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Abstract:

Some multi-species fisheries are characterised by production jointness in the sense that several species are caught through a joint production process (literally in the same haul of the net). Other multi-species fisheries (so called purse seine fisheries) are specialized in the sense that species are targeted individually and by-catch is negligible, but over the fishing season the same boat chooses to target several species with varying intensity which also results in a sort of jointness. Both types of fisheries are typically modelled using standard multi-input multi-output profit function forms (e.g. translog, normalized quadratic). In this paper we argue that jointness in the latter, essentially separable fishery is caused by allocation of fishing days input among harvested species. We developed a structural model of a multi-species fishery where the allocation of fishing days input causes production jointness. We estimate the model for the Norwegian purse seine fishery and find that it is characterised by non-jointness, while estimations for this fishery using the standard multi-input multi-output profit function imply jointness.

JEL classification: Q22; C51

Key words: Production jointness, multi-species fisheries, structural modeling

1. Introduction

Fishing industries characterized by multi-species harvesting have been studied extensively in the fisheries economics literature, and the investigation of production jointness has been a major area of interest. Both trawl fisheries (see e.g. Squires (1987a, 1987b, 1987c) and Alam, Ishak and Squires (2002) and purse seine fisheries, (see e.g. Campbell and Nicholl 1995). Asche, Gordon and Jensen (2007) and Ekerhovd (2007)) are generally found to be characterised by jointness. This can have important implications for fisheries regulation since jointness may imply spill-over's between harvests of the different species undertaken by the industry.

All the studies cited above use the multi-input multi-output profit function approach using standard forms (e.g. translog, normalized quadratic). However, whereas trawl production is joint in the sense that several species are caught in the same production process, the type of jointness that may arise in a purse seine fishery has a different structure. Purse seine fishers specifically target individual species, and by-catch is typically negligible (Jensen (2002)).Although different species are caught in separate production processes over the fishing season, the same boat may choose to target several species with varying intensity, which in turn may result in the annual harvests of the different species being characterised by jointness. This is our point of departure.

In the following we develop a structural model of a purse seine fishery. In this model, production jointness between different basically separate fisheries comes about through the mechanism of allocating fishing day input. If the vessel has idle time in harbour (not used for maintenance, rigging etc.), input of fishing days is not restricted. In this case there is no production jointness because fishing day input to a given fishery can be increased without reducing input to other fisheries by reducing idle harbour time. If, on the other hand, there is no idle harbour time and all vessel time is allocated either to fishing or maintenance, etc., jointness *may* occur. This foundation provides a framework for understanding and empirically modelling the interactions between different fisheries undertaken by such a purse seine fishing industry. We also derive a number of constraints implied by the theoretical model that can be empirically tested. As an example, we apply the model to the Norwegian purse seine fishery and find that this fishery is characterised by non-jointness. When estimating a model of this fishery based on the standard multi-input multi-output profit function we find evidence of production jointness as have prior studies of this fishery using the standard model (Asche, Gordon and Jensen (2007) and Ekerhovd (2007)). Thus it seems that basing empirical models on the structural foundation we propose can seemingly have important implications for the results.

Though fishing days input is seldom included in estimated fishery models, Dupont (1991) is a notable (and in our context important) exception. Dupont develops and estimates a model of single species harvesting constrained by quotas on fishing days (and other input) with the purpose of comparing efficiency of different types of input regulation. Though with a different focus and in a single species framework the resulting empirical model estimated by Dupont has much the same structure as the model we estimate here. Essentially we extend the fishing days constrained profit function developed by Dupont to the multi-output situation and develop the underlying theoretical foundation for applying it to output-regulated multi-species purse seine fisheries.

We take outset in the fixed but allocatable land-input setup developed in agricultural economics for modelling land constrained multi-crop farming (see e.g. Moore and Negri (1992) and Moore, Gollehon and Carey (1994) for an early application). The multi-crop farm production model lets each crop production process be completely separable from the others with all inputs available at fixed prices except for land which the farmer only has in a fixed amount. Though fixed in its total quantity, land is allocatable between crops and so jointness is created through this fixed but allocatable input. This basic production set up resembles that of a fisherman allocating fishing days between specialized fisheries. However, specialized multispecies fisheries production differs from agricultural crop production in several ways. First of all, in most fisheries one or more species are subject to some form of quota regulation. Second, the total number of fishing days may to some extent be adjustable in the short run by reallocating vessel time for maintenance, rigging etc. Finally, fishing days may not always be allocated freely between species. Fishing of some species is highly seasonal so that the fisherman may be constrained as to how he can reallocate fishing days between different fisheries (for example fishing days cannot be reallocated directly from a fishery whose season is in the winter months to a fishery with a summer season).

In the next section we develop the theoretical model and clarify its underlying assumptions. In section 3 we derive a number of testable implications and other useful results implied by our model. In section 4 we present our empirical case and data. In section 5 we develop and estimate our empirical model and present results, while section 6 concludes.

2. The theoretical model

In this section we develop a model of a purse seine net fishery where the mechanism casing jointness between the different basically separable fisheries undertaken by the industry is the allocation of fishing days. We then make explicit how the vessel time allocation mechanism causes jointness and discuss the key assumptions underlying the model.

The fishing vessel is a fixed capital input (fixed in the short run) in principle available 365 days a year. However, there are periods where vessels are not at sea due to maintenance, rigging etc., and so the total number of fishing days allocated is typically lower. Underlying these allocations of time are decisions where the fisherman weighs costs of quicker maintenance and rigging against the gains from having more fishing days at sea. This suggests that even though vessel capital is fixed in the short run, the number of fishing days may be variable in the and found as an integrated part of the fisherman's optimisation problem.

We characterize the production function describing the harvest of separately targeted species as a two-step process. In the *first* step the profit maximising fisherman allocates vessel time between 'maintenance' and a number of separate single species fisheries. In the *second* step other inputs are combined with the allocated vessel time to produce fish of the targeted type and needed maintenance.

In the *second* step, when the fisherman has allocated a certain amount of vessel time d_i to a specific fishery *i*, he faces a time dependant production function (where *t* is a specific point in time during the one-year fishing season):

$$\tilde{y}_i^t = \tilde{f}_i(\tilde{x}_i^t, t) \tag{1}$$

Thus, if the fisherman at time *t* has allocated his vessel to fishery *i* and invests other inputs at a rate of $\tilde{x}_i^t$ per unit of time (where $\tilde{x}_i$ is a vector of *n* other input rates) he catches species *i* at a rate of $\tilde{y}_i^t$ per unit of time. We assume that these fisheries are distinct single species fisheries separated geographically or in time, and that there is no by-catch[2]. Given market prices for other input $r = (r_1, ..., r_i, ..., r_n)$ and fish output $p = (p_1, ..., p_i, ..., p_q)$ standard convexity conditions (Chambers, 1988) ensure the existence of corresponding dual profit functions:

$$\tilde{\pi}_i^t(p_i, r, t) \tag{2}$$

[2] As noted in the introduction by catch is typically negligible and often discarded in purse seine fisheries, Jensen (2002).

where $\tilde{\pi}_i^t$ is the rate of profit at time *t*. For most species the fishing season is shorter than 365 days implying that the out of season profit rate is low. Onset of the fishing season implies rising profit rates as *t* moves into the season with the profit rate reaching a maximum and then falling again toward the end of the season. Assuming a well behaved profit rate function with a single maximum during the year, the fisherman's problem is to decide when to start fishing and when to stop, given the amount of vessel time (fishing days) allocated to the species, i.e.:

$$\begin{aligned} &\underset{t_{start},t_{stop}}{Max} \int_{t=t_{start}}^{t_{stop}} \tilde{\pi}_i^t(p_i,r,t)dt \\ &s.t. \quad t_{stop}-t_{start} \leq d_i \end{aligned} \tag{3}$$

Given the well behaved profit rate function start and stop dates are set so that the time constraint is binding and so that start and stop dates have the same profit rate. Letting $t^*_{start}(d_t), t^*_{stop}(d_t)$ denote the solution to the problem implies a profit function conditional on prices and the allocated amount of time:

$$\pi_i(p_i,r,d_i) = \int_{t=t^*_{start}(d_t)}^{t^*_{stop}(d_t)} \tilde{\pi}_i^t(p_i,r,t)dt \tag{4}$$

Thus, when there are no other constraints then the allocated vessel time for fishery of a species the result of profit maximisation may be described by a conditional profit function with a corresponding production function of the dual problem:

$$y_i = f_i(x_i,d_i) \tag{5}$$

where x_i is the vector of variable inputs and d_i is the number of fishing days allocated to production/catch of species *i*, and y_i is the resulting catch. Except for being connected by the allocation of vessel time these fisheries are separable.

We must also allow for the fact that some targeted species are subject to quota regulation implying added constraints of the form:

$$y_i \le \overline{y}_i \qquad \text{for } i = h+1, \ldots q \tag{6}$$

So that the first h species are unregulated and described by profit functions (4) while the remaining are output quota regulated. We assume quotas to be binding so that equality applies, and corresponding to (4) we can derive

dual cost functions conditional on allocated vessel time d_i:

$$C_i(\overline{y}_i, r, d_i) \quad \text{for } i = h+1, \ldots q \tag{7}$$

for the remaining constrained outputs.

Finally we assume that the timing of maintenance is flexible so that there is no 'season' variation in maintenance costs. However, we will allow for the possibility of substitution between total maintenance costs and total vessel time allocated to maintenance. Thus, allocating less time to maintenance increases maintenance costs, e.g. because of overtime payment or the extra costs of postponing needed maintenance in the form of extra depreciation or more expensive maintenance later. Let

$$C_m = C_m(d_m) \tag{8}$$

be the functional relationship between maintenance costs C_m and vessel time d_m (measured in days) allocated to maintenance. Note that the model allows for the situation where there is little short run flexibility in the time allocation to maintenance (i.e. where fishing days actually are a quasi fixed input). This will be the case if the $C_m(.)$ function is steep ($dC_m / dd_m \ll 0$).

We now turn to the *first* step of the fisherman's maximisation problem. Barring other constraints than the overall time constraint ($d_m + \sum_{i=1}^{n} d_i \leq 365$), the fishermen's overall maximisation problem can be formulated as allocating vessel time to the profit and cost functions (4), (7) and (8), describing second step profit maximisation/cost minimisation i.e.:

$$\begin{aligned} &\underset{d_1,\dots,d_q,d_m}{Max} \sum_{1}^{h} \pi_i(p_i, r, d_i) - \sum_{h+1}^{q} C_i(\overline{y}_i, r, d_i) + \sum_{h+1}^{q} p_i \overline{y}_i + C_m(d_m) \\ &s.t. \quad d_m + \sum_{i=1}^{n} d_i \leq 365 \end{aligned} \tag{9}$$

with the following first order conditions for profit maximum (assuming the restriction is binding) [3]:

$$\begin{aligned} &\frac{\delta \pi_i(p_i, r, d_i)}{\delta d_i} = \lambda && \text{for } i = 1, \dots h \\ &\frac{\delta C_i(\overline{y}_i, r, d_i)}{\delta d_i} = \lambda && \text{for } i = h+1, \dots q \\ &\frac{\delta C_m(d_m)}{\delta d_m} = \lambda \end{aligned} \tag{10}$$

Here λ is the shadow price of vessel time originating from the overall time constraint (i.e. the marginal profit that could be reaped by allocating an extra unit of vessel time to the most profitable alternative task). If the time constraint is binding, the shadow price of vessel time will be positive ($\lambda > 0$) while if it is not binding, the shadow price will be zero ($\lambda = 0$). This is the fisherman's maximisation problem from which we will derive estimable output supply and input demand equations as well as parameter restrictions that can be used to test the model. The model is illustrated in the top graph of figure 1 were we have species profit rate $\tilde{\pi}_i^t$ up the y-axis and time *t* out the x-axis. The illustrated fishery targets three species (A, B and C) where the curves labelled A, B and C are their respective profit rates as functions of time *t* (corresponding to (2)). The horizontal punctured line is the marginal savings in maintenance costs resulting from increasing time allocation to

[3] We also assume an interior solution so that none of the non negativity constraints are binding (i.e $.d_m > 0, d_1 > 0, \dots, d_q > 0$.

maintenance in optimum (i.e. $-dC_m / dd_m$). Since maintenance costs are not affected by the timing of vessel maintenance, the same marginal cost savings apply over the entire season (i.e. no seasonal variation) and this is then equal to the shadow cost of vessel time. The optimal timing of in harbour maintenance is the two maintenance periods indicated below the graph. This is optimal because profit rates from fishing in these periods are below the marginal maintenance costs saved from allocating time to maintenance. During the remaining time, the vessel is allocated to each of the three indicated fisheries because profit rates of the respective fisheries are larger than the alternative marginal savings of allocating vessel time to maintenance.

Intuitively if the shadow price falls to zero then no maintenance costs are saved by allocating more vessel time to in harbour maintenance. In this situation the vessel has idle time in harbour where no maintenance is performed. In this case the different fisheries are separable and there is no production jointness because the fisherman can allocate more time to one fishery without reducing vessel time to other fisheries or maintenance by reducing idle harbour time.

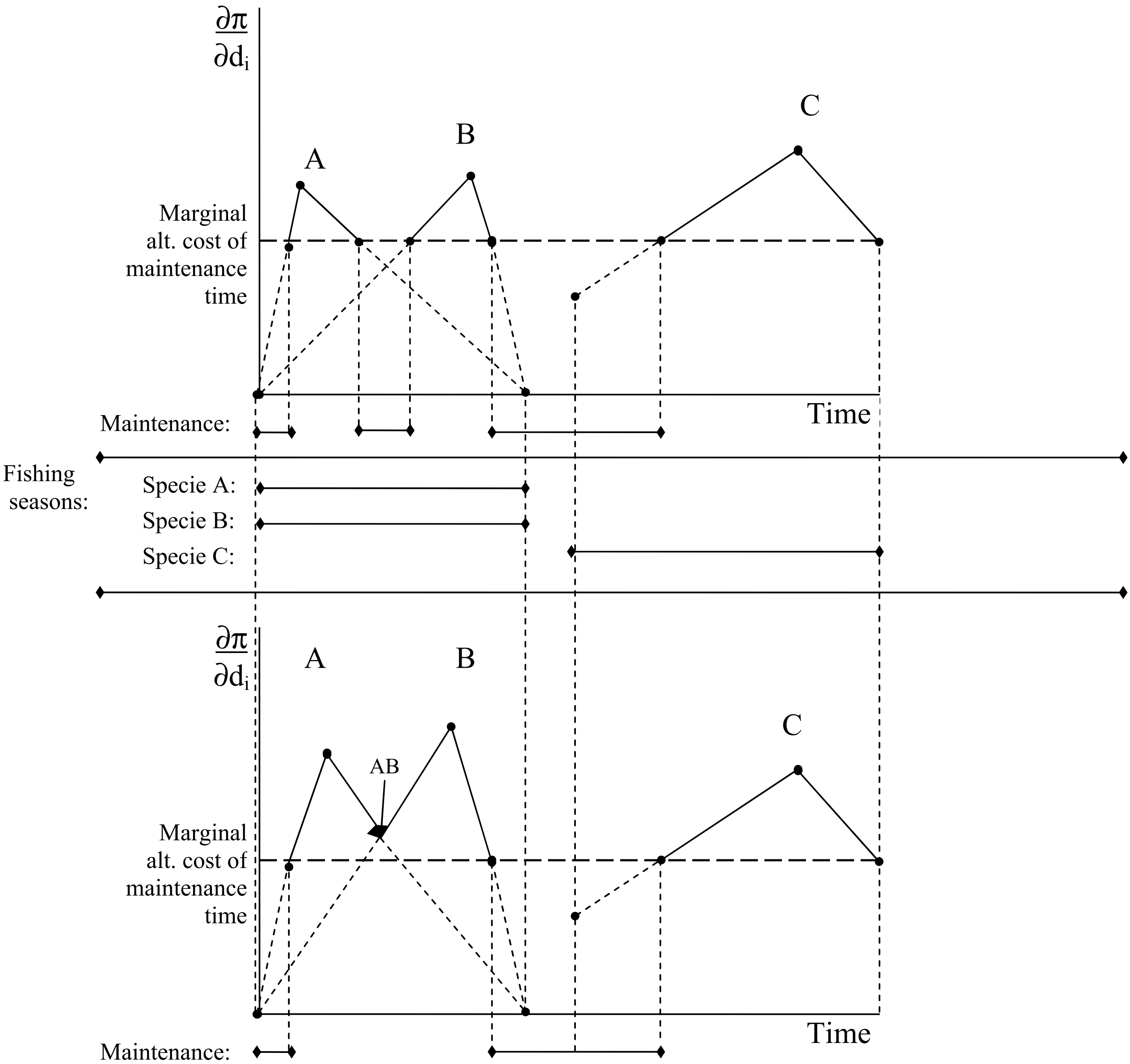
If on the other hand the shadow price is positive, this implies that there is no idle harbour time so that all vessel time is allocated to a profitable task (either profitable fishing or cost saving in harbour maintenance time) in which case production jointness *may* occur. However, even when the shadow price of vessel time is positive, this mechanism of jointness may be blocked. If a price (or other) chock to a fishery results in reallocation of other inputs than vessel time, then the shadow price of vessel time will not be affected. Further if marginal maintenance cost savings are insensitive to the amount of time allocated to maintenance (so that the shadow price is more or less constant) then production jointness may still be close to zero because time substitution is with maintenance – not other fisheries. Thus, in addition to a positive shadow price of vessel time, production jointness in this type of fishery requires that:

1) Time allocation to a fishery is *responsive* to price (or other) chocks to a fishery, and that
2) Marginal maintenance cost savings (the shadow price of vessel time) is *responsive* to changes in time allocation to maintenance.

If these conditions hold (substantial) jointness may occur.

Thus the proposed theoretical model does not as such imply anything about the strength of production jointness – this is an empirical question. However, as we will see, the model does have important implications for how to specify a model for estimating production jointness. It is therefore critical to understand the underlying assumptions and discuss their applicability to the purse seiner fishery that we are modelling.

Figure 1: Jointness through allocatable fishing days input



In the maximisation problem (9) we have no other binding constraints than the overall time constraint. Critical for this is the following assumption:

Assumption 1: When ever fishing is optimal, maintenance is the best alternative application of vessel time.

This assumption requires that profit rate curves of fisheries with overlapping seasons always intercept at a point in time where the common profit rate is bellow the marginal value of investing vessel time in maintenance. This implies that there will always be maintenance time between the time slots that it is optimal to allot to fisheries with overlapping seasons as illustrated in the top figure for fisheries A and B. This ensures that the only interaction between tasks is through the common shadow price of vessel time (i.e. that the only mechanism of jointness is the common shadow price of time provided by the maintenance alternative. If maintenance is the best alternative, then a chock to another fishery that does not affect the shadow price will not affect the other fisheries.

The bottom figure illustrates a plausible situation where this assumption does not hold. The marginal profit curves of the two fisheries A and B with overlapping seasons intersect at a point with so high a profit rate that no time is allocated to maintenance between the time slots allocated to the two species. Here a chock to fishery A could affect fishery B even if the shadow price remains unchanged. Without a change in the shadow price, the stop time of fishery B is not affected, however, a shift in profitability of A could affect the start time of this fishery if the intersection of the two fisheries marginal cost curves (the point AB) is shifted, even though the shadow price remains unaffected. In this situation there is another mechanism for production jointness between these two specific fisheries so that another binding constraint is required in (9), and so our specification no longer applies.

In conclusion, the model (9) is only applicable in this form if it is reasonable to assume that there is no seasonality of maintenance and if it is reasonable to assume that the time slots allocated for all individual species are 'separated' by maintenance time slots[4].

[4] Clearly the theoretical model (9) is easily augmented to take account of such additional mechanisms of jointness. Two interacting fisheries can be described by a joint profit function conditional on allocated total vessel time to these two species. Then insert this into (9) in place of the two separable species profit functions. However, in this paper we use the simple specification (9)

3. Implications of the model

In this section we derive a number of empirically testable implications of the model. We develop a constrained version of the fisherman's maximisation problem that is useful for empirical applications and show that the same testable implications apply, and we also prove propositions that are useful for drawing conclusions about the unconstrained profit function from estimations based on the constrained problem.

The specified theoretical model (9) has a number of implications that provide us with empirically testable parameter restrictions and aids the interpretation of results.

The core result from the model is the first order conditions for profit maximum (10). These implicitly define allocated vessel time to each task $d_1,...,d_i,...,d_q,d_m$ as functions of market prices, quota constraints and the shadow price of time, i.e.:

$$
\begin{aligned}
& d_i = \tilde{d}_i(\underset{+}{w_i}, \underset{-}{r}, \underset{-}{\lambda}) \qquad \text{where } w_i = p_i \text{ for } i = 1,...h \text{ and } w_i = \bar{y}_i \text{ for } i = h+1,...q \\
& d_m = \tilde{d}_m(\underset{-}{\lambda})
\end{aligned} \tag{11}
$$

with the indicated partial derivative signs. If the time constraint is binding ($\lambda > 0$), we have:

$$
\tilde{d}_m(\lambda) + \sum_{i=1}^{q} \tilde{d}_i(w_i, r, \lambda) = 365 \tag{12}
$$

which implicitly defines $\lambda > 0$ as a function of market prices and quota constraints. Here derivatives of the shadow price λ with respect to output price and constraint can be found by implicit differentiation:

$$
\frac{\delta \lambda}{\delta w_i} = -\frac{\delta d_i}{\delta w_i} / \left(\frac{\delta d_m}{\delta \lambda} + \sum_{i=1}^{q} \left(\frac{\delta d_i}{\delta \lambda}\right)\right) > 0 \tag{13}
$$

This allows us to easily derive a number of useful implications. Differentiating (5) for *i=1...h* and using (11) and (13) to sign derivatives, we have that:

$$\frac{dy_i}{dp_i} = \frac{\delta y_i}{\delta p_i} + \frac{\delta y_i}{\delta d_i}\frac{\delta d_i}{\delta \lambda}\frac{\delta \lambda}{\delta p_i} \geq 0$$

$$\qquad + \qquad + \quad - \quad +$$

$$\frac{dy_i}{dw_j} = \frac{\delta y_i}{\delta d_i}\frac{\delta d_i}{\delta \lambda}\frac{\delta \lambda}{\delta w_j} \leq 0 \qquad \text{where } w_i = p_i \text{ for } i = 1,..h \text{ and } w_i = \overline{y}_i \text{ for } i = h+1,..q$$

$$\qquad + \quad - \quad +$$

(14)

with the indicated partial and total derivative signs.

As we have noted above, maintenance costs C_m may by highly responsive to allocated time (i.e. when fishing days are close to being quasi fixed). Thus capturing this interaction correctly when undertaking empirical modelling is important. However, sound estimates of depreciation and future maintenance expenditures due to postponed maintenance that are critical elements of maintenance costs (C_m) are not available in many practical applications. On the other hand sound estimates of the total amount of fishing days input are often available. It may therefore be preferable to undertake empirical investigation of the constrained problem of allocating vessel time *only among fishing tasks conditional on the total number of fishing days input* ($\overline{d}_{tot}$) available for use by the fisherman (i.e. $\sum_{i=1}^{q} \tilde{d}_i(w_i, r, \lambda) \leq \overline{d}_{tot}$ where $\overline{d}_{tot} = 365 - \overline{d}_m$ implying the constraint $d_m = \overline{d}_m$ on maintenance time). This is in fact what we choose to do in the following empirical section and so it is useful to develop results for this problem also.

This condition problem is found from (9) by adding the constraint $d_m = \overline{d}_m$ i.e.:

$$\begin{aligned} &\underset{d_1,\ldots,d_q}{Max} \sum_{1}^{h} \pi_i(p_i, r, d_i) - \sum_{h+1}^{q} C_i(\overline{y}_i, r, d_i) + \sum_{h+1}^{q} p_i \overline{y}_i + C_m(\overline{d}_m) \\ &s.t. \quad \sum_{i=1}^{n} d_i \leq (365 - \overline{d}_m) = \overline{d}_{tot} \end{aligned} \qquad (15)$$

The corresponding constrained set of first order conditions (10) apply (where $\frac{\delta C_m(d_m)}{\delta d_m} = \lambda$ is dropped), implying the same implicit allocation functions as (11) (except that $d_m = \overline{d}_m$, implying that $\frac{\delta d_m}{\delta \lambda} = 0$). Thus the equation corresponding to (13) becomes:

$$\frac{d^c \lambda}{d^c w_i} = -\frac{\delta d_i}{\delta w_i} / (\sum_{i=1}^{q} (\frac{\delta d_i}{\delta \lambda})) > 0 \qquad (16)$$

where $\frac{d^c}{d^c}$ indicates total derivatives in the constrained problem (15). Differentiating (5) for *i=1...k* and using (11) and (16) to sign derivatives we have that:

$$\underset{}{\frac{d^c y_i}{d^c p_i}} = \underset{+}{\frac{\delta y_i}{\delta p_i}} + \underset{+}{\frac{\delta y_i}{\delta d_i}} \underset{-}{\frac{\delta d_i}{\delta \lambda}} \underset{+}{\frac{d^c \lambda^c}{d^c p_i}}$$

$$\frac{d^c y_i}{d^c w_j} = \underset{+}{\frac{\delta y_i}{\delta d_i}} \underset{-}{\frac{\delta d_i}{\delta \lambda}} \underset{+}{\frac{d^c \lambda^c}{d^c w_j}} \quad \text{where } w_i = p_i \text{ for } i = 1, \ldots h \text{ and } w_i = \overline{y}_i \text{ for } i = h+1, \ldots .q$$

$$(17)$$

with the indicated partial derivative signs. The following propositions follow directly.

Proposition 1: In both (9) and (15) all variable output derivatives with respect to other output prices and constraints are non-positive, i.e. $\frac{dy_i}{dp_j} \leq 0$ for *j=1...h,* $j \neq i$ and $\frac{dy_i}{d\overline{y}_j} \leq 0$ for *j=h+1....q*

Proof: Follows directly from (14) and (17)

When the only mechanism of jointness is through changes in the shadow price of vessel time, a rise in time allocation to a fishery causing a rise in the shadow price must result in allocation reductions to all other fisheries (complementarity is ruled out)

Proposition 2: In both (9) and (15) for the derivatives of any two outputs *i, j* with respect to any two not overlapping prices or constraints *k, ,l* the following ratio equality applies $\frac{dy_i}{dw_l}/\frac{dy_j}{dw_l}=\frac{dy_i}{dw_k}/\frac{dy_j}{dw_k}$ where $w_k = p_k$ or $w_k = \overline{y}_k$ and $w_l = p_l$ or $w_l = \overline{y}_l$, whichever applies.

Proof: Follows directly when inserting from (14) and (17)

Intuitively these regularities of output derivatives with respect to other outputs, result from all these interactions working through the allocatable input shadow price. Both propositions emit constraints implied by the assumed model that are easily empirically tested.

When investigating the constrained problem, it is useful to know what implications can be drawn concerning the unconstrained problem. Here the following proposition and corollary are useful.

Proposition 3: All variable output derivatives with respect to other output prices and constraints applying to a constrained problem (15) are numerically larger or numerically equal to the corresponding derivatives applying to the corresponding unconstrained problem (9).

Proof: comparing (13) and (16) it is clear that $0<\frac{d\lambda}{dw_i}\leq\frac{d^c\lambda}{d^c w_i}$ for $w_i = p_i$ or $w_i = \overline{y}_i$ which ever applies. Using this when comparing the relevant derivatives in (14) and (17) the propositions follow.

Corollary to proposition 3: All variable output derivatives with respect to their own output price applying to a constrained problem are numerically smaller or numerically equal to the corresponding derivatives applying to the corresponding unconstrained problem.

Proof: Using $0 < \frac{d\lambda}{dw_i} \leq \frac{d^c\lambda}{d^c w_i}$ when comparing the relevant derivatives in (14) and (17) the corollary follows.

Corollary to proposition 3: If fishing days are in fact a quasi fixed ($dC_m / dd_m \to \infty$), the solution to problem (9) approaches that of (15) so that the difference between the constrained and unconstrained solutions goes to zero.

Proof: Since $dC_m / dd_m \to \infty$ implies that $\frac{\delta d_m}{\delta\lambda} \to 0$, the corollary follows directly from (14) and (17).

The intuition is that the optimal reduction in output caused by e.g. a price or quota increase for another input when the allocatable input is fixed, will be mediated when the allocatable input is allowed to be adjusted (upwards) in response to the price/quota rise because this mediates the initial rise in the shadow price of the allocatable input. In the same way the optimal increase in output from a rise in its price is *greater* in the unconstrained problem since time to maintenance here is also allowed to adjust downward, freeing more vessel time for reallocation. Finally, as these mediating affects approach zero so must the difference between the two problem solutions.

The important take-away point is that results from the estimations based on the constrained problem are 'correct' if fishing days are quasi fixed and that they overestimate cross effects and underestimate own price effect if fishing days are not quasi fixed.

4. Description of empirical example and data

In this section we describe the Norwegian purse seine fishery between 1992 and 1999 and the available data.

The Norwegian purse seine fleet targets a number of different species (capelin, herring and mackerel) that are subject to individual (non-tradable) quota regulation. In addition a number of unregulated species are targeted mainly Atlantic horse mackerel and sand eel distributed over the fishing season as well as over a large geographic area. Capelin is harvested in the Baltic Sea and at Jan Mayen during spring and autumn, spring-spawning herring is caught along the Norwegian coast during spring and autumn, and mackerel and North Sea herring are harvested in the North Sea during summer and autumn. The fishing seasons of the main species are illustrated in table 1

Table 1 Fishing season for the Norwegian purse seiner fleet, by species, area, gear and month

		month	Jan	Feb	March	April	may	June	July	Aug	Sept	Oct	Nov	Dec
Species	Area	Gear												
Capelin	Barents sea	PS[4)]	X	X	X	X								
Capelin	Iceland	PS						X	X	X	X			
BW[1)]	Norwegian sea	PT[5)]					X	X	X	X	X			
BW[1)]	Atlantic	PT	X	X	X	X								
Mackerel	Norway	PS								X	X	X		
Mackerel	North sea	PS					X	X	X	X	X	X	X	
NSH[2)]	North sea	PS					X	X	X	X	X	X	X	X
SSH[3)]	Norway	PS	X	X	X							X	X	X

X indicates in what months and areas each species is fished.
Source: Ekerhovd (2007)
1) Blue whiting
2) North Sea herring
3) Spring-spawning herring
4) Purse seine gear
5) Pelagic trawl gear

Initial econometric estimation reveals a singularity problem due multicollinearity between mackerel and North Sea herring. These species are harvested within the same geographical areas and under similar environmental conditions and quotas are determined under similar regulation principles. We there for use a Fisher index to aggregate the harvesting of North Sea herring and mackerel. In addition, the fisher index is used for aggregating the harvested of the unregulated species into a single output.

We do not have data indicating the extent of idle harbour time nor the precise timing of each fishery nor the distribution of maintenance (in harbour) time. Thus we are not able to check directly if vessels are constrained in their fishing days input nor if species time slots are separated by periods of maintenance (as implied by assumptions 1). However, fishing seasons span the entire year and after aggregation of North Sea herring and mackerel no species have seasons that overlap both geographically and in time and so the assumptions do not seem unreasonable in our case.

The individual non-transferable vessel quotas for regulated species are grandfathered on an annual basis[5]. Generally allocated quotas are utilized and so our assumption of binding quota constraints seems reasonable.[6]

Our panel dataset is provided by The Norwegian Directorate of Fisheries and Statistics Norway and consists 84 purse vessels with 250 annual observations in all between 1992 and 1999 (so an average of about 3 observations per vessel). Vessels are sampled randomly on annual basis (with participation varying between 26 and 40 vessels in the data period). Thus the panel is unbalanced with 45 vessels participating 1 or 2 years, 23 vessels participating between 3 and 5 years, and 17 vessels participating more than 5 years.

The data set contains annual landings in tons and sales revenue for each species for each vessel enabling us to calculate average output prices for each vessel. Costs for various input types for each vessel are also registered. Input price indexes are calculated using the relevant Statistics Norway price indices and assumed to apply for all vessels. In addition various indicators characterizing size etc. of each boat are available. The sample consists of 89 vessels having an average length of 50 meters and an average tonnage of 672 gross register tonnages (Table 1). Capacity costs (maintenance, insurance, depreciation etc.) on average account for about 39% of the total gross costs, the crews salary accounts for about 39%[7], fuel expenditures account for about 9%), and vessel cost like ice, food account for another about 9%.

Table 1 shows values and quantities of landings and costs for the sample of purse seiners.[8] The gross earnings (landing values) indicate that 31% in generated by spring spawning-herring, 49% is obtained by the mackerel and herring harvested in the North Sea, capelin (9%) and unregulated species (10%).

[5] However, permission has sometimes been given to sell quotas allotted to vessels being scrapped during the current season.
[6] This is based on communication with the Directorate Fisheries in Norway.
[7] The salary for the crew members is typically a fixed share of the total landed value
[8] The purse seine vessels having individual quotas for blue whiting are not included in the sample

Table 1. Summary statistics of sample purse seines vessel 1992-1999

Catch and vessel characteristics	Mean of all observations	Standard deviation
89 Vessels, 250 Observations		
Fishing days	273.32	43.21
Vessel tonnage (GRT)	672.78	253.60
Length (Meters)	50.74	9.11
Quantity of spring spawning herring	2609.4	1548.8
Quantity of capelin	2023.1	2261.7
Quantity of mackerel and North Sea herring	2191.9	878.0
Quantity of unregulated species	1192.2	1343.8
Value of spring spawning herring landings	4473.8	2823.0
Value of capelin landings	1294.1	1324.1
Value of mackerel/North Sea herring landings	7047.0	2143.6
Value of landings of unregulated species	1456.7	1476.8
Vessel costs	1154.5	736.4
Fuel costs	1044.9	431.4

Source: The Norwegian Directorate of Fisheries and Statistics Norway.
1) The quantities are in tons, prices in 1000 Norwegian kroner.
2) The vessel cost is defined as cost for ice, bait, provisions and other unspecified costs.

5. Estimation

In this section we develop our empirical application based on the constrained problem (15). We estimate the input demand/ output supply system and present results which we compare with other studies of the Norwegian purse seine fishery for same time period.

We only observe total profit, total fishing days input and totals of other inputs – not allocations to each fishery. For this reason we choose the normalized quadratic form because it has the advantage that the dual problem can be derived explicitly.

We now introduce the normalized quadratic functional specification (with r_n as the numeraire) of profit and cost functions for each species (see Kohli, 1993 for a classical fisheries application of this functional form):

$$\pi_i = \tfrac{1}{2}[r_n \quad r_n d_i \quad p_i \quad r\,']A_i \begin{bmatrix} r_n \\ r_n d_i \\ p_i \\ r \end{bmatrix} / r_n \qquad \text{for } i=1,\ldots h \tag{18}$$

$$C_i = \tfrac{1}{2}[r_n \quad r_n d_i \quad r_n \overline{y}_i \quad r']A_i \begin{bmatrix} r_n \\ r_n d_i \\ r_n \overline{y}_i \\ r \end{bmatrix} / r_n \qquad \text{for } i\text{=1+ } h,...q$$

where A_i are matrices of parameters. We insert these quadratic specifications into (15) and derive total profit as the following function of total fishing days and prices of other inputs and outputs (See appendix for details):

$$\pi = \tfrac{1}{2}[r_n \quad r_n \overline{d}_{tot} \quad \mathrm{w}' \quad r']A \begin{bmatrix} r_n \\ r_n \overline{d}_{tot} \\ w \\ r \end{bmatrix} / r_n \quad \text{where } A = \begin{bmatrix} a_{kk} & a_{kd} & \overline{a}_{ky} & \overline{a}_{kr} \\ a_{dk} & a_{dd} & \overline{a}_{dy} & \overline{a}_{dr} \\ \overline{a}_{yk} & \overline{a}_{yd} & A_{yy} & A_{yr} \\ \overline{a}_{rk} & \overline{a}_{rd} & A_{ry} & A_{rr} \end{bmatrix} \quad (19)$$

$$\text{and} \quad \begin{array}{l} w_i = p_i \ \text{ for } i = 1...h \\ w_i = r_n \overline{y}_i \ \text{ for } i = h+1...q \end{array}$$

The *k* subscripts in the parameter matrix *A* indicate coefficients in the linear part of the quadratic function, and the *kk* subscript indicates the constant.

For the normalized quadratic specification this is the aggregated profit function for a fishery with quota regulation for some outputs, where jointness is caused by the predetermined but allocatable input of total fishing days. The profit function in (19) is like a standard NQF, except that the total number of fishing days $\overline{d}_{tot}$ is included as a fixed input. In addition it must satisfy the constraints implied by propositions 1 and 2 derived above. Finally, we can use proposition 3 and correlaries to make inferences concerning, e.g., production jointness in the unconstrained problem (9).

Applying the normalized quadratic functional form

We have one unrestricted (aggregated) output and three quota restricted outputs (spring-spawning herring, capelin and the North Sea herring and mackerel aggregate). Capacity costs and maintenance go to producing the fishing days input on which we condition. The salary for the crew member is typically a fixed share of the total landed value and we assume that this cost element can be treated as part of profit (i.e. that fishing is in effect a joint venture project). Thus we assume that output of each fishery is produced using fishing days, fuel and vessel costs (with the underlying skipper and crew input, reaping residual profit) where we use vessel cost as the numeraire input.

From the profit function (19) we derive the systems of supply and demand functions to be estimated. The supply function for the unregulated output is found by differentiation (19):

$$y_1 = \frac{d\pi}{dp_1} = a_{yk}^1 + a_{yd}^1 \bar{d}_{tot} + a_{yy}^{11}(p_1 / r_2) + \sum_{j=2}^{q} a_{yy}^{1j}(\bar{y}_j) + a_{yr}^{11}(r_1 / r_2) + a_{yr}^{12}(r_2 / r_2) \tag{20}$$

The demand function for fuel input becomes:

$$x_1 = \frac{d\pi}{dr_1} = a_{rk}^1 + a_{rd}^1 \bar{d}_{tot} + a_{ry}^{11}(p_1 / r_2) + \sum_{j=2}^{q} a_{ry}^{1j}(\bar{y}_j)_i + a_{rr}^{11}(r_1 / r_2) + a_{rr}^{12}(r_2 / r_2) \tag{21}$$

Finally the demand equation for vessel cost input (the numeraire) becomes:

$$x_n = \frac{d\pi}{dr_2} = d(½[r_2 \quad r_2\bar{d}_{tot} \quad \mathrm{w}' \quad r'] \begin{bmatrix} a_{kk} & a_{kd} & \bar{a}_{ky} & \bar{a}_{kr} \\ a_{dk} & a_{dd} & \bar{a}_{dy} & \bar{a}_{dr} \\ \bar{a}_{yk} & \bar{a}_{yd} & A_{yy} & A_{yr} \\ \bar{a}_{rk} & \bar{a}_{rd} & A_{ry} & A_{rr} \end{bmatrix} \begin{bmatrix} r_2 \\ r_2\bar{d}_{tot} \\ w \\ r \end{bmatrix} / r_2)/dr_2 =$$

$$½a_{kk} + ½a_{rr}^{22} + a_{kd}\bar{d}_{tot} + \bar{d}_{tot}a_{dr}^{22} + ½\bar{d}_{tot}a_{dd}\bar{d}_{tot} - (½a_{yy}^{11}p_1p_1 + a_{yr}^{11}p_1r_1 + ½a_{rr}^{11}r_1r_1) / r_2^2 + ½\sum_{i=2}^{q}\sum_{j=2}^{q} a_{yy}^{ij}\bar{y}_i\bar{y}_j \tag{22}$$

and so, the corresponding unit price of vessel costs is used for normalization. A number of parameters enter several equations of the system, and in addition we have the usual symmetry restrictions (here only one $a_{yr}^{11} = a_{ry}^{11}$). The regressors include prices of variable inputs and outputs, the fixed quantities of quoted regulated species (spring-spawning herring, capelin and the North Sea herring and mackerel aggregate) and the allocatable total input of fishing days.

We assume that coefficients are homogenous across vessels except for the fixed effects in each equation. However, we assume that variation in fixed effects between vessels is proportional to vessel tonnage (i.e. we estimate with a homogenous constant term but include vessel tonnage as an explanatory variable to capture this in all equations). In addition, the annual stock fluctuations of unregulated species may affect the harvest and as control for this we have included annual dummies into each model equation (20)-(22).

Selection and endogeneity issues

If panel participation was endogenous, we would have a potential selection bias problem. However, the panel participants are randomly selected by the Norwegian Fisheries Directorate following procedures developed by Statistics Norway and there is virtually no attrition (fishermen that do not report when selected to the panel) because the reported variables are a mandatory part of the Norwegian fisheries regulation system.

The main endogeneity issue here arises because, the system (20) to (22) is estimated conditional on fishing days and using imputed prices. The total number of fishing days may be decided on as an integrated part of the fisherman's short-run problem and so this variable is potentially endogenous and should be instrumented. We use 'vessel age' as an instrument (since required maintenance and thereby maintenance time presumably correlates with vessel age whereas there is no reason to suspect that vessel age should be affected by, e.g., the relative input and output price fluctuations that generate fishing day endogeneity). Technically we use three stages least squares estimation (3SLS). With only one instrument we cannot test instrument validity, but significance of the instrumental estimation is checked with a Hausman test (comparing 3SLS estimates with SUR estimates of the same system) showing that there is no significant difference between the SUR and 3SLS.[9] Unfortunately this is because our instrument is weak.[10] As emphasized by Bound, Jaeger and Baker (1995), use of weak instruments may in itself result in biased estimates so we have settled on our SUR

[9] The Hausman test statistics is 8.26 so that significance of instrumentation is just rejected (the critical value chi-square (4) 5% value is 9.488).

[10] We have tried to include regional dummies and vessel length in the instrument set without a significant increase in instrument strength. We have also tried using lagged variables as instruments but this critically reduced our unbalanced panel.

estimation as the result that we are most comfortable with. However, the fact that the limited information contained in our data prevents a proper instrumentation of fishing days is worrying.

Estimation and results

The estimated parameters from the restricted SUR estimation of the system (20) – (22) are presented in Table 2. The model clearly significant and captures a large part of the variation in left hand variables (with R^2 values for unrestricted output, fuel input and vessel input are respectively 0.510, 0.945 and 0.784). Four cross equation restrictions implied by the theoretical system (symmetry and parameter equality involving $a_{yy}^{11}, a_{rr}^{11}, a_{yr}^{11}$) have been accepted and imposed on the unrestricted system[11]. Since we just have one unregulated species, only the implication of proposition 1 (that all cross effects are non-positive) can be tested in our case. A Wald test of jointly restricting all three effects to zero is clearly accepted (see table 5) and none are significantly positive and so, according to this test, our estimations are consistent with the assumed model.

[11] The Wald test of imposing all four restrictions is clearly accepted with the test statistics of 3.87 substantially below the critical 5% $\chi^2(4)$-value of 9.488.

Table 2. Estimated parameter values for model with allocatable input jointness 1)

Parameter	Coeff.	t-value	Parameter	Coef.	t-value
Unres. output			Vessel Input		
a_{yy}^{11}	433.963	1.54	-($a_{kd} + a_{dr}^{22}$)	0.595	0.76
a_{yr}^{11}	-156.119	-3.68	-½ a_{dd}	-0.002	-1.17
a_{yd}^{1}	9.122	3.28	-½ a_{yy}^{11}	-216.981	-1.54
a_{yy}^{12}	0.499	1.81	a_{yy}^{22}	$4.79*10^{-7}$	0.05
a_{yy}^{13}	0.300	0.41	a_{yy}^{23}	$7.59*10^{-5}$	-1.95
a_{yy}^{14}	-0.094	-0.63	a_{yy}^{24}	$6.86*10^{-6}$	0.79
β_y	-0.880	-1.09	a_{yy}^{33}	$5.57*10^{-5}$	1.04
			a_{yy}^{34}	$-4.37*10^{-5}$	-1.58
Fuel Input			a_{yy}^{44}	$6.06*10^{-6}$	1.41
a_{ry}^{11}	-156.11	-3.68	- a_{yr}^{11}	156.119	3.68
a_{rr}^{11}	295.48	3.33	-½ a_{rr}^{11}	-147.742	-3.33
a_{rd}^{1}	-0.80	-4.31	β_{x2}	-0.179	-1.89
a_{ry}^{12}	0.008	0.58			
a_{ry}^{13}	-0.08	-1.75			
a_{ry}^{14}	-0.015	-1.90			
β_{x1}	-0.381	-8.37			

1) Parameter values for the annual dummies are not included in table 2. Coefficients to β_y, β_{x1}, β_{x2} reflect the variation in fixed effects between vessels assumed to be proportional to vessel tonnage (TE), i.e. we include vessel tonnage as an explanatory variable to capture this in all equations, and the corresponding parameters are β_y, β_{x1}, β_{x2}.

In table 3 we show derived own- and cross-prise elasticities with respect to inputs and unrestricted output. Own price elasticities of fuel and vessel inputs are significant and have the expected negative relationships, though numerically smaller than one. The estimated own price elasticity of output is small and insignificant. This is not surprising since these vessels typically focus their efforts on high value quoted species and therefore are less responsive to price changes in unregulated low valued species. The cross price elasticities between inputs are also significant with the positive sign implying that the inputs are gross substitutes. The cross-prise elasticities between unrestricted output and inputs have the expected signs but only elasticities with respect to fuel are significant.

Table 3. Own and cross price elasticities of input and outputs[1)]

Prices	Quantity Output	Fuel	Vessel input
Output	0.061	0.125**	0.026
	(0.041)	(0.034)	(0.079)
Fuel	-0.079**	-0.795**	0.579**
	(0.022)	(0.239)	(0.202)
Vessel input	0.019	0.671**	-0.605**
	(0.040)	(0.234)	(0.228)

** Significant at 5% level.
The parentheses contain the standard errors on the estimates.

Several other studies have estimated models for the Norwegian purse fleet using more or less the same data. Asche, Gordon and Jensen (2007) estimating a normalized quadratic profit function find an insignificant own price elasticity for the harvest of unregulated output.[12] Nøstbakken (2006), Bjørndal and Gordon (2000) estimating a cost function for the Norwegian purse fleet find small elasticities for inputs.[13] Weninger also reports inelastic- input price response for purse seiner fishery operating in the surf clam and ocean quahog fishery.[14] When comparing with our results, it is important to remember that our elasticities are conditional on fixed input of fishing days while all the above cited studies allow adjustments of input of fishing days. We know from the corollary to proposition 3 that conditional output own-price elasticities are numerically smaller then unconditional elasticities. Given this and other differences in model structure and data, the basic behavioural reactions implied by the estimated allocatable input model seem reasonable and generally consistent with other comparable studies.

Of primary interest here is how the shift in structural model (from the standard jointness structure, usually applied to the jointness structure using the fixed but allocatable input we have developed) affects parameter estimates indicating production jointness. For this we compare the model

[12] Asche, Gordon and Jensen (AGJ) estimate a symmetric quadratic profit function on Norwegian purse seiners. Similar to the purse seine vessels addressed in the present study. The specification in AGJ is includes unrestricted output, operating cost including fuel, wages, insurance, bait and other variables cost expressed as the operating cost per fishing day. In AGJ the elasticity on unrestricted output is insignificant, and the elasticity on operating cost is small (-0.12) but significant. In this study we find similar to AGJ and insignificant elasticity on unregulated output, and the elasticities on fuel (-0.795) and vessel input (-0.605) are statistical significant.

[13] Bjørndal and Gordon (2000), Nøstbakken (2006) are estimating translog cost function for the Norwegian purse seine fleet. They studies are applying data on the same fleet as addressed in present study, which is based on the period 1994-1996 in Bjørndal and Gordon and 1998-2000 in Nøstbakken. The input elasticity on fuel is -0.046 in Nøstbakken and -0.18 in Bjørndal, moreover is reported elasticity on vessel input, which incorporates insurance, maintenance, bait and other cost.

[14] Weninger (1998) is estimating a translog cost function for the Mid-Atlantic surf clam and quahog fishery in United States. The input elasticities on fuel is 0.28, moreover is found an elasticity on 0.72 for fishing gear.

we have estimated with a corresponding 'standard' normalized quadratic multi-output model (the only difference being that the number of fishing days is dropped as a regressor).[15] Table 4 presents elasticities of intensity expressing the per-cent effect on inputs and the unrestricted output of a 1% increase in restricted outputs and fixed fishing days inputs for both models. Table 5 presents Wald tests of jointly restricting various sets of these effects to zero in both models.

Table 4. Elasticity with respect to restricted outputs and fishing days (N)[1)]

Quantity	Output	Fuel	Vessel input
Model with allocatable input jointness:		**Fishing days included**	
Fixed input			
Fishing days	1.295**	0.592**	0.032
	(0.395)	(0.137)	(0.237)
Regulated outputs			
Spring-spawning herring	0.735*	-0.066	0.464**
	(0.421)	(0.114)	(0.168)
North Sea herring and mackerel	0.206	0.292*	0.592*
	(0.519)	(0.167)	(0.344)
Capelin	-0.0952	0.065*	0.174
	(0.152)	(0.034)	(0.143)
Model with standard jointness:		**Fishing days <u>not</u> included**	
Regulated outputs			
Spring-spawning herring	0.311	-0.127	0.428**
	(0.387)	(0.136)	(0.173)
North Sea herring and mackerel	1.149**	0.412**	0.677**
	(0.421)	(0.198)	(0.347)
Capelin	-0.003	0.079	0.235
	(0.148)	(0.042)	(0.145)

** Significant at 5% level. * Significant at 10% level.
1) The parentheses contain the standard errors on the estimates.

The first four rows show intensity elasticities implied by the *allocatable input jointness* structure while the following three rows show corresponding elasticities implied by the *standard jointness structure*.

The first row shows intensity elasticities with respect to fishing days where we see a substantial positive and significant effect on unrestricted output and fuel input which is as expected – but there is a curiously small and insignificant effect on vessel input. The Wald test of jointly restricting

[15] The estimated parameters for the translog system without the number of fishing days are presented in table 2A in the Annex.

these effects to zero is clearly rejected (see table 5). The next three rows show intensity elasticities with respect to restricted outputs. We see that increasing the constrained outputs generally has the expected positive effect on input use (where one elasticity is significant at the 5% level and three others are significant at the 10% level). The Wald test of jointly restricting these effects to zero is also clearly rejected (see table 5).

Our main interest is the intensity elasticities with respect to the unrestricted output in the first column where we see that the allocatable input jointness structure implies insignificant effects. A Wald test of jointly restricting all three effects to zero is clearly accepted (see table 5). We know from proposition 1 that our theoretical model implies that these effects are non-positive so on this point our estimations are (as already noted) consistent with the assumed model. Given our model, this suggests that effects are close to zero. We further know from proposition 3 that corresponding unrestricted elasticities (where fishing days are allowed to adjust) are numerically smaller (or equal to) the estimated elasticities conditional on fixed fishing days input. Thus, our results imply that the Norwegian purse seiner fleet is *not* characterised by production jointness.

Turning to the effects implied by the *standard jointness* structure in the next 3 rows we see the same pattern of effects on inputs with elasticities that tend generally to be larger – as we would expect since this model allows adjustment of fishing days input. The corresponding Wald test of jointly restricting to zero is also clearly rejected (see table 5). However, the pattern of effects on the unrestricted output is substantially different. Estimating with the standard jointness structure implies significant spill over effects between restricted and unrestricted species and complementarity relationship between unrestricted output and North Sea herring and mackerel. The corresponding Wald test of jointly restricting affects to zero is clearly rejected (see table 5) in contrast to acceptance under the *standard jointness structure*.

Table 5. Wald test of joint hypothesis for purse seine vessels

Null hypothesis	Test statistics	Critical value 5%	Degrees of freedom	Conclusion[1)]
	Allocatable input jointness (Fishing days included)			
Zero effect of fishing days on unrestricted output and inputs	25.67	9.488	4	Reject null
Zero effect of restricted output on unrestricted input	29.33	16.92	9	Reject null
Zero effect of restricted output on unrestricted output	4.38	7.815	3	Cannot reject null
	Standard jointness (Fishing days not included)			
Zero effect of restricted output on unrestricted input	36.50	16.92	9	Reject null
Zero effect of restricted output on unrestricted output	18.18	7.815	3	Reject null

Thus it seems that the main effect of changing the jointness structure of the model is that the implied production jointness with a standard structure disappears when the allocatable input structure is used. The effects of this model change on other elasticities are less significant. Comparing this with the literature, our result contrasts earlier findings in the Norwegian purse seine fishery by Asche, Gordon and Jensen (2007) and Ekerhovd (2007) who find evidence of substantial spill over effects between restricted and unrestricted species. These studies use the 'standard' jointness structure and our results suggest that this may explain why our results differ. Thus when we model jointness in what we have argued to be the structurally correct way, the effect disappears.

6. Conclusion

The main contribution of this paper is that we develop a structural model of the mechanism casing jointness between the different basically separable fisheries undertaken by a purse seine net fishery. In this model production jointness between different fisheries can only be through the mechanism of allocating fishing day input. If the vessel has idle time in harbour (not used for maintenance, rigging, etc.) then input of fishing days is not restricted. In this case there is no output jointness because fishing day input to a given fishery can be increased without reducing input to other fisheries by reducing idle harbour time. If, on the other hand, there is no idle harbour time so that all vessel time is allocated to either fishing or maintenance, etc., jointness *may* occur. If a price (or other) chock to a fishery results in a change in allocation of vessel time to this fishery then the shadow price of vessel time will be affected. If in addition, time allocation to maintenance is *unresponsive* to changes in the shadow price (i.e. if fishing days are close to being a quasi fixed input) then this reallocation will affect fishing days allocation to other fisheries causing production jointness. This foundation provides a framework for understanding and empirically modelling the interactions between different fisheries undertaken by such an industry.

We derive a number of implications that can be used to test and interpret empirical applications based on the model. Assuming the normalized quadratic form, we estimate a model based on this set up for the Norwegian purse seine fishery and find that it implies non-jointness which contrasts the findings of prior studies of this fishery, using the standard multi-input multi-output profit function forms. Since the endogeneity issues in connection with our estimation are not optimally resolved, this outcome should be interpreted with caution. However, it does illustrate the potential practical importance of modelling the underlying jointness in the way we suggest.

The structural model of jointness we propose may also have different implications for the design of regulation schemes than do standard multi species models. This could be an interesting direction for future research.

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Appendix A

From (15) we have::

$$\pi_i = \tfrac{1}{2}[r_n \quad r_n d_i \quad p_i \quad r'] A_i \begin{bmatrix} r_n \\ r_n d_i \\ p_i \\ r \end{bmatrix} / r_n \qquad \text{for } i=1,\ldots h \qquad \text{(A1)}$$

$$C_i = \tfrac{1}{2}[r_n \quad r_n d_i \quad r_n \bar{y}_i \quad r'] A_i \begin{bmatrix} r_n \\ r_n d_i \\ r_n \bar{y}_i \\ r \end{bmatrix} / r_n \qquad \text{for } i=h+1,\ldots q$$

$$\text{where } A_i = \begin{bmatrix} a^i_{kk} & a^i_{kd} & a^i_{ky} & \bar{a}^i_{kr} \\ a^i_{dk} & a^i_{dd} & a^i_{dy} & \bar{a}^i_{dr} \\ a^i_{yk} & a^i_{yd} & a^i_{yy} & \bar{a}^i_{yr} \\ \bar{a}^i_{rk} & \bar{a}^i_{rd} & \bar{a}^i_{ry} & A^i_{rr} \end{bmatrix}$$

The k subscripts indicate coefficients in the linear part of the quadratic function and the kk subscript indicates the constant.

Inserting (15) into (12) and differentiating the corresponding lagrangian

$L = \sum_{i=1}^{q} \pi_i - \lambda(\bar{d}_{tot} - \sum_{i=1}^{q} d_i)$ we get shadow prices for predetermined (in the first production step) but allocatable inputs:

$$\frac{\delta\pi_i}{\delta d_i} = \begin{bmatrix} a^i_{dk} & a^i_{dd} & a^i_{dy} & \overline{a}^i_{dr} \end{bmatrix} \begin{bmatrix} r_n \\ r_n d_i \\ w_i \\ r \end{bmatrix} / r_n - \lambda = 0 \quad \forall i \quad \text{where} \quad \begin{matrix} w_i = p_i \text{ for } i = 1...h \\ w_i = r_n \overline{y}_i \text{ for } i = h+1...q \end{matrix}$$

(A2)

$$\overline{d}_{tot} - \sum_{i=1}^{q} d_i = 0$$

Dividing by r_n and subtracting the equation for output q after inserting $d_q = \overline{d}_{tot} - \sum_{i=1}^{q-1} d_i$ and collecting terms we get for each species i:

$$\begin{bmatrix} a^i_{dk} & a^i_{dd} & a^i_{dy} & \overline{a}^i_{dr} \end{bmatrix} \begin{bmatrix} 1 \\ d_i \\ w_i / r_n \\ r / r_n \end{bmatrix} - \begin{bmatrix} a^q_{dk} & a^q_{dd} & a^q_{dy} & \overline{a}^q_{dr} \end{bmatrix} \begin{bmatrix} 1 \\ \overline{d}_{tot} - \sum_{j=1}^{q-1} d_j \\ w_q / r_n \\ r / r_n \end{bmatrix} = 0 \quad \forall i \neq q$$

$$\Leftrightarrow$$

$$\begin{aligned} &\begin{bmatrix} a^i_{dk} - a^q_{dk} \end{bmatrix} + \begin{bmatrix} a^q_{dd} & ... & a^q_{dd} + a^i_{dd} & a^q_{dd} & ... & a^q_{dd} & 0 \end{bmatrix} d + \begin{bmatrix} -a^q_{dd} \end{bmatrix} \overline{d}_{tot} + \\ &\qquad \begin{bmatrix} 0 & ... & a^i_{dy} & 0 & ... & 0 & a^q_{dy} \end{bmatrix} w / r_n + \qquad\qquad \forall i \neq q \\ &\qquad\qquad \begin{bmatrix} \overline{a}^i_{dr} - \overline{a}^q_{dr} \end{bmatrix} r / r_n = 0 \end{aligned}$$

(A3)

where $w = \begin{bmatrix} w_1 & w_2 & ... & w_q \end{bmatrix}$ and $d = \begin{bmatrix} d_1 & d_2 & ... & d_q \end{bmatrix}$ and the last equation (the sum restriction) can be written:

$$\begin{aligned} &[0] + [1 \quad ... \quad 1 \quad 1 \quad ... \quad 1 \quad 1] d + [-1] \overline{d}_{tot} + \\ &\quad [0 \quad ... \quad 0 \quad 0 \quad ... \quad 0 \quad 0] w / r_n + \\ &\quad [0 \quad ... \quad 0 \quad 0 \quad ... \quad 0 \quad 0] r / r_n = 0 \end{aligned} \qquad \text{(A4)}$$

giving the matrix equation covering all q equations:

$$\tilde{\alpha} + \tilde{A}d + \tilde{b}\overline{d}_{tot} + \tilde{B}w / r_n + \tilde{C}r / r_n = 0 \tag{A5}$$

Solving for d gives

$$d = \tilde{A}^{-1}(\tilde{\beta} + \tilde{b}\overline{d}_{tot} + \tilde{B}w / r_n + \tilde{C}r / r_n) = \beta + b\overline{d}_{tot} + Bw / r_n + Cr / r_n \tag{A6}$$

Inserting (A6) in (A1) we have:

$$\pi_i = ½[1 \quad r_n(\beta_i + b_i\overline{d}_{tot} + \overline{b}_i w / r_n + \overline{c}_i r / r_n) \quad \mathrm{w}_i \quad r']A_i \begin{bmatrix} 1 \\ r_n(\beta_i + b_i\overline{d}_{tot} + \overline{b}_i w / r_n + \overline{c}_i r / r_n) \\ w_i \\ r \end{bmatrix} / r_n \tag{A7}$$

which like above by factoring out and collecting terms gives:

$$\pi_i = ½[r_n \quad r_n\overline{d}_{tot} \quad \mathrm{w}' \quad r']\tilde{A}_i \begin{bmatrix} r_n \\ r_n\overline{d}_{tot} \\ w \\ r \end{bmatrix} / r_n \tag{A8}$$

where $\tilde{A}_i$ is symmetric. Adding over outputs and defining $A = \sum \tilde{A}_i$ (which then is also symmetric)

we have:

$$\pi = ½[r_n \quad r_n\overline{d}_{tot} \quad \mathrm{w}' \quad r']A \begin{bmatrix} r_n \\ r_n\overline{d}_{tot} \\ w \\ r \end{bmatrix} / r_n \quad \text{where } A = \begin{bmatrix} a_{kk} & a_{kd} & \overline{a}_{ky} & \overline{a}_{kr} \\ a_{dk} & a_{dd} & \overline{a}_{dy} & \overline{a}_{dr} \\ \overline{a}_{yk} & \overline{a}_{yd} & A_{yy} & A_{yr} \\ \overline{a}_{rk} & \overline{a}_{rd} & A_{ry} & A_{rr} \end{bmatrix} \tag{A9}$$

This is the aggregated profit function in (16)

Appendix B

Table 2A. The estimated parameter values from the translog system without including fishing days[1]

Parameter	Coeff.	t-value	Parameter	Coef.	t-value
Unres. output			Vessel Input		
a_{yy}^{11}	739.281	2.75	$a_{kd} + a_{dr}^{22}$		
a_{yr}^{11}	-191.684	-3.72	$-½\, a_{dd}$		
a_{yd}^{1}			$-½\, a_{yy}^{11}$	-369.640	-2.75
a_{yy}^{12}	0.213	0.80	a_{yy}^{22}	$3.68*10^{-6}$	-0.38
a_{yy}^{13}	1.684	2.73	a_{yy}^{23}	$6.15*10^{-5}$	-1.56
a_{yy}^{14}	-0.003	-0.02	a_{yy}^{24}	$9.83*10^{-6}$	1.10
β_y	-1.363	-1.68	a_{yy}^{33}	$5.05*10^{-5}$	0.90
			a_{yy}^{34}	$-6.06*10^{-5}$	-2.19
Fuel Input			a_{yy}^{44}	$8.70*10^{-6}$	1.98
a_{ry}^{11}	-191.684	-3.72	$-a_{yr}^{11}$	191.684	3.72
a_{rr}^{11}	119.500	3.33	$-½\, a_{rr}^{11}$	-59.750	-1.32
a_{rd}^{1}			β_{x2}	-0.187	-1.89
a_{ry}^{12}	0.017	0.93			
a_{ry}^{13}	-0.117	-2.08			
a_{ry}^{14}	-0.018	-1.88			
β_{x1}	-0.374	-6.74			

1) The parameter values for the annual dummies are not included in the Table 2.