an extension of the rule stated by Diewert and Wales (1987) for the one-output case.

$$= \left(\sum_{r=1}^{M} \delta_r y_r\right)\left[b_{nn} + \sum_{j\neq n} b_{nj} \frac{w_j^{1/2}}{2w_n^{1/2}} + t \cdot b_{nt} + t^2 b_{ntt} + k \cdot b_{nk} + k^2 b_{nkk}\right]$$

$$+ a_n + t \cdot a_{nt} + k \cdot a_{nk} + \sum_{r=1}^{M}\sum_{s=1}^{M} \beta_{nrs} y_r y_s .$$

Economic Optimality

The cost function estimates the lowest cost of a firm (fishing vessel), given the observed output, fixed input, and input prices. However, if the firm is subject to restrictions on the output; *i.e.*, in the case of fishing subject to catch quotas, it may not be operating in an economically optimal situation. Three measures of economic optimality, as defined by optimal individual vessel quotas, will be discussed below: the optimal quotas yielding: (*i*) minimum average costs, (*ii*) maximum profit for the vessel, and (*iii*) long-run maximum profit.

Given the output restrictions for the individual vessel, it may be operating in a short-run temporary cost equilibrium, but not necessarily be utilising its potential catch capacity in a long-run optimal way (Morrison 1985). However, if the vessel is not bound by the output restrictions, it can adjust the output freely and thereby move to a full, long-run economic equilibrium, with a lower average cost per output unit. The output y^* corresponding to this equilibrium is, as such, the optimal long-run quota level for the vessel (Morrison 1985; Nelson 1989), given the fixed (capital) input k^*. This long-run equilibrium output is determined by the tangency point between the short-run average cost curves, given k^*, and the long-run average cost curve, as illustrated in figure 1. The area of interest is where the long-run marginal costs are increasing, and the condition for optimal adaptation is where the marginal revenue is equal to the marginal costs.

For the output defining the tangency point, the (fixed) vessel capital that classifies the short-run average cost curve, will simultaneously be the long-run equilibrium capital; *i.e.*, the capital that minimizes the total short-run cost function (2). Thus, for the output at the tangency point, the derivative of (2) with respect to k will be equal to zero:

$$\frac{\partial VC(y_1, ..., y_N, w_1, ..., w_N, k)}{\partial k} + w_k = 0. \qquad (9)$$

The optimal long-run quota, given k^*, is therefore estimated by solving equation (9) with respect to the output.

When more than one output is present, as is the case in the present context, it is not so straightforward. Segerson and Squires (1990) suggest several different approaches. One approach is solving equation (9) for the outputs one at a time, thereby determining the optimal quota of individual species under the assumption that the quotas of the remaining species are not changed. This approach, however, is not applicable when the aim is to estimate the economically optimal quotas of all species simultaneously. Another approach is to find the optimal quotas of the catch species along a ray through the original quota vector; *i.e.*, to assume that the average vessel catches the different species in fixed proportions. Thus, if the vessel quota vector is given by $(y_1^0, ..., y_M^0)$, it is assumed that the vessel catch will be given by some ex-

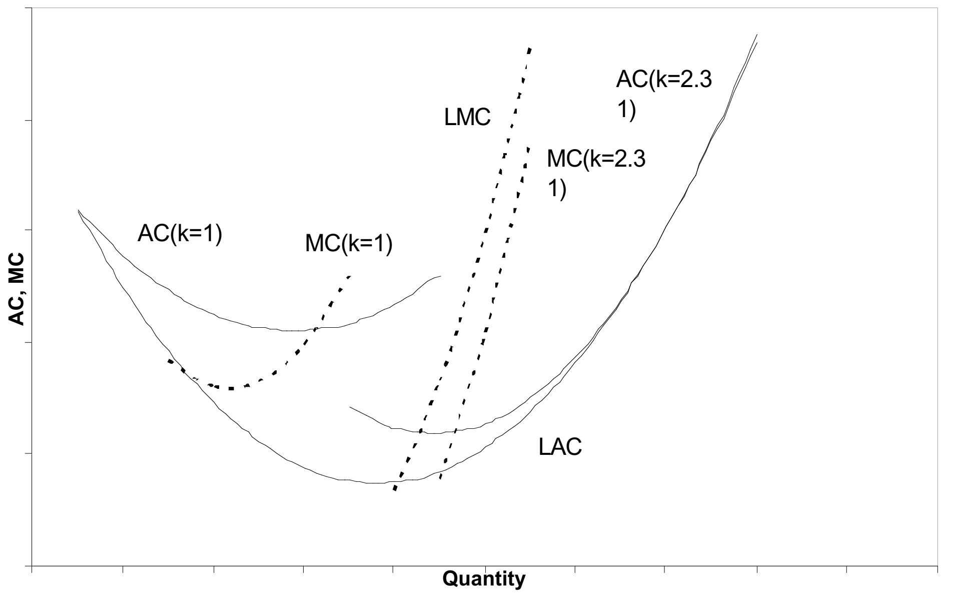

Figure 1. Long-run Average Cost (LAC) and Short-run Average Cost (AC) Curves, the Latter at Fixed Capitals, k = 1 and k = 2.31

Note: Constant returns to scale (CRS) are defined by the minimum points on the AC-curves, while maximum profit is determined by the intersection of the (upwards sloping) MC-curves and the marginal revenue (not indicated).

pansion factor, r, times this vector; *i.e.*, by $r \cdot (y_1^0, ..., y_M^0)$. The optimal long-run quota vector is then estimated by finding the value r^* that solves the equation:

$$\frac{\partial VC(r \cdot y_1^0, ..., r \cdot y_M^0, w_1, ..., w_N, k)}{\partial k} + w_k = 0. \qquad (10)$$

This approach is used in the present context. The fleet's optimal long-run quota expansion factor, r, is established using the vector of average catch weights over the total period as the individual vessel quota vector (table 1). The resulting optimal long-run quota vector is used to: (*i*) estimate the potential long-run yearly profit for the average vessel in the fleet and (*ii*) determine the overcapacity of the fleet. The latter is defined as the amount by which the number of vessels in the fleet must be reduced, when the individual vessel quota vector is increased, in order for the fleet not to exceed its TAC.

While it is assumed that the average vessel catches different species in fixed proportions, the overall returns to scale [ORTS, equation (5)] gives the inverse percentage change in total costs per percentage change in the output expansion factor. When ORTS > 1, the average cost decreases as the output vector increases, providing incentives to increase the output until ORTS = 1. Likewise, while ORTS < 1, the average cost increases as the output vector increases, thus creating incentives to decrease the production until ORTS = 1. ORTS = 1; *i.e.*, the point at which the average cost is minimum (figure 1), is therefore the optimal situation, seen from the short-run cost perspective, even though this may not be the optimal long-run solution. In the present context, individual vessel quota vector expansion factors resulting in ORTS = 1 (constant returns to scale [CRS]) have been calculated and reused to determine the potential yearly CRS rent, as well as the yearly overcapacity of the fleet when the average vessel is operating at CRS.

Finally, the question of how much the present quota vector must be expanded in order to secure maximum short-run profit of the individual vessels remains. The profit is given by:

$$P_{SR}(y_1, ..., y_M, p_1, ...p_M, w_1, ..., w_N, k, w_k) \qquad (11)$$
$$= \sum_{j=1}^{M} y_j p_j - C_{SR}(y_1, ..., y_M, w_1, ..., w_N, k, w_k),$$

where C_{SR} is the total short-run cost function given in equation (2), and p_j is the price of the j'th output. While it is assumed that the fleet catches different species in fixed proportions; *i.e.*, that the catch of the vessels in the fleet will always be given by some factor, p, times to original quota vector $(y_1^0, ..., y_M^0)$, the above equation can be maximized with respect to p, indicating how large the quota of the individual vessels must be in order to secure maximum profitability of the average vessel in the fleet.

The long-run quota and capacity are obtained by estimating the long-run average costs (envelope curve) based on short-run average costs. The quota vector yielding the maximum profit is then calculated.

Estimation Results

The variable short-run generalized Leontief Cost function (6) has been estimated for the fleet of Danish trawlers below 50 GRT as described above, with the $N = 2$ variable input prices given in table 2 (wages and running costs), the $M = 4$ output groups given in table 1 (cod, lobster, flatfish, other species), and a fixed capital input, k; *i.e.*, tonnage. The time parameter t spans $t = 1$ (1995) to $t = 6$ (2000). The cost function is estimated with the two input demand equations for days at sea and the number of crewmen derived by equation (8); *i.e.*, the demand for days at sea is equal to the derivative of equation (6) with respect to the running costs, and the demand for crewmen is equal to the derivative of equation (6) with respect to wages. The three equations are estimated using seemingly unrelated regression (SUR), thus increasing the accuracy of the estimated function parameters. In the estimation, the restriction $\beta_{irs} > 0$ and has been included for $i = 1,2$, and $r,s = 1,\ldots,4$ to ensure monotonicity. The model has been estimated for normalised values of the short-run variable costs, the outputs, and the capital input; *i.e.*, all values have been divided by their averages. The SUR results for this variable short-run Leontief cost function, estimated for the dataset described above, are shown in tables 3A and 3B.

The model was tested for collinearity using the condition number method. Some collinearity was suggested between the different terms that are functions of the capital, k. This is expected, as lower- and higher-ordered terms in the same variable are usually correlated in polynomial regression. This may increase the standard error for the lower-ordered term regression parameters, but will not generally change the value of the estimated coefficients, as these are still the best linear unbiased esti-

Table 3A
Parameters of the Restricted Generalized Leontief Variable Cost Function (Equation 6) for the Danish Trawler Fleet (<50 GRT)

Parameter	Value	Parameter	Value
δ_2	1.8971 (0.5960)*	b_{1k}	–0.2348 (0.0942)*
δ_3	2.3018 (0.9981)*	b_{2k}	–0.0018 (0.0319)
δ_4	0.7279 (0.4008)	b_{1kk}	0.0511 (0.0212)*
b_{11}	0.0233 (0.0387)	b_{2kk}	–0.0017 (0.0081)
b_{12}	0.2258 (0.0762)*	a_1	0.1047 (0.1697)
b_{22}	–0.0807 (0.0373)*	a_2	0.2522 (0.1124)*
b_{1t}	–0.0069 (0.0074)	a_{1t}	0.0028 (0.0198)
b_{2t}	–0.0003 (0.0048)	a_{2t}	0.0146 (0.0135)
b_{1tt}	0.0004 (0.0009)	a_{1k}	0.6915 0.1887)*
b_{2tt}	$4 \cdot 10^{-6}$ (0.0006)	a_{2k}	0.1803 (0.1147)

Note 1: '*' indicates that the parameters are significantly different from zero at the 5% level.
The subscripts for inputs are: '1'=wages, '2'=running costs. The subscripts for outputs are: '1'=cod, '2'=lobster, '3'=flatfish, '4'=other species.
Note 2: Numbers in parentheses are standard errors on the parameters.

Table 3B
Parameters of the Restricted Generalized Leontief Variable Cost Function (Equation 6) for the Danish Trawler Fleet (<50 GRT)

Parameter	Value	Parameter	Value
β_{111}	0.0073 (0.0115)	β_{211}	0.0199 (0.0051)*
β_{112}	0.0206 (0.0252)	β_{212}	0.0008 (0.0124)
β_{113}	0.0457 (0.0226)*	β_{213}	~0
β_{114}	0.0304 (0.0135)	β_{214}	~0
β_{122}	0.0284 (0.0138)*	β_{222}	0.0004 (0.0059)
β_{123}	0.0937 0.0337)*	β_{223}	0.0253 (0.0190)
β_{124}	~0	β_{224}	~0
β_{133}	0.0010 (0.0171)	β_{233}	~0
β_{134}	~0	β_{234}	~0
β_{144}	~0	β_{244}	~0
Adjusted R^2	0.48		

Note 1: '*' indicates that the parameters are significantly different from zero at the 5% level.
The subscripts for inputs are: '1'=wages, '2'=running costs. The subscripts for outputs are: '1'=cod, '2'=lobster, '3'=flatfish, '4'=other species.
Note 2: Numbers in parentheses are standard errors on the parameters.

mates of the true coefficients (Gujarati 2003). The collinearity has been ignored in the present context, although it should be kept in mind that the standard errors on some of the *k*-parameters may be overestimated.

The model was also tested for heteroskedasticity using the White test, which showed that the residuals of the model are homoskedastic. Further, the Shapiro Wilk test has shown that the residuals of the model are normally distributed. Chow's test has shown that no structural breaks are present for the model from one year to the next. The cost function presented in table 3 has finally been shown to be locally concave in input prices on the domain specified by the observed output values and input prices. This has been done by evaluating the matrix of second-order derivatives of the cost function (6) with respect to input prices and examining whether this matrix is negative semi definite for each observed set of output values and input prices. As the predictive power of the model is also relatively high with $R^2 = 0.52$, it is concluded that the estimated Leontief cost function is well specified in the present case study.

Table 4 shows the own- and cross-price elasticities for the variable inputs evaluated with equation (4) for the Leontief cost function with parameters given in table 3. The elasticities are calculated for average (over all years) input prices, output values, and capital (tables 1 and 2). All the elasticities have the expected sign.

The overall returns to scale (ORTS) for the estimated cost function have been evaluated from equation (5) using average (over all years) input prices, capital, and output values (tables 1 and 2). The result is ORTS = 5.80, indicating strong overall economies of scale for the fleet in the current situation.

In order to find the long-run (LR) equilibrium output, *i.e.*, the optimal quota size in the long-run, cf. figure 1, equation (10) has been solved assuming that the yearly individual vessel quota $(y_1^0,...,y_4^0)$ for the selected fleet is equal to the vector of average catch weights over the total period (see table 1). Average (over the total period) values of variable input prices and capital cost have been used in the estimations. The optimal quota size has been estimated at a capital input of $k = 1$, corresponding to the average vessel size, and at $k = 2.31$ times the average. The latter reflects the size of the largest vessels in the sample compared to the average size. The resulting long-run individual vessel quota expansion factors are $r = 1.17$ and $r = 9.33$, respectively, which is the amount by which the vector of average vessel catches $(y_1^0,...,y_4^0)$ must be multiplied to reach LR cost equilibrium.

If the yearly individual vessel quota is increased by the factor r, the number of vessels in the fleet must be decreased by a factor $1/r$ in order for the total catch of the fleet to not exceed the TAC. Thus, when the individual vessel quota is increased by the LR expansion factors noted above, the number of vessels in the fleet must, on average, be reduced by 15% and 89%, respectively, corresponding to $k = 1$ and $k = 2.31$.

The economic equilibrium discussed in connection with optimising individual vessel quotas is the CRS equilibrium. In this case, the aim is to identify the output vector for which the average cost (per unit output) is minimized, or correspondingly, the output vector for which the ORTS given in equation (5) is equal to unity. When ORTS is set equal to unity, using average values of the variable input prices and the capital equal to 1 and 2.31, respectively, and solved for the vessel quota expansion factor as in the LR equilibrium case, it is found that the average catch vector must be multiplied by the factor $r = 2.30$ ($k = 1$) and $r = 3.20$ ($k = 2.31$) for the average vessel to reach minimum average cost. This corresponds to a reduction of the fleet size/capacity by 57% (1/2.30 = 0.43) and 69%, respectively.

Table 4
Own- and Cross-price Elasticities for the Generalized Leontief Variable Cost Function (6) with Parameters given in Tables 3A and 3B

	Wage Expenses	Running Costs
Labour	–0.52	0.53
Days at Sea	0.52	–0.53

In order to discover by what amount the average catch vector must be increased to reach maximum profit (MP), equation (10) has been maximised with respect to quota expansion factor *r*, again using average input prices and average output prices over the total period for the four species. These are p_1 = 1.43 ¤ (10.63 DKK) per kilo cod, p_2 = 7.74 ¤ (57.59 DKK) per kilo lobster, p_3 = 2.11 ¤ (15.68 DKK) per kilo flatfish, and p_4 = 1.44 ¤ (10.72 DKK) per kilo of other species. The resulting maximum profit expansion factor is *r* = 2.61 for *k* = 1, corresponding to a fleet reduction of 62% (1/2.61=0.38). Results for quota expansion and capacity reduction factors for *k* = 2.31 and long run are shown in table 5, from which it appears that the long-run solution is very close to the solution for *k* = 2.31, which is the maximum vessel size of the fleet sample.

The results for the CRS and maximum profit, Π^*, optima are summarised in table 6. The observed average (per vessel) yearly revenues, costs, and profits of the vessels are ¤173,000, ¤180,000, and ¤-7,000. The table shows that substantial gains may be obtained. The impact on these gains resulting from a change in the capital remuneration factor of 12% has been investigated accordingly at 3%, 6%, and 18%. The result being that the optimal quota expansion, and hence the capacity reduction, are influenced only to a minor degree. The profit, however, will increase with lower remuneration factors and *vice versa*.

Table 5

Optimal Individual Vessel Quota Expansion Factors and Fleet Reduction Factors for the Danish Trawler Fleet (<50 GRT) Calculated at Average and Maximum Vessel Size

	Average Size (k = 1)		Maximum Size (k = 2.31)		Long Run
	CRS	Π	CRS	Π	Π
Quota Expansion Factor	2.30	2.61	3.20	3.79	3.66
Fleet Reduction Factor	0.43	0.38	0.31	0.26	0.27

Note: 'CRS' = Constant Returns to Scale; Π = Maximum Profit.

Table 6

Optimal CRS and Maximum Profit (Π) Yearly Revenues, Costs, and Profits, with Vessel Capacity at Average and Maximum Vessel Size, for the Danish Trawler Fleet (<50 GRT)

	Average Size (k = 1)		Maximum Size (k = 2.31)		Long Run
	CRS	Π	CRS	Π	Π
Average Revenue (¤ 1,000*)	398	452	554	656	633
Average Costs (¤ 1,000*)	352	404	412	503	490
Average Profit (¤ 1,000*)	46	48	142	153	143

* The exchange rate between DKK and ¤ is 7.44 to 1.
Note: Costs, profits, and revenues are averaged per vessel.

It is clear that the IQs vary, depending on individual vessel characteristics. The individual vessel quota expansion factors will, therefore, also vary, and the fleet reduction factor, based on the average vessel, should be seen as a desirable target for fleet reduction following a possible increase in individual vessel quotas, rather than a direct recommendation for an exact fleet reduction.

Summary and Conclusion

The paper presents an analysis of the optimal quota mix of the fleet of Danish trawlers below 50 GRT targeting cod, lobster, and flatfish during the period 1995–2000. The fleet is regulated through individual non-transferable quotas, and the revenue of the vessels in the fleet is consequently fixed assuming exogenous fish prices. Therefore, as it can be assumed that the fishermen are cost minimisers, the economic behaviour of the fleet has been analysed through a dual cost function approach using the generalized Leontief cost function.

Three measures of optimal economic behaviour, as measured through optimal individual non-transferable vessel quotas, have been calculated for the fleet. These measures evaluate how much the individual vessel quota must be increased for the average vessel to have: (*i*) minimum short-run average costs, (*ii*) maximum short-run profit, and (*iii*) long-run maximum profit. In all three cases, it has been assumed that the average vessel in the fleet will catch the target species (cod, lobster, flatfish, and other species) in fixed proportions. Correspondingly, it is evaluated how much physical overcapacity there is in the fleet in each of the three cases; *i.e.*, how much the number of vessels in the fleet must be reduced when the individual vessel quotas are increased in order not to exceed the TAC.

It is shown that the average individual vessel quota vector must be multiplied with a factor of between 2.3 and 3.79. In the latter case, the average vessel should be able to obtain a potential maximum profit of ~¤ 150,000 (~DKK 1.1 million). When the individual vessel quotas are increased to the maximum profit level, the fleet should correspondingly be reduced by 74%.

An even greater profit could be expected if the non-transferable quota mix was allowed to change. The underlying general TAC for each species is determined on an individual species basis by the International Council for the Exploration of the Sea (ICES). The likely result is that this quota mix does not comply with the optimal mix for the vessel, leading to discards or underexploited species quotas.

Generally the results of the analysis indicate that the present fleet is operating at severe economic overcapacity, leading to profit dissipation. The analysis has, however, shown that positive profit can be generated if vessel quotas are increased, followed by a reduction in the number of vessels in the fleet, so as not to exceed the TAC of the fleet.

Individual non-transferable quotas became effective for this particular fleet segment in 1993. Neither the incentive of the non-transferable individual vessel quotas inducing cost minimizing behaviour, nor the availability of a decommissioning programme within the European Union, has been strong enough to reach an optimal quota or fleet size in the short or long term. An obvious explanation is that the quotas were not transferable, leaving the fisherman with only one option: to stay—or to leave, if decommissioning grants were made available at a high enough level.

References

Chambers, R.G. 1988. Applied Production Analysis. A Dual Approach. Cambridge: Cambridge University Press.

Diewert, W.E., and T.J. Wales 1987. Flexible Functional Forms and Global Curvature Conditions. *Econometrica* 55(1):43–68.

FOI, 1995-. Account Statistics for Fisheries (Fiskeriregnskabsstatisik). Annual Report from the Institute of Food and Resource Economics. www.kvl.foi.dk/Publikationer/Statistikker/Fiskeri.aspx

___. 2001-. Economic Situation the Danish Fishery (Fiskeriets Økonomi). Annual Report from the Institute of Food and Resource Economics. www.kvl.foi.dk/Publikationer/Rapporter/Fiskeriets%20%C3%98konomi.aspx

Gujarati, D.N. 2003. *Basic Econometrics*. New York, NY: McGraw Hill Higher Education.

Heathfield, D.F., and S. Wibe 1987. *An Introduction to Cost and Production Functions*. Houndsmill, Basingstoke, Hampshire, and London: MacMillan Education.

Jensen, C.L. 2002. Application of Dual Theory in Fisheries: A Survey. *Marine Resource Economics* 17:309–34.

Kumbhakar, S.C. 1994. A Multiproduct Symmetric Generalized McFadden Cost Function. *Journal of Productivity Analysis* 5:349–57.

Larsson, J. 2003. Testing the Multiproduct Hypothesis on Norwegian Aluminium Industry Plants. Discussion Paper No. 350, Statistics Norway. www.ssb.no

Lindebo, E. 2000. Capacity Development of the EU and Danish Fishing Fleets. Danish Research Institute of Food Economics, Institute of Food and Resource Economics Working Paper no. 10/2000. www.kvl.foi.dk/upload/foi/docs/publikationer/working%20papers/2000/10.pdf

Morrison, C.J. 1985. Primal and Dual Capacity Utilization: An Application to Productivity Measurement in the U.S. Automobile Industry. *Journal of Business & Economic Statistics* 3(4):312–24.

Nelson, R.A. 1989. On the Measurement of Capacity Utilization. *The Journal of Industrial Economics* 37:237–86.

Segerson, K., and D. Squires. 1990. On the Measurement of Economic Capacity Utilization for Multi-product Industries. *Journal of Econometrics* 44:347–61.