

**SNF-Report No. 4/03**

**Modelling Fisherman Behaviour under new Regulatory Regimes:  
Methodological Report**

**by**

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SNF- project No. 5900  
"Modelling Fishermen Behavior Under New Regulatory Regimes"  
The project is financed by the European Commission

*Centre for Fisheries Economics  
Report no. 93*

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION  
BERGEN, MARCH 2004

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ISBN 82-491-0259-2

ISSN 0803-4036

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## 1. Introduction

The purpose in this report is to outline the methodology and underlying theory to be used in the EU funded project 'Modelling fisherman behaviour under new regulatory regimes'. The objective of the study is to examine how fishermen may respond to the introduction of individual quotas, nontransferable (IQs) and transferable (ITQs). Various studies have addressed different aspects of fishermen's response to management, including ITQs, with respect to effort production and allocation, input and output substitution, discarding and other aspects of behaviour. The principal focus of this study is how the introduction of IQs or ITQs may affect the profitability in the fishery. In particular we focus on to what extent the changed incentives from a race to fish to IQs allows rents to be generated, or whether the capacity reduction associated with ITQs are necessary. We also estimated potential rents with the given fleet technology, and are using this to obtain a measure of the required capacity in a fishery that maximise rents.

The primary approach proposed for the study is the estimation of cost functions, from which optimal (least cost) vessel characteristics can be determined assuming a given level of output (quota). The estimation of cost functions is a part of the 'dual' approach to the estimation of production functions. In the dual approach, profit maximisation can be achieved through the maximisation of revenue for a given level of inputs, through minimising costs of production for a given level of outputs, or both simultaneously. The dual approach take into account economic factors like prices, in contrast to the 'primal' approach. In the 'primal' approach, production or distance functions are used to investigate the technological relationships between inputs and outputs. The former is

often considered to be preferable to the latter as it allows for changes in the output and input composition due to economic factors like prices, resulting in improvements in allocative efficiency and potentially greater levels of profits.

The dual approach is highly suitable for revealing disaggregated structures in fishing processes that consist of several inputs and outputs. Building on the functional forms of cost, profit, or revenue functions, the dual approach has improved our understanding of economic and technological production conditions based on data at firm level. This is done by addressing a variety of different technological issues for multispecies harvesting firms, such as transformation between species, substitution between fishing inputs, economies of scope and scale, industrial organization, etc. Moreover, the approach has been useful as a means of providing information on public management of resource exploitation by dealing with various regulatory regimes; i.e., input management, output management, and prospects for future regulation.

When some factors are fixed the firm's optimisation problem is also restricted. However, one can from the restricted problem also find the optimal level for the fixed factors. In fisheries regulated with individual quotas, this allows us to derive the optimal quota for a vessel based on an estimated cost function. Based on this one can also derive actual and potential resource rents in a fishery and optimal number of vessels if one know the TAC.

The report is organised as follows: First, we consider the set of incentives created by the introduction of an ITQ programme. Second, we consider the theory of the firm and

duality theory to reveal economic and technological conditions of fish harvesting firms, and survey empirical studies that utilise this theory. Third, we investigate how these models can be used to obtain information about actual rents, optimal rents and capacity with focus on fisheries managed with individual quotas.

## 2. Fisher behaviour and fisheries management

The public management of marine fisheries is often seen as the only possible means of preventing overexploitation of our fish resources. The seminal paper of Gordon (1954) shows that because fish stocks in an unregulated state is a common pool resource, the tragedy of the commons will unfold. One main insight about fishermen behaviour comes out of this analysis. Because a fish stock in an optimal state gives a resource rent that act as pure profits for the fishermen, the fishery will attract excess capacity until this resource rent is fully dissipated due to the competition between the fishermen. In addition, in an unregulated or open access fishery the fish stocks will be at a lower level than what is both biologically and economically optimal.

During the last half of the 20<sup>th</sup> century most fisheries have been regulated, making open access an imprecise description of the fishery. Indeed, with a correctly set TAC, one can prevent the stock from being biologically overfished. However, economists soon realised that a TAC did nothing to solve the economic problem (Wilens, 2000). In fact, a TAC and most other regulations that have been used to limit fishing effort, does not change the economic incentives for the fishermen at all. As long as the resource is sufficiently valuable, as it seems to be in all commercial fisheries, the incentive for fishermen is to maximise their *share* of the catch. This incentive will lead to a race among fishermen to capture the largest share possible of the TAC and to over-capacity in harvesting as fishermen substitute away from those inputs restricted by regulation (Munro and Scott, 1985). These regulations can, in many cases, make the overcapacity problem even more severe than in unregulated fisheries because of the race to fish (Homans and Wilens, 1997). What is more, since the common property nature of the



resource is essentially unaltered by these regulations, the resource rent are still in most cases fully dissipated.<sup>1</sup>

## 2.1 The bioeconomic model

The basic bioeconomic model introduced by Gordon (1954) outlines the common property problem or the tragedy of the commons, and makes it clear why economic analysis of fisheries should differ from analysis of traditional landbased industries. The model can briefly be outlined as follows.<sup>2</sup>

The net natural growth in the biomass is

$$F(x) = rx(1 - x/k)$$

where  $x$  is the biomass,  $r$  is the intrinsic growth rate and  $k$  is environmental carrying capacity. This function also gives the sustainable yield for different levels of the biomass. The value of the sustainable yield can be found by multiplying this equation with a price  $p$ , giving the sustainable revenue curve, TR. We will here, as in most analysis assume that the price is given from a world market. Harvest  $H$  is given as

$$H = \gamma x^\alpha E$$

where  $\gamma$  is a catchability coefficient,  $\alpha$  gives the strength of the stock effect and  $E$  is fishing effort. The fishery is in equilibrium when growth of fish stock equals harvest,  $F(x)=H$ . Fishing cost is

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<sup>1</sup> See e.g. Dupont (1990) or Homand and Wilen (1997). However, if the fishermen are not able to fully substitute away from input factor restrictions, some resource rent can be realized (Flaaten, Heen and Salvanes, 1995).

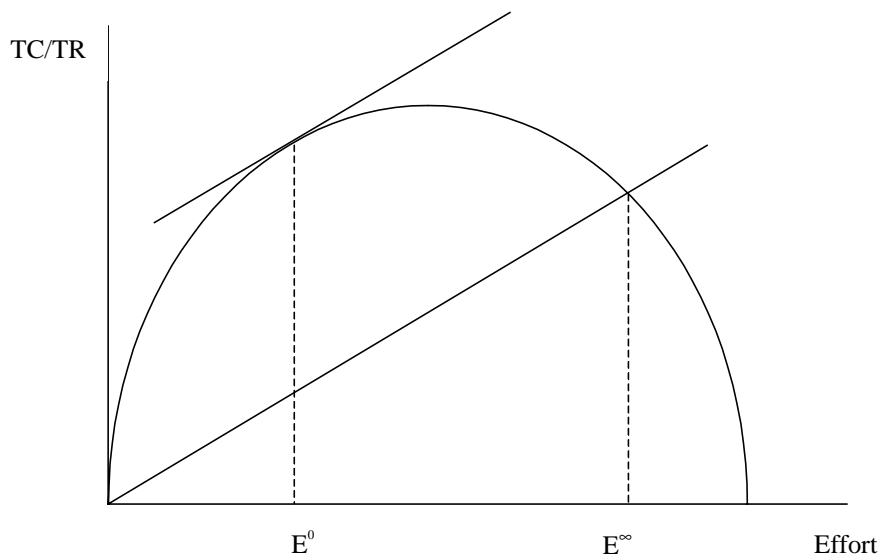
<sup>2</sup> A number of reviews and textbooks gives good presentations of the bioeconomic model, including Munro and Scott (1985), Anderson (1988) and Hannesson (1993).

$$C = cE = cH / \gamma^\alpha$$

where  $c$  is the unit cost of fishing effort. Total profits or rent are

$$\Pi = pH - cE$$

This model has two equilibria: Under open access the equilibrium condition is that price equals average cost, and all rents are dissipated like in all competitive industries. The effort level is then  $E^\infty$ . Under optimal management the equilibrium condition that price should equal marginal cost, leading to an effort level  $E^0$ . However, in contrast to the standard competitive case rents will be generated because of the biological production process. This is graphed in Figure 1, where the sustainable revenue curve, TR, is shown together with the cost curve, TC. As one can see,  $E^\infty > E^0$ , implying that under open access, not only are all rents dissipated, but society also waste its resources by employing too much effort.



**Figure 1: profit maximising effort level**

The key insight from this model is that the incentives of the fishermen are to move to the open access equilibrium. Because the stock level is too low one then induces higher costs than necessary and therefore wastes resources. If one rather had been able to limit the effort some rent would be generated, and if effort could be reduced to  $E^0$ , a level that gives the Maximum Economic Yield (MEY) and the full potential resource rent in the fishery would be generated. Munro and Scott (1985) shows that fisheries with all traditional regulatory tools, regulated open access fisheries, the incentives for the fishermen will still be to dissipate rents, although one can protect the stock with a TAC. This is highlighted in Dupont (1991), where all rents are dissipated in the BC salmon fishery despite TAC and effort regulations. Homans and Wilen (1997) take this one step further by showing that the race to fish that is often created in a regulated open access fishery, the effort will often be even higher than in an open access fishery. The only known regulatory tool that changes these incentives is individual quota systems, and the full resource rent will be reflected in the quota value in a well-designed ITQ system. However, it should be noted that one can at least in principle achieve the same outcome as with an ITQ system with appropriate set output taxes. In fact, for a fisherman without quota, the optimization problem is the same in the two cases, as he would either have to pay the quota rent to the owner of the quota, or a tax at the same level to the government.

It follows from this discussion that the main economic predictions with respect to firm behaviour that are particular to a fishery are that in general fishermen will have incentives to dissipate all rents and to employ too much effort. This is also the principal issues addressed in most general fisheries economics texts like Munro and Scott (1985),

although there are of course a number of less important issues. It is also well known that in most fisheries where ITQs are introduced, the capacity reduction takes time, and one can wonder if it is ever complete so that the full resource rent is generated.

We have not discussed dynamic bioeconomic models here. However, as shown in Munro and Scott (1985), the primary insights from allowing for dynamics is that the discount factor changes the optimal equilibrium somewhat, although not very much with most commonly observed growth rates and discount rates, and one can specify the adjustment path towards an equilibrium. Hence, when one are not concerned about the optimal harvest, little is gained by using a dynamic bioeconomic model. Although economist have often been concerned about optimal harvest levels, in the real world economic considerations have little impact when quotas are set as noted e.g. by Homans and Wilen (1987). However, the two main behavioural implications, rent dissipation and too much effort persist as long as the common pool characteristics of the fishery are present.

## **2.2 ITQs, rent generation and capacity reduction**

During the 1990s, individual vessel quota (IVQ) schemes, where the quota may or may not be transferable, have become an important management tool. For these schemes, each participant in the fishery is entitled to a *quantity or quota* share of the TAC. This eliminates the race to fish as fishermen are ensured their quota share. Moreover, it changes the fishermen's incentives to maximise the profit for their quota. As the output quantity in this setting is given by the quota, this is equivalent to minimise the cost of harvesting the quota. That the race to fish is eliminated also make rent generation

possible. However, to ensure rent generation, capacity in the fishery cannot be too high. This is a problem as there tends to be substantial overcapacity in fisheries when individual vessel quotas are introduced. In most cases, the practice has been to initially allocate quota shares to fishermen *gratis*, usually based on historical catch records.

Transferability of individual quota provides incentives for efficient harvesters to acquire quota from less efficient harvesters, which then leave the fishery, reducing harvesting capacity. This will improve overall harvesting efficiency in the fishery and generate rent. In principle, a well designed individual transferable quota system will allow all resource rents to be generated and reflected in the value of the quota (Arnason, 1990). An interesting question is whether it is the changed incentives due to individual quota or the capacity reduction due to transferability of quota that is most important in generating rent in individual vessel quota schemes. This question has great practical implications as several countries, have chosen IVQ schemes that do not allow or have put in place strict limits on transferability of quota. Such countries risk the possibility of substantial rent dissipation through over-capacity in harvesting. In the European Economic Area there are several examples of different hybrids of individual quota schemes, including fisheries in the countries of all partners in this project. This ranges from full ITQ systems at Iceland, to systems with limited or no transferability in Denmark, Norway, Sweden and the United Kingdom.

Virtually all studies of fisherman behaviour show that fishermen respond strongly to their incentives.<sup>3</sup> Furthermore, as noted above, these incentives changes strongly when one goes from traditional regulatory measures to the new regulatory schemes based on individual quotas. Studies of behaviour have focused on a range of issues, including effort allocation (Pascoe and Robinson, 1998; Holland and Sutinen, 2000; Sampson, 2002), effort production and capacity utilisation (e.g. Campbell and Lindner, 1990; Vestergaard, 2002), response to risk (Eggert and Tveteras, forthcoming; Herrero and Pascoe, 2003), and discarding behaviour (Anderson, 1994; Arnason, 1994).

The main objective in this project is to investigate how these different individual quota systems work with focus on the main issues that Gordon (1954) raised about fisherman behaviour, that is; to what extent do they allow resource rent to be collected and what is the overcapacity in the fishery if some of the resource rent is dissipated. To investigate these effects, we must also be able to measure the potential resource rent in the fisheries in question (or at least the potential rents given the biological management regime one are operating under and technology employed in the fleet).

These issues are well understood in theory (Munro and Scott, 1985; Arnason, 1993; Wilen, 2000). However, few studies actually measure their magnitude, and it is accordingly difficult to assess their real importance. However, with the conflict that often arise when individual quotas systems are introduced, and the often strong negative attitude towards transferable quotas, the magnitudes are important for the changes in

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<sup>3</sup> This is as as expected from an economic point of view. Varian (1993, pp. 23) states that " A basic assumption of most economic analysis of firm behaviour is that a firm acts so as to maximize its profits".

regulatory systems to be worthwhile. To address these issues, we will first review the empirically oriented literature on fishermen behaviour under traditional regulatory schemes. This literature contains methods for measuring capacity and rent dissipation in these settings. However, because of the changed incentives in individual quota schemes, a different specification that reflects these incentives is necessary to obtain the information of interest. There are of course a number of other issues that are of interest in relation to fishermen behaviour with individual quotas like high grading, safety etc. However, these are outside the scope of the present study, as they will require different approaches.

In order to assess the consequences of regulations, regulators need detailed knowledge of the technologies employed in a fishery. This is because the success or failure of a given regulatory system depends on how firms with given technological features respond to regulation. For example, output regulation might mean that firms will alter their harvesting strategies to catch different species, or alternatively that they will reduce their fishing effort, or some combination of these two options might be introduced. In general, different economic outcomes can be expected from the alternative responses. It needs to be emphasized that the economic consequences of a policy depend critically on the technological profiles of the firms that participate in the fishery concerned.

### **2.3 Modelling profit maximisation under ITQs**

From the previous section, the incentives facing fishers under an ITQ programme is to maximise their profits given their level of quota holdings. In the short term, these quota

holdings are fixed, so the incentive is to minimise the costs of harvesting their given quota. In the longer term, quota holdings can vary. An optimally configured vessel is one where returns to scale are constant,<sup>4</sup> and costs are minimised at this level of production.

Estimating returns to scale has been undertaken in several fisheries using either a production function or production frontier approach,<sup>5</sup> with production often expressed in terms of revenue. A production function defines the relationship between the level of inputs and the resultant level of outputs, and is estimated from observed outputs and input usage in the fishery. The production frontier approach is similar to that of the production function, but takes account of technical inefficiency in production. Kumbhakar (2001) demonstrated that failure to take into account this inefficiency component may result in biased elasticity estimates, and hence biased measures of returns to scale.

Under traditional management regimes, landed quantity is a choice variable for the fishermen. Profit or revenue functions have therefore been the preferred specifications when empirically modelling fishermen's behaviour. However, individual vessel quotas restrict the quantity the fishermen can harvest, and quantity landed is therefore not a

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<sup>4</sup> If the vessel had increasing returns to scale, there are benefits in increasing the level of both ionputs and output. Conversely, if there are decreasing returns to scale, then there would be benefits in moving to a smaller vessel and decreasing quota holdings.

<sup>5</sup> Examples of production functions in fisheries include Hannesson (1983), Squires (1987, 1988), Campbell and Lindner (1990), Dupont (1990), and Pascoe and Robinson (1998), while examples of production frontiers include Kirkley, Squires and Strand (1995, 1998), Campbell and Hand (1988), Sharma and Leung (1999), Grafton, Squires and Fox (2000), Pascoe, Anderson and de Wilde (2001), Pascoe and Coglán (2002) and Herrero and Pascoe (2003).



choice variable as under traditional management regimes.<sup>6</sup> Since the quantity landed is given by the quota, the economic behaviour of the fishermen is to minimise the cost of harvesting. In order to determine how fishermen's behaviour under management regimes with individual vessel quotas, estimation of a cost function rather than a profit function is more appropriate.<sup>7</sup> The cost function is the dual of the production function, and produces identical estimates of elasticities under certain conditions.<sup>8</sup> As noted by Grafton, Squires and Fox (2000), it is primarily data limitations that are used as argument in favour of using primal approaches, and in general one will prefer dual approaches.

Detailed knowledge of the technological and economic conditions that apply to fishing firms can be obtained by employing the dual approach, and many empirical studies of fishermen behaviour use this approach. There are several good reasons for this, which we will come back to in chapter 3. This means that information about profit, cost, and revenue functions at the firm level is used to describe technological conditions in the production process.

The disaggregated technological structure is a central topic that is clarified in the dual applications, thus uncovering detailed relationships between inputs and outputs in the

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<sup>6</sup> In individual quota systems where transferability is possible, short-term leases are in most cases for one year (season). Hence, although it may be argued that with transferability the amount of quota and therefore output is a part of the fishermen's optimisation problem, this is not so under the systems considered here. Moreover, one may also argue that the purchasing/selling of quota is separable from other factors, since quota will be purchased/sold given the expectations of future prices, and each vessel will have a given stock of quota after transfers.

<sup>7</sup> Cost function specifications have been used by Weninger (1998) and Bjørndal and Gordon (2000).

<sup>8</sup> In particular, when the production function is homogenous, such as is the case in the Cobb-Douglas production function (Grafton, Squires and Fox, 2000).

production process. Most fish harvesting firms are multiproduct; i.e., they produce several outputs by means of a range of different inputs. This means, for example, that the firm's aggregated fishing effort consists of disaggregated input components, such as vessel tonnage, engine power, technological equipment, fishing gear, and crew. The disaggregated structure of fishing effort is addressed by identifying the relationships between individual input components by, for example, stating their substitution or complementary relationships. The disaggregated view of the production process opens up the possibility of performing a variety of different analyses of the applications; e.g., the transformation between outputs of the multiproduct firm (see Squires 1987a,b,c; Kirkley and Strand 1988), the input demand of the multiproduct firm (Dupont 1990; Squires 1987a), the cost structure of multiproduct firms (Squires 1988; Squires and Kirkley 1991), and the industrial organization of the fishing industry (see Lipton and Strand 1992; Campbell and Nicholl 1995), and optimal capacity (Dupont, 1990; Bjørndal and Gordon, 1993). Moreover, the dual approach reveals technological conditions under different regulatory regimes; e.g. output-regulated firms (Bjørndal and Gordon 2000; Weninger 1998), input-regulated firms (Dupont 1991), or the prospects *ex ante* of imposing trip quotas (Squires and Kirkley 1991, 1996; Segerson and Squires 1993).

In this project, a cost function approach is the basic specification used to model the production technology for a fishery regulated with individual vessel quotas. Based on such an approach we will measure rent generated and potential rent in fisheries managed with individual vessel quotas at the vessel as well as the fleet level. Actual rent can be measured based on earned income and the cost of harvesting. Potential rent

requires calculating a measure of optimal harvest (quota) from the fishermen's total profit function. Furthermore, optimal vessel (quota) size combined with the TAC for the fishery allows a measure of over-capacity in the existing fleet. These measures are derived in a similar fashion to those provided by Dupont (1990) in a restricted profit function framework. In contrast to Weninger (1998) we focus on rent rather than just efficiency gains and cost reduction due to the individual vessel quotas. This is important when investigating the full potential of an individual quota system since the changed regulatory structure allows the fishermen to serve different and potentially more valuable markets (Homans and Wilen, 2002).<sup>9</sup> This also indicates that the regulatory system itself can be a source of rent dissipation in regulated open access fisheries when it does not allow the fishermen to serve the most valuable markets.

Individual quotas are often introduced for the most valuable species, but not all species targeted by a group of fishermen. To model this requires a specification where some outputs can be treated as fixed, while other are treated as variable. Although this is not a common setting, the theory necessary for our analysis has largely been developed by Lau (1976). In particular, he provides a framework where distinctions between inputs and outputs are unnecessary, and hence where cost functions, revenue functions and any other representation of the firm's problem where some factors are treated as fixed are special cases of a restricted profit function. He also anticipates profit functions where some but not all outputs are treated as fixed naming pollution quotas as an example, and also raises the possibility of a negative output prices, which will be the case if the quota

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<sup>9</sup> For instance, Homans and Wilen (2002) show that harvest value in the Pacific halibu fishery increase substantially since fishermen are able to sell a much larger share of their fish in a fresh product form after individual vessel quotas was introduced.

is traded. We will here use this framework to model fisheries where there is an individual quota only on some species. To obtain information about the fishermen's behaviour and the impact of the regulations in this setting, one can provide measures of elasticities of intensity, jointness, separability and economies of scope in this context.

Before we investigate the methodological approaches that we actually will use, we will review the current practice in the literature when investigating fishermen behavior. However, please note that since most of these studies deals with fisheries under traditional management schemes, profit and revenue functions are the common approaches.

### 3. The Dual Approach

#### 3.1 Outline and assumptions

Neoclassical production theory employs two different ways of obtaining knowledge of the technological structure of a firm. The primal approach refers to the optimization problem in which the technological condition is derived explicitly from the production function. The dual approach denotes the optimization problem in which technological properties are derived by employing the envelope theorem, based, for instance, on the profit function. Diewert (1974) and McFadden (1978) show that the primal and the dual approaches represent two different ways of expressing the same technological conditions, and there is no theoretical difference regarding which approach is employed to measure the properties of the technology. However, there are often strong statistical or econometric reasons for choosing one approach over another, related to what are the agents choice variables. Incorrect specifications can lead to inconsistent parameter estimates and therefore incorrect conclusions (Brown and Christensen, 1981). In addition, using prices will give more precise information about firm behaviour than just looking at the technology. In particular, a harvesting (production) function gives the output level based on a set of input factors, but a cost function will give the exact input factor combination that gives the lowest cost for producing this output level (Chambers, 1988). A good discussion of these issues in a different context can be found in Paul and Siegel (1999).

Campbell (1991), Hannesson (1983), and Pascoe and Robinson (1998) use the primal approach to describe the technological properties in the fish harvesting industry. A

problem with using this approach to describe harvesting technology is that the regressors of input quantities are often highly collinear, which may cause multicollinearity problems in the estimation. Simultaneity bias may also be a problem of the primal approach when it is doubtful whether the input quantities are exogenous in the production process (Hoch 1958).<sup>10</sup> By employing prices as regressors, the dual approach offers a complementary approach that is highly suitable for dealing with problems of the input quantities. However, this does not mean that the dual approach is without problems; for example, insufficient price variability may cause problems in estimating technological properties. The remuneration system in the fishing industry, whereby the crew takes a share of the total catch value, may also cause problems of simultaneity bias. An advantage of the dual approach is that it builds on price data, which are often more readily available and accurate than quantity data. The dual approach has the advantage of being easy to use in modelling multiproduct technology properties. Pope (1982) argues that no first-order conditions require to be solved when applying the dual approach. This means that a broad range of functional forms can be employed by the dual approach. Additional arguments for and against the dual approach can found in Binswanger (1974), Lopez (1982), and Shumway (1995).

In modelling fishing technology, it is crucial that the applied theoretical model should agree with the behavioural hypothesis and market conditions of the firm. Applications of the dual approach in the fishing industry utilize three different sets of behavioural hypotheses and accompanying objective functions to describe firm behaviour. These

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<sup>10</sup> The Hausmann test can be employed to test variable exogeneity of the regressors (see Hausmann 1978).

are: profit maximization, input constrained revenue maximization, and output constrained cost minimization.

Squires (1987a,b,c), Alam, Ishak, and Squires (1996, 2002), and Salvanes and Squires (1995) employ the multiproduct profit function,  $\pi(p,w)$  to describe the profit-maximizing firm expressed by

$$\pi(p, w) = \text{Max}\{py - wx\}.$$

It is assumed that the firm is a price-taker in the input and output markets. The firm determines the demand for inputs,  $x$ , and supply of outputs,  $y$ , based on perceived input and output prices denoted by  $w$  and  $p$ , respectively. The regularity properties imply that  $\pi(p, w)$  is nonnegative, nondecreasing in  $p$ , nonincreasing in  $w$ , positively and linearly homogeneous, convex, and continuous  $(p, w)$ .

Kirkley and Strand (1988), Squires and Kirkley (1991), Campbell and Nicholl (1995), Diop and Kazmierczak (1996), and Thunberg, Bresnyan, and Adams (1995) employ revenue maximizing behaviour to describe the short-run multiproduct supply structure at given levels of inputs. In the short run, inputs are fixed and the firm maximizes the revenue function:

$$R(p, x) = \text{Max}\{py; x\}.$$

The firm is a price taker in the output markets, and the inputs are fixed at their short-run levels. The output supply is conditioned on perceived output prices,  $p$ . The regularity conditions imply that  $R(p,x)$  is nondecreasing in  $p$ , positively and linearly homogeneous in  $p$ , convex and continuous in  $p$ , nondecreasing in  $x$ , and nonnegative.

Bjørndal and Gordon (2000), Lipton and Strand (1992), and Weninger (1998) all use the behavioural hypothesis of cost minimization to describe firms operating under output regulation. The output-constrained firm minimizes the cost function,

$$C(w, y) = \text{Min}\{wx; y\}.$$

Such firms are assumed to base their input demand on the input prices for given output levels. The regularity properties imply that  $C(w, y)$  is positive for  $y > 0$ , nondecreasing in  $w$ , concave and continuous in  $w$ , positively and linearly homogeneous in  $w$ , nondecreasing in  $y$ , and  $C(w, 0) = 0$ .

It is essential to ascertain that the employed behavioural hypothesis correctly specifies the features of the multiproduct firm. The profit function is an appropriate specification with which to address the behaviour of firms that alter their input demand and output supply compositions on the basis of exogenous market prices for inputs and outputs, while the revenue function is more suitable for studying short-term behaviour; e.g., that based on fishing trip data where inputs are assumed to fixed, but the species composition can be varied. Cost minimization is a relevant option for describing firms that vary their input compositions, while output supply functions are restricted and vertical; e.g., due to output regulation or biological constraints. However, employing the cost function when it is questionable that outputs are restricted for the firm raises the question of whether outputs are exogenous or not. In cases in which outputs are endogenous for the firm, dealing with outputs as if they were exogenous outputs creates a simultaneity bias. For this reason, if not all outputs are exogenous for the firm, then employing a revenue or profit function might provide a better description of its behaviour.



### 3.2 Econometric estimation of the cost function

As with production functions, the cost function to be estimated econometrically can take a variety of functional forms. Generally, a translog functional form is preferred, as it does not impose any restrictions on the partial elasticities nor the elasticity of substitution. In contrast, the Cobb-Douglas functional form imposes constant partial elasticities, and an elasticity of substitution of 1.

The translog functional form of the cost function can be written as:

$$\ln C = \ln \alpha_o + \sum_{i=1}^n \alpha_i \ln w_i + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \alpha_{ij} \ln w_i \ln w_j + \alpha_Q \ln Y + \frac{1}{2} \alpha_{QQ} (\ln Y)^2 + \sum_{i=1}^n \alpha_{iQ} \ln w_i \ln Y + e$$

where  $C$  is long-run cost,  $i, j = l, k$  and  $m$ ,  $Y$  is aggregate output and  $e$  is a random error term assumed to be i.i.d.

Estimating a flexible dual function such as the translog cost function can be complex, due to the large number of parameters that need to be estimated. Further, the model must satisfy a range of theoretical considerations to ensure that the results are consistent with economic theory, as will be described below. More efficient estimation can be obtained by simultaneously estimating the cost function with a set of input demand equations derived using Shephard's Lemma (Coelli et al 1998).

The input demand equations (or cost share equations) are given by

$$S_i = \alpha_i + \sum_{j=1}^n \alpha_{ij} \ln w_j + \alpha_{iQ} \ln Y + u_i$$

where  $S_i = w_i x_i / C$  is the cost share of the  $i$ -th input and  $u$  is random error term assumed to be i.i.d. One equation is estimated for each input. The system of equations (i.e. the cost equation and the set of input demand equations) are estimated simultaneously using Zellner's Seemingly Unrelated Regression (SUR) procedure.

As mention above, the cost function must satisfy a number of properties to ensure it is consistent with optimising behaviour (i.e. cost minimisation), and to ensure that it is consistent with the production function. The two main properties are homogeneity and symmetry. These are satisfied by imposing the restrictions:

$$\text{Homogeneity: } \sum_{i=1}^n \alpha_i = 1, \quad \sum_{i=1}^n \alpha_{ij} = 0, \quad \sum_{j=1}^n \alpha_{ij} = 0, \quad \sum_{i=1}^n \alpha_{iQ} = 0$$

$$\text{Symmetry: } \alpha_{ij} = \alpha_{ji}$$

Imposing these constraints reduces the flexibility of the translog functional form, so the full advantages of its use are not realised (Diewert and Wales, 1987). However, these restrictions are necessary to ensure that the resultant model satisfies economic theory.

The translog is the most common functional form in empirical applications. However, the fact that it is formulated in logarithms can create problems in some application. In particular, one needs numerical routines to solve for optimal levels of fixed factors (Brown and Christensen, 1982) and one cannot impose the curvature conditions implied by economic theory. The most common alternative is the Generalized Leontief (See Diewert and Wales for a discussion). A Generalized Leontief cost function is given as

$$C = y \left( \sum_i \sum_j a_{ij} p_i^{1/2} p_j^{1/2} \right) + b_{YY} \left( \sum_i \beta_i p_i \right) y^2 + \sum_i b_i p_i$$

In this functional form the homogeneity restriction is imposed through the functional form, while the symmetry restriction is given as:

$$\text{Symmetry: } a_{ij} = a_{ji}$$

The  $\beta_i$  parameters are arbitrary constants set by the researcher. The input demand equations can be derived in a similar fashion as above using Shephard's lemma. Since this functional form is formulated in levels, one can easily solve explicitly for  $Y$ , and also for fixed factors if they are introduced.

### 3.3 Separability in inputs/outputs of the multiproduct firm

Fishing technologies are often multidimensional because several production inputs are employed to catch different species. The dual approach is highly suitable for acquiring immediate and detailed knowledge of the technological conditions of a multidimensional production process. The complexity of multidimensional production technology can be reduced if it is possible to aggregate inputs or outputs into subsets. Input-output separability is the aggregation concept most often addressed in studies of fishing technologies. The concept indicates whether input and output compositions are independent. The results shown in table 1 indicate that input-output separability is rejected for most fisheries and for various types of fishing gear. This invokes the dilemma that important technological structures may be overlooked if the disaggregated structure of inputs and outputs is not taken into account.

Table 1. Test for Separability

Study	Gear	Functional Form	Separability <sup>1)</sup>	Details
Alam, Ishak, and Squires (1996)	Gill net	Translog profit	Accept, Reject	Input-output separability is accepted but global separability is rejected.
Alam, Ishak, and Squires (2002)	Trawl	Translog profit	Reject	Input-output separability and global separability are rejected.
Campbell and Nicholl (1995)	Purse seine, long line	Leontief revenue	Reject	Input-output separability is rejected.
Diop and Kazmierczak (1996)	Trawl	Leontief revenue	Reject	Input-output separability is rejected.
Kirkley and Strand (1988)	Trawl	Leontief revenue	Reject	Input-output separability is rejected.
Salvanes and Squires (1995)	Trawl	Translog profit	Reject	Rejects input-output separability and weak separability between cod and haddock.
Squires (1987a)	Trawl	Translog profit	Accept	Input-output separability is accepted.
Squires (1987b)	Trawl	Translog profit	Reject, Accept	Input-output and global separability is rejected, but weak separability between cod and haddock is accepted.
Squires and Kirkley (1991)	Trawl	Leontief revenue	Reject	Input-output separability is rejected.
Thunberg, Bresnyan, and Adams (1995)	Gill net	Translog revenue	Reject	Input-output separability is rejected.
Weninger (1998)	Surf clam and ocean quahog vessels	Translog cost	Reject	Output separability is rejected.

1) Accept –  $H_0$ : separability cannot be rejected; Reject –  $H_1$ : separability is rejected.

The necessary conditions for input-output separability for the profit-maximizing firm are  $\delta(x_i/x_j)/\delta p = 0$  and  $\delta(y_i/y_j)/\delta w = 0$  (see Chambers 1994). The first condition implies that output prices,  $p$ , do not influence the composition of inputs  $x_i$  and  $x_j$ . The second

condition means that the input prices,  $w$ , will not affect the composition of outputs  $y_i$  and  $y_j$ . Rejecting input-output separability means that a change in input (output) price alters the relative composition of output (input) quantities.<sup>11</sup> The survey indicates that the majority of fishing technologies should be modelled in a disaggregated context. Aggregated modelling of harvesting conditions involves the potential error of misspecification, where the relationship between input composition and output composition is ignored. In a management setting, the results of input-output separability indicate that imposed regulation of aggregated output means that high-value species will be targeted (highgrading). Furthermore, rejecting input-output separability means that imposed input management might, for example, alter catch composition for the firm. Generally speaking, the results of tests of input-output separability speak in favour of disaggregated modeling of fishing technologies.

Evidence in favour of accepting separability is found in a few cases. Alam, Ishak and Squires (1996) find no evidence to reject input-output separability in the gill net fishery of Peninsular Malaysia in the short run. This implies that inputs and outputs can be aggregated into theoretically consistent variables consisting of a single aggregated input and a single aggregated output. This implies that a quantity restriction on a single output will reduce the input and output at the aggregated level, but that the mix of single

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<sup>11</sup> In the studies of Kirkley and Strand (1988), Campbell and Nicholl (1995), Thunberg, Bresnayan, and Adams (1995), Squires and Kirkley (1991), and Diop and Kazmierczak (1996), fishing effort is measured through the use of a single composite input, thereby implicitly assuming that inputs are separable from outputs. In these applications, the test on input-output separability is, therefore, only addressing whether outputs are separable from the composite input.

elements of inputs and outputs will remain the same. Aggregation over some variables permits substantial simplifications to be made in the economic modelling of the fishery, as it permits the analysis to be undertaken using fewer estimated relationships.

In two studies of New England otter trawl technology, Squires (1987a,b) indicates different separability results. Building on identical data, the diversity in the separability results of studies probably arises from slightly different output group specifications. The separability test in Squires (1987b) indicates that roundfish (cod and haddock) and flatfish (yellowtail and other flounders) are weakly separable subgroups, and input-output separability is rejected. Weak separability means that the marginal transformation between cod and haddock does not depend on inputs or outputs outside the subset. Squires (1987a) does not reject input-output separability for otter trawler technology, thereby obtaining a result that differs from Squires (1987b). On the basis of the information available in Squires (1987a,b), it is difficult to determine exactly what causes the difference in the input-output separability tests, but the specification of subgroups of outputs might be a reasonable explanation.

The specification of the output groups is often problematic in applied studies because many firms do not catch certain species, which leaves a zero value on the regressant. Using censored estimation might solve the problem of missing output observations, but econometrics packages capable of dealing with this problem have not been developed. Applied studies might instead aggregate output into groups whereby the missing observation problem is avoided. Kirkley and Strand (1988), Squires and Kirkley (1991),

and Campbell and Nicholl (1994) overcome the statistical problem of zero catches of certain species by assigning them an arbitrarily small value of 0.01 tons.<sup>12</sup>

### **3.4 Nonjointness in inputs of the multiproduct firm**

Fish stock regulation is often done by regulating individual species.<sup>13</sup> Single-species regulation is based on the assumption that distinct production functions for individual species exist. However, separate regulation of species ignores the transformation in output supply of the multiproduct firm. The condition of nonjointness in inputs is central to the task of determining whether it is appropriate to regulate the fishing industry in a single-species or multispecies context. A summary of studies that test for nonjointness is presented in table 2. The majority of these studies reject nonjointness in inputs for fishing technologies, thus suggesting that imposed regulation will probably alter the multispecies composition of harvests.

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<sup>12</sup> Problems encountered by employing the 0.01 values might be discovered by comparing sign and statistical significance to estimates of the nonzero observations.

<sup>13</sup> This is, for example, seen in the fisheries of the European Community, where the species are mainly regulated in a single-species context by applying a total allowable catch (TAC) for each single species. Although multi-species TACs (MSTAC) have been introduced by 3760/92 (see Council Regulation, Official Journal L 389, 31.12 1992.), the multi-species management has not been widely used.

Table 2. Test for Nonjointness in Inputs

Study	Gear	Functional Form	Non-jointness <sup>1)</sup>	Details
Alam, Ishak, and Squires (1996)	Gill net	Translog profit	Accept	Nonjointness for all outputs cannot be rejected.
Alam, Ishak, and Squires (2002)	Trawl	Translog profit	Reject	Nonjointness for all outputs is rejected.
Campbell and Nicholl (1995)	Purse seine, long line	Leontief revenue	Accept, Reject	Nonjointness is rejected for purse seine (specialized firms) and accepted for the generalist firms.
Kirkley and Strand (1988)	Trawl	Leontief revenue	Reject	Nonjointness for all species is rejected.
Salvanes and Squires (1995)	Trawl	Translog profit	Reject	Rejects nonjointness for all outputs in common and for each single output separately.
Segerson and Squires (1993)	Trawl	Leontief revenue	Reject	Nonjointness for all outputs is rejected.
Squires (1987a)	Trawl	Translog profit	Reject	Nonjointness for all outputs is rejected.
Squires (1987b)	Trawl	Translog profit	Reject	Nonjointness for all outputs is rejected.
Squires and Kirkley (1991)	Trawl	Leontief revenue	Reject, Accept	Nonjointness is rejected for all species except for Dover sole.
Thunberg, Bresnayan, and Adams (1995)	Gill net	Translog revenue	Reject	Nonjointness for all outputs is rejected.
Diop and Kazmierczak (1996)	Trawl	Leontief revenue	Reject	Nonjointness for all species is rejected.
Weninger (1998)	Surf clam and ocean quahog vessels	Translog cost	Accept	Nonjointness in inputs cannot be rejected.

1) Accept –  $H_0$ : Nonjointness in inputs cannot be rejected; Reject –  $H_1$ : Nonjointness in inputs is rejected.

Nonjointness in inputs determines whether or not a firm will maximize its production for each output separately. If it maximizes each output separately, this means that there



is no interdependence among its production of the various outputs. Hall (1973) set out a necessary condition for nonjointness in inputs for the profit function as:

$$\pi(p, w) = \sum_{i=1}^n \pi_i(p, w),$$

meaning that the firm maximizes the individual profit functions for each output. This is the same as saying that its total profit from producing all outputs is the sum of the profits generated by each output. Testing for nonjointness in inputs for the profit-maximizing firm means that a change in the price of the single output will not affect the profit or the quantities produced of other outputs. This implies the restriction:

$$\frac{\delta^2 \pi}{\delta p_i \delta p_j} = 0, \quad i \neq j,$$

which is a necessary condition for:

$$\delta y_i / \delta p_j = 0, \quad i \neq j.$$

That is, a price change in the *j*th output will not affect the firm's output supply of the *i*th nonjoint output. Similarly, a multioutput cost function will be nonjoint in inputs if

$$\frac{\partial^2 C}{\partial y_i \partial y_j} = 0, \quad i \neq j$$

The tests for nonjointness in inputs reveals that results differ, depending on the fishing gear employed. For trawlers, the null-hypothesis of nonjointness in inputs is rejected in most studies. This is not surprising, since trawl gear is designed for harvesting a wide range of species. In a management setting, the jointness in inputs implies that individual regulation of species (for example through TAC) will also change the quantity of other species landed by trawlers. This implies that fishing managers need to acknowledge the consequences of TAC regulation on a given species will have on other species landed

by the firm. In order to allow this to be done, the proper specification of the joint production technology contains an explicit modelling of the transformation in production between different species.

Failure to reject nonjointness in inputs for trawlers is seen in a single case. Squires and Kirkley (1991) find that catches of Dover sole are a nonjoint production in the Pacific coast trawl fishery, implying that Dover sole are harvested independently of other species by trawlers. No intuitive explanation is given for the nonjointness of Dover sole. However, a situation that might cause nonjointness in inputs occurs when different species are harvested during different seasons of the year.

It is noteworthy that Weninger (1998) and Alam, Ishak, and Squires (1996) find evidence for nonjointness in inputs for technologies in the mussel and gill net fishery. This indicates an important difference between trawling, on the one hand, and the technologies employed in mussel and gill net fisheries, on the other.

In the mid-Atlantic surf clam and ocean quahog fisheries studied by Weninger, the nonjointness in inputs indicates that these species are harvested independently. This has the policy implication that surf clams and ocean quahogs might be regulated independently, because no spillover effect of the regulation of one species would be expected on the other species. In this sense, nonjointness in inputs traditionally legitimizes the individual regulation of species because they are harvested independently in separate production processes.

However, the study of Alam, Ishak, and Squires (1996) indicates an exception where it is inappropriate to regulate species individually, although nonjointness in inputs is found in the fishery. The reason for this is that no evidence in favour of rejecting neither nonjointness in inputs nor input-output separability is found in the Peninsular Malaysia gill net fishery examined. Therefore, there is an overlap in the technology of both nonjointness in inputs and input-output separability (see Hall, 1973). This implies that gill net technology consists of individual production functions for each species, and in addition, that the production functions are identical and scalar multiples of one another. This means that there is a consistent aggregated output in fixed proportions, and the firm cannot alter its output mix. If the regulator employs a single-species TAC, the gill netters will be forced to reduce all catches proportionally in order to satisfy the regulation. In this sense, harvests of the individual species cannot be regarded as being independent. However, regulation of a single species might prove to be costly for the firm, because in order to satisfy the regulations, the harvest of all species would have to be reduced. Instead, general biomass management might be regarded as an alternative for such fisheries. Yet, employing biomass regulation would make it difficult to ensure the sustainable development of species that are overexploited.

### **3.5 Modelling biological conditions constraining the multiproduct firm**

Modelling the technological conditions that affect individual fishing firms requires biological conditions to be explicitly addressed. For the individual firm, the biological conditions; e.g., resource abundance, affect the production environment, but the single firm has no means of controlling stocks, which, therefore, must be treated as exogenous. In this sense, as argued by Squires (1992, 1994a), treating stock abundance as an input

factor in the production process like capital, labour, or energy is inappropriate in a positive, as opposed to a normative analysis based on the theory of the firm. Biological conditions like stock abundance should rather be modelled as an exogenous component that shifts the level of production.

This put the role of biological conditions like stock size well into a restricted profit function specification, which McFadden (1978) claims is the most general representation of firm behaviour. A restricted profit function,  $\Pi^R(p, w; z)$ , gives profits as a function of output and input prices,  $p$  and  $w$ , and the levels of exogenous factors,  $z$ . What is of interest here is that profits are an increasing function of the exogenous factor. Hence, if the exogenous factor is the stock level, higher stock abundance gives higher profits. This is also as expected from the bioeconomic model since higher stock abundance gives lower cost and *ceteris paribus* higher profits. As such, the stock variable plays a similar role to other exogenous factors like technological change or agglomeration. It should be noted that in modelling the firm behaviour, truly exogenous factors like stocks are treated in the same fashion as quasi-fixed factors like capital which the firm can change, although it generally does not in the short run because of high adjustment costs. Capital is here a good example. In the short run, the effect of changing the levels of a quasi-fixed factor is therefore similar to the effect of changing the levels of factors that are exogenous in the long run.

McFadden (1978) and Lau (1976) also note that the separation of netputs into outputs and inputs is largely artificial, although convenient for expositional purposes. However, this implies that revenue as well as cost functions are special forms of the restricted

profit function where respectively all inputs or all outputs happen to be quasi-fixed. This implies that an exogenous variable like stock size should be treated in the same manner in restricted profit functions, cost functions and revenue functions.

The obvious way to model stock effects is then to include stock size as an exogenous variable in the function that is specified. Bjørndal (1987), Dupont (1990), Weninger (1998), and Pascoe et al (2001) are examples of studies that employ indices to measure fluctuations in stock abundance.

However, somewhat surprisingly given the use of stock indices close link to theory, most applications of the dual approach use annual or seasonal dummy operators to measure fluctuations in resource stocks (see Squires 1987a,b,c; Bjørndal and Gordon 1993; Salvanes and Squires 1995; Campbell and Nicholl 1995; Squires and Kirkley 1996; Diop and Kazmierczak 1996). There are several reasons for this that mostly relates to data and statistical issues. In many fisheries, particularly multi-species fisheries, information on stock abundance of all species (or in some cases any of the species) may not be available. In such cases, deriving a composite stock index is not straightforward.<sup>14</sup> As a result, other means of estimating the effect of changes in stock abundance on production need to be employed.

A stock variable is exogenous to all firms, but since all firms fish the same stock(s), the variable(s) are identical for all firms. Hence, there is no variation in this variable in each

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<sup>14</sup> Pascoe and Herrero (2001) developed a method for compensating for stock changes in multispecies fisheries when stock information was unknown. The method was developed for use in production functions, but could be equally adapted to cost functions.

cross section. Hence, if one has observations for only one year (or season), the variable will be perfectly collinear with the constant term, and accordingly one cannot explicitly model the effect of the stock size in such a situation. When one has observations over several seasons, the stock variables are identical for all vessels within a season. One can then model the effect of the changes almost as precise with dummy variables as with stock indices. When one take into account that there are also other factors that can vary between seasons like weather, oceanographic conditions etc., that changes in a similar fashion as stock size but which is very difficult to obtain measurements for, one will econometrically be better off by modelling the combined effects of all these variables with dummies. Indeed, if one estimates a specification which only includes stock indices, the estimated parameters is likely to be inconsistent as estimates of the stock influence. This is because the weather effects etc. give an omitted variable problem, and the estimated parameters will pick up some of the effect of the omitted variables. Finally, it is often hard to obtain data for the stock in the relevant geographical area, and given that the statistical issues, it may then be preferable to use dummy variables to represent these effects.

A problem with the use of dummy variables to capture stock change is the loss in degrees of freedom. In the case of production functions and frontiers, models are often estimated using monthly landings data. While a series of month and annual dummy variables could be used, this assumes that seasonal conditions do not vary from year to year. A dummy variable for each time period, which allows for interannual variations in seasonal conditions, adds considerably to the number of parameters to be estimated in

the model. This problem is less prevalent in cost functions as costs are generally only available at an annual level. As a result, the potential loss of degrees of freedom is less significant than in studies based on production functions.

A further problem with the use of dummy variables is that it does not allow for interactions between the inputs and stock. For example, larger boats may be more able to capitalise on a stock increase, and be more heavily affected by a stock decrease, than smaller boats. Failure to capture this interaction may result in misspecification of the underlying production process, and hence the elasticity estimates. This problem is relevant to both production and cost functions.

An alternative approach is to derive an index of stock abundance based on relative catch rates. Kirkley, Squires and Strand (1995, 1998) developed such an index based on the catch rate of survey vessels undertaking routine stock monitoring. Pascoe and Coglán (2002) developed an index based on the average value per hour fished of the boats that operated in the same month in the same métier. Hence, it takes into account the differences in the composition of the catches taken by the different gear types at each point in time and in each area, as well as the different set of prices in each time period. Were price changes not accounted for in the model, then changes in the set of prices may have affected the estimates of efficiency (as the output measure may change without any change in the physical inputs). The index was calculated as a geometric mean of the observed values in each period/métier to limit the effects of extreme observations on the mean.

Sharma and Leung (1999) argue against the use of catch per unit effort (CPUE) as a measure of stock abundance on the basis that average CPUE is affected by the characteristics of the boats in the area at the time. A change in CPUE from one period to the next may reflect the different composition of the boats from which the CPUE was derived as well as changes in the stock abundance. While this was recognised as a problem, the advantages of using the measure were that the effects of changes in prices can be factored into the model, and greater flexibility in terms of interactions between gear use, month and year effects can be incorporated. Use of dummy variables for these assumes fixed effects across the data, whereas seasonal effects are likely to vary in their timing between years, while catch compositions may vary between years differently for the different gear types based on previous exploitation patterns.

As the index is the average of the catch rates of the boats operating together, deviations from the average that cannot be attributed to the boat characteristics are either differences in efficiency or stochastic error. In this way, the stock index assumes the same role as the set of dummy variables (which account for systematic changes in average performance), with the added advantage that interactions with the other inputs can also be incorporated through the translog function and substantially fewer degrees of freedom are lost.



## 4. Applications of the dual approach in fisheries

The dual approach has been used in numerous studies of fisheries to consider a wide range of issues. These include examination of the supply elasticities in fisheries, input demand and the effects of effort controls, cost structures in fisheries and, also, the organisational structure of the fisheries. In this chapter, these studies are summarised.

### 4.1 Transformation between outputs of the multiproduct firm

The condition of jointness in inputs found in most studies of trawl fisheries indicates that there is dependence between production functions for the various outputs. This has implications for fisheries management, because regulations imposed on single species also have an impact on landings of other species. This follows because firms do not produce their catches of individual species as separate outputs, but there are interactions in harvesting decisions regarding different species. For this reason, regulators ought to take account of the technological ability of the firm to alter its harvesting pattern within a given fishing season. One way to clarify the features of joint production is to describe substitutions and complementary transformations in output supply.

The output supply elasticities presented in table 3 are based on the assumption that firms maximize their production supply based on exogenous market prices for landings. The table discloses inelastic own-price elasticities in most studies, indicating that a 1% increase in the output price increases the output supply by less than 1%.<sup>15</sup> The fairly

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<sup>15</sup> There are two exceptions. Thunberg, Bresnayan, and Adams (1995) find an elastic short-run elasticity for the output of mullet in the gill fishery of Florida. Squires (1987c) finds elastic long-run elasticities in the otter trawl fishery of New England. The latter confirms that the elasticities are higher in the long run.

small price reaction in output supply indicates rigidity in the firm's ability to alter its harvesting pattern in the short run. There are various reasons for rigidity in harvesting patterns. Squires (1987c) stresses that search costs in exploiting new species or fishing grounds imply rigidity in the harvesting pattern because search costs outweigh the gain in revenue that could be obtained by the search.<sup>16</sup> Insufficient price variability might be an empirical explanation for the inelasticity given that the studies are based on cross-section data that cover a rather short time span. Kirkley and Strand (1988) also argue that aggregation of outputs might cause potential aggregation bias and thereby inelastic output supply elasticities. Further, multicollinearity might cause problems of inadequate variability in the output prices and thus insignificant parameter estimates.

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<sup>16</sup> Search cost in the form of energy consumption, risk, quality deterioration for some species, opportunity cost foregone, and labors cost.

Table 3. Product Supply Elasticities

<b>Study</b>	<b>Gear</b>	<b>Elasticity with Respect to Outputs<sup>1)</sup></b>	<b>Own-price Elasticity</b>	<b>Cross-price Elasticities</b>	<b>Fishery Featured by:</b>
Kirkley and Strand (1988)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches
Alam, Ishak and Squires (2002)	Trawl	SM	Inelastic	Mainly Complements	Inconclusive <sup>2)</sup>
Salvanes and Squires (1995)	Trawl	SM	Inelastic <sup>3)</sup>	Substitutes, Complements	Flexible catches
Squires (1987b)	Trawl	SM	Inelastic	Not reported	Not reported
Squires (1987c)	Trawl	LM	Elastic, Inelastic <sup>4)</sup>	Substitutes, Complements	Flexible Catches <sup>5)</sup>
Segerson and Squires (1993)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches
Squires and Kirkley (1991)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches
Squires and Kirkley (1996)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches
Thunberg, Bresnayan, and Adams (1995)	Gill net	SH	Elastic, Inelastic <sup>6)</sup>	Complements	Key species
Diop and Kazmierczak (1996)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches

1) SM – short-run Marshallian, LM - long-run Marshallian, SH – short-run Hicksian, LH – long-run Hicksian.

2) The Marshallian cross-price elasticities indicate that the output effect dominates the substitution effect, whereby increased landing of high- or medium grade species will increase the landings of low-grade species indicating bycatch of low-grade species.

3) The own-price elasticities of the most important species cod and haddock are inelastic but insignificant.

4) The own-price elasticity for roundfish is elastic, but inelastic for flatfish and all other outputs.

5) Based on Allen elasticities.

6) The own-price elasticity for the “key species” is elastic.

The cross-price supply elasticities reveal the interaction in the supply of different outputs for the multiproduct firm. The cross-price elasticities clarify an important technological difference between trawl and gill net technologies. For trawl technology, the cross-price elasticities uncover a “flexible” fishery of both substitution and complementary relationships in the output supply of the various species (Hicksian elasticities).<sup>17</sup> For the gill net technology, all outputs are produced as complements. Although Thunberg, Bresnayan, and Adams (1995) is the only study to have revealed cross-price elasticities for gill net technology, it is important to stress the difference in results obtained for trawl and gill net technologies. The possibility of substituting between outputs expressed for the trawl technology indicates that the firm switches between targeting different species. In doing so, trawler technology involves a degree of flexibility that may enable the firm to change its target species, for example, as a result of regulations imposed on a particular species. This kind of flexibility is not found in gill net fisheries, where outputs are produced as complements and it is difficult for the firm to change its target species. In this sense, the gill net fishery is characterized as a “key” fishery where one or two key species are targeted and other species are harvested as bycatches.<sup>18, 19</sup>

The feature of “key” or “flexible” fishery has implications for fisheries management. In a “flexible” fishery, the regulator should take into account the substituting/complementary relationship that exists between outputs. This means that

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<sup>17</sup> The Hicksian elasticity measures the pure substitution effect (see Lopez 1984).

<sup>18</sup> If there are two “key” species, they are produced as complements.

<sup>19</sup> The missing ability to substitute between outputs is also found in the gill net fishery described by Alam, Ishak, and Squires (1996).

regulation that restricts a single target species often implies that a firm has the option of increasing its harvest of some other species. This possibility does not exist in “key” species fisheries that consist of complementary outputs. Thus, in a “key” fishery, the regulation of a single output implies that the firm will either discard the regulated species or reduce its fishing effort, with the latter option reducing its total earnings.

## **4.2 Input demand of the multiproduct firm**

Restricting fishing effort is often put forward as a means of preventing overexploitation of stocks. However, effective effort management is hindered by the multidimensionality of fishing efforts. Pearse and Wilen (1979) emphasize that the successful reduction of fishing effort depends on the regulator’s ability to simultaneously restrict all dimensions of fishing effort. Strand, Kirkley and McConnell (1981) demonstrated the multidimensionality of fishing effort through the marginal rate of substitution to plot isoquants between input pairs. The success of imposed effort management depends on the disaggregated structure of fishing effort. Employing the dual approach, the disaggregated structure of fishing effort is often uncovered by addressing the own-price and cross-price elasticities of the input demand functions summarized in table 4.

Table 4. Factor Demand Elasticities

Study	Gear	Variable Effort Items	Functional Form	Elasticity with Respect to Inputs <sup>1),2)</sup>	Own-Price Elasticity	Cross-Price Elasticities
Alam, Ishak, and Squires (2002)	Trawl	Labor, energy	Translog profit	SM, SH	Elastic <sup>3)</sup>	Substitutes
Bjørndal and Gordon (1993)	Purse seine	Fuel	Translog profit	SM	Elastic, Inelastic <sup>4)</sup>	Not reported
Bjørndal and Gordon (2000)	Purse seine, trawler, coastal vessel	Fuel, vessel maintenance	Translog cost	SH	Inelastic	Not reported
Dupont (1991)	Seine, gill net troll	Fuel, labor, gear	Quadratic profit	SM	Inelastic	Substitutes, Complements
Squires (1987a)	Trawl	Labor, energy, capital services	Translog profit	SM, SH	Elastic <sup>5)</sup>	Substitutes, Complements
Squires (1987b)	Trawl	Labor, energy, capital services	Translog Profit	SM	Elastic	Complements
Squires (1987c)	Trawl	Energy and labor	Translog profit	LM	Elastic <sup>6)</sup>	Complements
Weninger (1998)	Surf clam and ocean quahog vessels	Fuel, gear	Translog cost	SH	Inelastic	Substitutes

- 1) SM – short-run Marshallian, LM - long-run Marshallian, SH – short-run Hicksian, LH – long-run Hicksian.
- 2) Marshallian elasticity includes substitution and expansion effects. Hicksian elasticity includes the pure substitution effect (see Sakai 1974; Lopez 1984).
- 3) Marshallian elasticities are elastic except for energy in the east coast fishery.
- 4) Elasticity is estimated on an annual basis for several years.
- 5) Marshallian elasticities are elastic for capital and labor but inelastic for energy.
- 6) Squires (1987c) estimates long-term elasticities from the restricted (short-run) profit function following the outline of Brown and Christensen (1981).

The firm's use of inputs such as fuel, labour, technical equipment, etc., builds on the exogenous market prices for these inputs. Deriving input demand functions can be obtained for firms that minimize costs or maximize profits. However, input demand function cannot be disclosed for firms that going for revenue maximization, e.g., during the fishing trip, because all inputs are fixed within this short period.

The results of the own-price elasticities reveal that input demand is influenced by whether the fishery is regulated or not. For unregulated fisheries, Bjørndal and Gordon (1993), Squires (1987abc), Alam, Ishak, and Squires (2002) find elastic own-price elasticities for trawlers and purse seiners while in the input-regulated fishery studied by Dupont (1991), the own-price elasticities for the unrestricted inputs were inelastic.<sup>20</sup> These results follow as a natural consequence of the Le Chatelier effect; i.e., the regulatory restrictions imposed create rigidity in the production process and thereby restrict the ability to alter composition of unrestricted input components (see Lau 1976; Squires 1994b). In this sense, input regulations will tend to reduce the flexibility (e.g., elasticities) of the unconstrained inputs compared to an unregulated industry. This is also the case in the output-regulated fishery studied by Weninger (1998) and Bjørndal and Gordon (2000). However, when reporting the inelastic own-price elasticities in the output-regulated fishery, it must be emphasized that these are Hicksian elasticities.<sup>21</sup> Hicksian elasticities will normally be smaller than Marshallian elasticities. This follows because Hicksian elasticities do not incorporate the reduction in production that follows

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<sup>20</sup> Bjørndal and Gordon report the own-price elasticity on fuel, which varies on a yearly basis between -0.713 and -1.108.

<sup>21</sup> The Hicksian elasticities, or constant output demand function, is derived from the cost function.

an increase in input price.

The cross-price elasticities reveal the internal structure among disaggregated factors that make up fishing effort. The cross-price elasticities presented include both Hicksian and Marshallian elasticities.<sup>22</sup> The Hicksian elasticities reported by Squires (1987a) Weninger (1998), and Alam, Ishak, and Squires (2002) show substitution between input factors.<sup>23</sup> This is not surprising since Hicksian elasticities measure the pure substitution effect between inputs at a given level of output. What is more interesting is to observe that the Marshallian elasticities in Squires (1987b,c) indicate a complementary relationship between capital, labor, and fuel in the otter trawler fishery. This implies that imposing input regulation on the single input will not be compensated for by increases in other inputs. The complementary Marshallian elasticities indicate that the expansion effect outweighs the substitution effect; i.e., the reduction in input demand that follows from a change in production level outweighs the expected change in input demand due to the substitution effect. Dupont (1991) finds a mixture of complementary and substitutional input demand relationships in the Canadian seine and gill net troll salmon fishery, thereby revealing that individual regulation of gears, fuel, or labour might be circumvented by substituting other inputs. Input management imposed on the gill and seiner fishery should, therefore, be done by restrictions on the use of several inputs at the same time.

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<sup>22</sup> The Marshallian and Hicksian elasticities of input build respectively on the profit and cost function. Lopez (1984) shows how to estimate Hicksian elasticities from the profit function.

<sup>23</sup> Squires (1987a) reports the Allen partial elasticities as well as Marshallian elasticities. The Allen partial elasticity is like the Hicksian elasticity, focusing on the pure substitution effect for the given level of product. The Hicksian and Allen elasticities are related by  $\sigma_{ij} = \epsilon_{ij}/s_j$ , where  $\epsilon$  and  $\sigma$  are the Hicksian and Allen elasticities respectively and  $s_j$  is the cost share of the  $j$ th input. The Allen partial elasticity separates the relative impact of the price changes.



*The Elasticity of Intensity*

Another achievement of Dupont (1991) is to clarify the relationships between regulated and unregulated inputs. This is accomplished by use of the elasticity of intensity, which describes the impact that a change in a restricted input will have on an unrestricted input (Diewert 1974). The elasticity of intensity is defined as:

$$E_{ij} = \frac{\delta x_i(p_v, w, z_i)}{\delta z_i} \frac{z_i}{x_i},$$

where  $x_i$  is the variable input that is conditioned on the output price,  $p_v$ ; input price,  $w$ ; and  $z$ .  $z_i$  is the quantity of the restricted input. A negative elasticity indicates a substituted relationship and a positive elasticity, a complementary one.

In the Canadian salmon fishery, both the number of fishing days and vessel tonnage are restricted by regulation. Based on the estimation of elasticity of intensity, the study of Dupont (1991) reveals that restricting the number of fishing days is an effective way to reduce the fishing effort for seiners and gill net-troll vessels, the reason being that the vessels find it difficult to compensate for a restriction in number of fishing days through an increase in the unregulated input of fuel, labour, and gear. Dupont suggests that estimates of elasticity of intensity could be used to implement input limitation programs aimed at regulating inputs, which have few or limited substitution possibilities, preventing fishermen from compensating for the restricted input by increasing their use of unrestricted inputs

### 4.3 The cost structure of multiproduct firm

Another important means of revealing the technological conditions of the multiproduct firm is via its cost structure. The cost advantage of certain categories of vessel may be a good indicator of competitive advantages; thus indicating which categories of vessel are most likely to survive in the future fleet structure. From a normative view, management authorities might also use information about cost structures for different vessel categories as an important building block in the industrial organization of the fishing fleet. Certain applications of the dual approach are devoted to revealing conditions for economies of scope and economies of scale. This means revealing the extent to which diversity in outputs embodies cost savings compared to specialized production plants, or whether relative cost savings in expanding the scale of outputs exist. A summary of the applications that reveal cost structures of harvesting technologies is presented in table 5.

The economies of scope reveal whether cost advantage exists in producing several outputs or not. The definition of economies of scope follows from the condition:  $C(y_T) + C(y_{v-T}) > C(y_v)$ , where  $C(\cdot)$  is a cost function and  $T$  is a subset of  $v$  (see Baumol, Panzar, and Willig 1982). The condition means that producing outputs  $y_T$  and  $y_{v-T}$  in separate productions results in higher costs than employing a joint production of  $y_T$  and

$y_{v-T}$ .<sup>24</sup>

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<sup>24</sup> The economies of scope are satisfied for one of two reasons, either because of fixed costs or due to weak cost complementarity. Firstly, in case the fixed costs do not depend on the quantities of outputs produced, but do vary depending on which outputs are chosen. This means that the fixed costs of multiproduct technology are less than the sum of costs from two specialized product technologies. Expressed by  $F_T + F_{v-T} > F_v$ , where  $F_T$ ,  $F_{v-T}$  and  $F_v$  are the fixed costs when producing the submatrices of output of  $\{T\}$ ,  $\{v-T\}$ , and  $\{v\}$ , respectively. Secondly, weak cost complementarity means that the marginal cost of producing the  $i$ th output will decrease with an increase in the production of the  $j$ th output. Weak cost complementarity can be expressed by  $\delta(\delta C[\cdot]/\delta y_i)/\delta y_j \leq 0$ , where  $C[\cdot]$  denotes the multiproduct cost function, and  $y_i$  and  $y_j$  denote the production of the  $i$ th and  $j$ th outputs.

Table 5. The Cost Structure of the Multiproduct Firm

<b>Study</b>	<b>Gear</b>	<b>Functional Form</b>	<b>Economies of Scope</b>	<b>Multiproduct Economies of Scale</b>	<b>Product Specific Economies of Scale</b>
Alam, Ishak, and Squires (2002)	Trawl	Translog profit	Economies of scope <sup>1)</sup>	Decreasing returns to scale	Both increasing and decreasing <sup>2)</sup>
Bjørndal and Gordon (2000)	Purse seiners, trawlers, coastal boats	Translog cost	Not reported	Increasing returns to scale for each vessel group <sup>3)</sup>	Not reported
Diop and Kazmierczak (1996)	Trawl	Leontief revenue	Not reported	Not reported	Decreasing and constant <sup>4)</sup>
Segerson and Squires (1993)	Trawl	Leontief Revenue	Not reported	Not reported	Decreasing for all
Squires (1987b)	Trawl	Translog profit	Economies of scope <sup>1)</sup>	Decreasing returns to scale	Both increasing and decreasing <sup>5)</sup>
Squires (1987c)	Trawl	Translog profit	Diseconomies of scope	Decreasing returns to scale	Both increasing and decreasing <sup>6)</sup>
Squires (1988)	Inshore and offshore trawlers	Translog profit	Economies of scope <sup>1)</sup>	Decreasing returns to scale for each vessel group	Both increasing and decreasing <sup>7)</sup>
Squires and Kirkley (1991)	Trawl	Leontief revenue	Economies of scope <sup>1)</sup>	Decreasing returns to scale	Both decreasing and constant <sup>8)</sup>
Weninger (1998)	Surf clam and ocean quahog vessels	Translog cost	Diseconomies of scope	Increasing returns to scale	Increasing for all <sup>9)</sup>

1) The economies of scope are verified due to weak cost complementarity in a subset of outputs.

2) Increasing for high-grade species on east and west coasts, and medium-grade species on east coast.

3) Increasing for multiproduct returns to scale for spring-spawning herring and other catches.

4) Constant returns to scale for finfish, decreasing returns to scale all other species.

5) Increasing returns to scale for yellowtail flounder, decreasing returns to scale for all other species.

6) Decreasing returns to scale for roundfish and flatfish, increasing returns to scale for residual catches.

7) Increasing returns to scale for flatfish, decreasing returns to scale for roundfish and other species.

8) Constant returns to scale for thornyheads and other rockfish, decreasing returns to scale for all other.

9) Increasing returns to scale for surf clams and ocean quahogs.

The results of economies of scope for fish harvesting technologies are ambiguous. Squires (1987b,c and 1988) indicate that there is a discrepancy in the tests for economies of scope for the otter-trawling fishery of New England. The reason for the statistical discrepancy in the studies follows because different output compositions and fleet categories are specified. Squires (1987b, 1988) undertake the most detailed specifications of output compositions and fleet categories, verifying the hypothesis of economies of scope. In this sense, an aggregation bias in Squires (1987c) might explain why economies of scope are rejected in this study. The presence of economies of scope in a fishery might be explained on the basis of seasonal harvest patterns or the spatial distribution of different fish stocks that cause cost complementarity in harvesting several outputs jointly.

Weninger rejects the idea that economies of scope are present in the mid-Atlantic surf clam and ocean quahog fisheries, where fishermen are restricted by output regulation. This result is not surprising, due to the condition of nonjointness in inputs previously reported for these fisheries, indicating that surf clams and ocean quahogs are produced in separate production processes. In this sense, cost complementarity in harvesting the two species can be excluded.<sup>25</sup> Moreover, the imposed output regulation might limit the possibility of achieving complementarity in production, but might instead create a cost disadvantage in joint production due to the Le Chatelier effect. In a management setting, imposing regulation such as bycatch limitation may distort the complementarity of jointly harvested species, leading to increased production costs. In this sense, imposed

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<sup>25</sup> Still, economies of scope cost could prevail due to sharing fixed costs in the harvesting of the two species.

regulation has consequences for the cost structure of the firm, and thereby might distort cost efficiency and create cost disadvantages for certain categories of vessel. Thus, regulation will have unintended impacts on the relative competition between vessel categories operating in the fishery.

Other elements of the cost structure addressed in the applications are the concepts of product-specific economies of scale and multiproduct economies of scale. The cost improvement due to product-specific economies of scale for the *i*th output,  $S_i(y)$ , is based on the condition:  $S_i(y) = AIC_i(y)/C_i$ .  $AIC_i(y)$  is the average incremental cost and  $C_i$  is the marginal cost. The condition states that the firm experiences decreasing cost in producing the last unit of output *i*, if the marginal cost of producing the last unit is less than the average incremental cost. This means that whenever  $S_i(y) > 1$ , the firm has an incentive to increase production. Likewise, the concept of multiproduct returns to scale,  $S_M(y)$ , measures the development of costs for proportional changes in all outputs and inputs.

The results of the product-specific economies of scale indicate that most species are harvested under conditions of decreasing returns to scale. In the multiproduct trawler fishery, increasing product-specific returns to scale is frequently found for individual species, which makes these species vulnerable to overharvesting due to decreasing marginal production costs. For the trawlers, the conditions of increasing product-specific returns to scale and economies of scope often overlap (see e.g., Squires 1987b, 1988; Alam, Ishak, and Squires 2002). However, the development of trawling

specialized for harvesting a single species is unlikely because economies of scope create cost advantage in jointly harvesting several species.

Increasing multiproduct economies of scale is rejected in most studies. However, Bjørndal and Gordon (2000) and Weninger (1998) find indications of increasing multiproduct returns to scale in the cases of the North Sea herring fishery and a mid-Atlantic mussel fishery. In both studies, the behaviour of the firm is restricted by output regulation, meaning that they minimize their production costs. The results of increasing economies of scale is expected, given that vessels minimize their costs by operating in regions of increasing returns to scale. However, insufficient management of overall capacity might induce certain vessels to operate in regions of decreasing returns to scale.

As a curiosity, the cost structure also determines the extent to which a natural monopoly will develop in the fishing industry. The condition necessary for a natural monopoly to prevail is subadditivity of cost, which is expressed in the condition:  $C(y) < \sum_k C(y_k)$ , where  $\sum_k y_k = y$ .  $C(y)$  measures the cost of the single firm producing  $y$ , and  $\sum_k C(y_k)$  measures the aggregated cost of the  $k$  firms producing the output vector  $y$ . The condition means that if it is cheaper for a single firm to produce the output vector  $y$  rather than distributing production over  $k$  different firms, a natural monopoly might be suitable.<sup>26</sup>

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<sup>26</sup> A sufficient condition for cost subadditivity is the presence of transray convexity and ray subadditivity. Transray convexity embodies cost convexity and economies of scope, these conditions imply that when the monopoly changes its output composition and at the same time keep the level of some aggregate output fixed, costs will be lower for diverse rather than for specialized output mixes. A sufficient condition for ray subadditivity is increasing multiproduct returns to scale (see Baumol, Panzar, and Willig 1982).

Squires (1998), and Alam, Ishak, and Squires (2002) reject for the presence of cost subadditivity in trawler fisheries of New England and Malaysia, respectively. Although economies of scope and scale in both fisheries are suggested, these conditions are insufficient to satisfy the conditions required for a natural monopoly to exist, the reason being that the technologies exhibit decreasing multiproduct returns to scale. Moreover, it is indicated that the cost surfaces are not convex due to the absence of positive-definite diagonal elements measured in the Hessian submatrix of the cost function.

The lack of the appropriate cost data in output supply is often regarded as a hindrance to indicating the cost structure of the multiproduct firm. However, Squires (1988) and Squires and Kirkley (1991) demonstrate that it is possible to reveal conditions of economies of scope and scale based on information contained in the revenue and profit functions. Building on findings by Sakai (1974), the relationship between the cost function,  $C$ , and the long-term profit function,  $\pi$ , follows as:  $\delta^2 C^*[\cdot]/\delta y_i \delta y_j = [\delta^2 \pi[\cdot]/\delta p_i \delta p_j]^{-1} \forall i, j \in M$ . This means that the inverse Hessian matrix of the long-term profit function  $\pi$  is identical to the Hessian matrix of the cost function,  $C$ . Therefore, given that the profit function is in long-term equilibrium, the conditions of the cost function can be revealed.

#### **4.4 The industrial organization of the fishing industry**

Welfare improvements resulting from reorganizing industrial structure are addressed in different applications. Restructuring of the fishing fleet and reallocation of catches between different categories of vessels are sources of welfare gains at the industry level. The potential welfare gains are revealed by disclosing the specific production conditions

for vessels of different types and sizes. For example, conditions of economies of scope and scale reveal whether a fleet containing specialized or generalized vessels is efficient in the fishery (Lipton and Strand 1989). Inefficient fleet structures due to overcapacity or an inefficient mixture of vessel categories are examined. An overview of the various applications on industrial organization is provided in table 6.

Table 6. Industrial Organization of Harvesting Technologies

<b>Study</b>	<b>Gear</b>	<b>Regulatory Regime<sup>1)</sup></b>	<b>Functional Form</b>	<b>Description</b>
Campbell and Nicholl (1995)	Long line, purse seine	None	Leontief revenue	Addresses reallocation of catch between vessel groups in presence of a stock externality.
Dupont (1990)	Seine, gill net, troll, gill net troll	Input regulation	Quadratic Profit	Addresses rent dissipation due to input regulation based on Kulatilaka test.
Lipton and Strand (1992)	Surf clam and ocean quahog vessels of different sizes	Output regulated	Quadratic cost	Compares open-access and limited-access management in a fishery with a stock externality.
Weninger (1998)	Surf clam and ocean quahog vessels of different sizes	Output regulation	Translog cost	Addresses the transition of regulation from limited entry to ITQ management.

1) Addresses the regulatory regime predominating the firm behaviour under study.

Different regulatory regimes are addressed in the applications. Each regulatory regime imposes certain behavioural restrictions on the behaviour of the firm. In the output regulated industry, addressed by Lipton and Strand (1992) and Weninger (1998), the firm is assumed to minimize its costs for pre determined outputs. Under input



regulation, examined by Dupont (1990), the firm is assumed to maximize profit at given levels of regulated inputs.

Lipton and Strand (1992) and Weninger (1998) both find an inappropriate mix of vessel categories and reluctant capacity in the mid-Atlantic surf clam and ocean quahog fisheries. Approaching different management regimes implies that there is a discrepancy in recommendations regarding fleet structure in the two studies. Theoretically, the total harvesting capacity is derived from the imposed TAC regulation. Lipton and Strand (1992) calculate the fleet capacity required under a limited-access management regime. To be of value over a longer time horizon, the capacity recommendation of Lipton and Strand needs to be adjusted for productivity growth in the industry, which is not done. The introduction of individual transferable quotas, addressed by Weninger (1998), implies that reluctant capacity due to productivity growth is dealt with through the quota market. Vessels that do not achieve minimum operating costs will earn a residual return that is less than the market lease in the ITQ market, and these firms will be bought out of the market (Weninger and Just 1997). In this sense, an efficient ITQ market ensures that reluctant capacity is bought out of the industry. The findings of Weninger (1998) indicate diseconomies of scope, increasing returns to scale of variable cost, and declining fixed costs for larger vessels. The transformation of regulation from limited-access management to ITQ management leads to significant cost reductions in the industry to be operated by large specialized vessels.

Dupont (1990) considers whether input regulation creates a nonoptimal industrial organization in a case study of the Canadian salmon fishery. The study rejects the

hypothesis that restrictions on vessel tonnage create a welfare loss in the industry. The finding is based on a Kulatilaka test, indicating that there is no significant difference between the actual level of regulated vessel tonnage and optimal vessel tonnage.<sup>27</sup> On the other hand, inappropriate fleet structures due to nonoptimal fleet composition and reluctant fleet capacity are found in the fishery.<sup>28</sup>

Campbell and Nicholl (1995) address the connection between stock externality and industrial organization in a case study of the yellowfin tuna fishery in the western Pacific. The stock externality implies that it is beneficial in terms of welfare to reduce catches of juvenile fish by purse seine vessels in order to increase catches of adult fish by long line vessels. A test on nonjointness in inputs for the purse seine vessels indicates that they are multiproduct firms producing several outputs. Two ways of reducing the multiproduct purse seiners' catch of juvenile fish are addressed: A royalty tax on landings of yellowfin or an effort tax based on the number of fishing days for the purse seiners.<sup>29</sup>

The empirical results indicate that the economic losses of the purse seiners will be lower under a royalty tax than under an effort tax regulation. This follows due to jointness in inputs, which implies that the royalty tax impacts, the vessels to harvest the non-taxed species. In contrast, the effort tax will reduce landings of all species, thus resulting in lower effort and earnings than under the royalty tax.

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<sup>27</sup> The Kulatilaka test is described more carefully in the section that addresses testing of full static equilibrium.

<sup>28</sup> Reluctant fleet capacity is derived based on the TAC in the fishery.

<sup>29</sup> If the production is characterized by diminishing marginal productivity of effort, the marginal cost of reducing the fishing effort of each vessel will be less than reducing the number of fishing vessels.

## 5. Capacity utilisation and rent dissipation

The dual approach has also been used to examine levels of capacity utilisation and rent dissipation. This is particularly relevant to this study, which aims to examine how ITQs may change the rent dissipating behaviour. An overview of the methods that have been employed are presented below, along with examples that relate explicitly to the ex-ante evaluation of individual vessel quota programmes. The implications for the situation, common in many fisheries, of quotas being only applied to some species is also considered.

### **5.1 Testing capacity utilization/full static equilibrium of quasi-fixed input**

Applications of the dual approach mainly outline the firm's short-term behaviour, treating vessel capacity as quasi-fixed. The incentive for a firm to alter the quasi-fixed input is addressed by analyzing capacity utilization or testing for full static equilibrium of the quasi-fixed input. Comparing the observed level of the quasi-fixed input with its optimal long-term level is an essential element in deriving incentives for investment in the quasi-fixed input. The different applications that investigate capacity utilization/full static equilibrium are presented in table 7.

Table 7. Tests for Full Static Equilibrium/Capacity Utilization

Study	Gear	Quasi-Fixed Input	Functional Form	Full Static Equilibrium/Capacity Utilization <sup>1)</sup>	Details
Alam, Ishak, and Squires (1996)	Gill net	GRT-capacity	Translog profit	Reject	Conrad and Unger test <sup>2)</sup>
Alam, Ishak, and Squires (2002)	Trawl	GRT-capacity	Translog profit	Reject	Conrad and Unger test <sup>2)</sup>
Bjørndal and Gordon (1993)	Purse seine	GRT-capacity	Translog profit	Reject	Conrad and Unger test <sup>2)</sup>
Dupont (1990)	Seine, troll, gill net, gill net-troll	GRT-capacity	Quadratic profit	Accept	Kulatilaka test <sup>3)</sup>
Segerson and Squires (1990)	Trawl	GRT-capacity	Translog cost	Reject, Accept <sup>3, 5)</sup>	Capacity utilization <sup>4)</sup>
Segerson and Squires (1993)	Trawl	GRT-capacity	Leontief revenue	Accept <sup>3)</sup>	Capacity utilization <sup>4)</sup> Kulatilaka test
Squires (1987c)	Trawl	GRT-capacity	Translog profit	Accept	Capacity utilization <sup>4)</sup> Kulatilaka test <sup>3)</sup>
Squires (1988)	Trawl	GRT-capacity	Translog profit	Accept	Kulatilaka test <sup>3)</sup>
Squires and Kirkley (1991)	Trawl	GRT-capacity	Leontief revenue	Accept	Kulatilaka test <sup>3)</sup>

1) Accept means that the  $H_0$  hypothesis of complete capacity utilization/full static equilibrium of the quasi-fixed input cannot be rejected.

2) The test is employed as based on Conrad and Unger (1987).

3) The test is based on Kulatilaka (1985).

4) See Morrison (1985).

5) Segerson and Squires (1990) employ alternative tests of primal and dual concepts on capacity utilization.

All applications specify GRT capacity (Gross Registered Tonnage) as the single quasi-fixed input.<sup>30</sup> The test of the quasi-fixed input is based on the behaviour of the firm in

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<sup>30</sup> The GRT measures the size of the vessel indicating its storage capacity.

the short run; i.e., when vessel capacity is quasi-fixed.<sup>31</sup> Applying the dual approach to revenue, profit or cost functions can be accomplished to identify incentives for the expansion or reduction of capacity. The test addresses the question of whether the actual level of vessel tonnage is equal to the optimal long-term level. The null hypothesis is that the observed vessel size is equal to the optimal level in the long term. In the case that the null hypothesis cannot be rejected, the firm has no incentives to alter tonnage capacity. If the firm has an incentive to expand its capacity, this has implications for the public management of fishing effort. Regulators might consider limiting the aggregated fishing effort by restricting the number of fishing vessels. To do so, there also needs to be an assessment of the firm's incentives to expand their individual capacity (size in GRT-capacity). Ignoring the firm's incentives for capacity expansion might lead to underestimation of the realized long-term fishing effort (number of vessels times GRT capacity) in the industry.

Mixed results of the capacity utilization/full static equilibrium are found. Alam, Ishak, and Squires (1996) and Bjørndal and Gordon (1993) identify incentives for capacity expansion for gill netters and purse seiners. Squires (1987c, 1988), Alam, Ishak, and Squires (2002), and Dupont (1990) indicate no incentive of capacity expansion for trawlers, seiners, gill net vessels, and trollers. However, the survey does not reveal any connection between fishing gear and incentives for capacity expansion. Mere incentives for expansion of the firm's capacity are closely related to stock abundance and capital costs in the specific fishery. A weakness with regard to identifying investment incentives in most applications is that these build on only one to two years of data. To

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<sup>31</sup> It is possible to address the situation where several inputs are quasi-fixed.

be relevant in a management setting, incentives for capacity expansion should remain in place for several years, since the adjustment of fishing capacity is a long-term process (Jensen 1998). Bjørndal and Gordon (1993) estimate the development of optimal vessel size over several years. Their study emphasizes the importance of conducting tests on full static equilibrium over several years, and the results reveal substantial variations in predicted annual optimal vessel size due to differences in the definition of the user cost of capital.

Several theoretical refinements of capacity utilization approaching conditions in fisheries have been made. Segerson and Squires (1990) emphasize the straightforwardness in defining the dual measure of capacity utilization for the multiproduct fishing firm, whereas it is difficult to apply the primal measure of capacity utilization to the multiproduct firms. Segerson and Squires (1995) develop the capacity utilization concept for the revenue-maximizing firm describing decisions made on the individual fishing trip, where input composition during the trip is assumed to be fixed. Segerson and Squires (1993) measure the capacity utilization under trip quota regulation imposed *ex ante* on the individual fishing firm.

## **5.2 *Ex ante* assessment of production quota on the multiproduct firm**

Quantity restrictions on inputs or outputs are often proposed as a means of regulating fish harvesting. Imposed on the multiproduct firm, assessments of the behavioural implications of quantity regulation are often complicated. Assessments of regulation *ex ante*; i.e., before quantity regulation is imposed, is often demanded by regulators. Different applications of the dual approach utilize *ex ante* assessments of quota

regulation that provide information about how the unregulated multiproduct firm would react to quantity restriction. Impacts of production quota on output composition and investment incentives are among the aspects that are addressed. A summary of the different contributions is provided in table 8. All applications address the short-run behaviour of the firm that maximizes revenue during the fishing trip, assuming fixed input composition.

Table 8. Applications Using *ex ante* Assessment of Production Quota on Firms

<b>Study</b>	<b>Gear</b>	<b>Functional Form</b>	<b>Contribution Addressing the Impact of Trip Quota on:</b>
Squires and Kirkley (1991)	Trawl	Leontief revenue	A single output for a) the reorganization of output supply, b) demand of effort.
Segerson and Squires (1993)	Trawl	Leontief revenue	A single output for c) incentives to invest in quasi-fixed inputs.
Squires and Kirkley (1995)	Trawl	Leontief revenue	Several outputs for d) aggregated rents and gains from quota trading.
Squires and Kirkley (1996)	Trawl	Leontief revenue	Several outputs for e) equilibrium market price for trade transferable quotas.

Combining the dual approach with rationing theory offers a basis for predicting the implications of quantity restriction. For the unregulated firm, output supply and other production decisions are based on exogenous prices. Imposing output regulation binds the output supply of the firm. Therefore, in order to determine the consequences of production quotas for the unregulated firm, the *ex ante* assessment should transform the quantity restriction into a price restriction. Using the framework of a virtual price, the output constraint is transformed into an equivalent price constraint (see Neary and

Roberts 1980). The virtual price,  $\varphi_i$ , is defined as the price that would induce an unconstrained firm to behave in the same manner as when facing an output constraint. In this sense, the methodology considers how a primal constraint is translated into a dual constraint.

Various implications of the trip quotas are considered. Squires and Kirkley (1991) looked at how a trip quota on a single output impacts the production conditions of the multiproduct firm. Two aspects are dealt with. First, they considered the impact of a trip quota on the multiple output supply of the firm. Secondly, they examined the extent to which the trip quota shifts a firm's output supply curve, thereby reducing effort and the supply of all outputs. Campbell and Nicholl (1995) considered similar problems in the context of price restriction that are more immediate to employ in a dual setting.

Segerson and Squires (1993) identify the consequences of production quotas on the capacity utilization of the multiproduct firm. This is accomplished by using the virtual price combined with the shadow value of the quasi-fixed input to measure impact on capacity utilization. Their results show that output quotas on individual species will not necessarily lead to disincentives for investment. For outputs with large revenue shares, output regulation will have strong disinvestment incentives. On the other hand, production quotas for outputs that have small revenue shares do not seem to induce any disinvestment incentives. The result is consistent with the findings of Segerson and Squires (1995) that the impact of price change on capacity utilization is critically dependent on the revenue share of the output relative to the shadow cost of the quasi-fixed input.



Squires and Kirkley (1995, 1996) contribute by making an *ex ante* assessment of ITQ regulation imposed simultaneously on several outputs. The success of introducing ITQ management on various species is critically dependent on whether the technology embodies nonjointness in inputs. Under conditions of nonjointness in inputs, the ITQ markets for multiple outputs can be managed separately for each output. Introducing ITQ management when the technology embodies jointness in inputs involves the problem that ITQ management does not meet the criterion of optimal market clearance in all markets. This means that well-functioning ITQ markets for each species will not necessarily be found. Squires and Kirkley emphasize that a necessary condition for well-functioning ITQ markets exists if the marginal rate of transformation between outputs is equal to the relative ITQ market prices. However, given that ITQ markets do not necessarily match the product transformation of the firms, this brings up the problem that species managed by ITQ will not be fully exploited. This is the case in the study of the ITQ management of sablefish and thornyheads in the Pacific coast trawler fishery, where sablefish are underfished under ITQ management. The result is not surprising given the technological feature of the trawlers, which are characterized by their ability to shift target species. ITQ management means that the trawlers will be precommitted to target thornyheads but this will happen at the cost that they will not be able fully utilize their technological potential in sablefish fishery (an example of the Le Chatelier effect). Therefore, underexploitation of sablefish implies that the potential welfare gain of the sablefish fishery is not fully obtained.<sup>32</sup> On the other hand, if

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<sup>32</sup> The gains by introducing ITQ management arise, as firms will reallocate their fishing activity to the most favourable periods of the year. Moreover, economic rent will also arise since the most efficient vessels will purchase quota from less efficient vessels.

sablefish and thornyheads are produced in separate production functions, jointness in inputs would not cause problems of underexploitation and incomplete exploitation of potential benefits of ITQ regulation.<sup>33</sup>

### 5.3 Rent dissipation and capacity

During the 1990s, individual vessel quota (IVQ) schemes, where the quota may or may not be transferable, have become an important management tool. For these schemes, each participant in the fishery is entitled to a *quantity or quota* share of the TAC. This eliminates the race to fish as fishermen are ensured their quota share and, moreover, can lead to rent generation. However, to ensure rent generation, capacity in the fishery cannot be too high. This is a problem as there tends to be substantial overcapacity in fisheries when individual vessel quotas are introduced. In most cases, the practice has been to initially allocate quota shares to fishermen *gratis*, usually based on historical catch records.

As seen above, when modelling the harvesting process, an assumption of profit maximisation is often the starting point and production parameters are estimated using a profit function specification. Without restrictions on the profit function all inputs used in harvesting and the harvest level are choice variables for the fishing vessel. The total profits can be written as

$$\Pi(p, w) = Yp - \sum_i q_i w_i$$

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<sup>33</sup> Vestergaard (1999) develops the framework to measure welfare effects of individual quotas in multiproduct industries.

where  $p$  is the price of fish,  $Y$  the harvest level, and  $w_i$  the price of the  $i$ th input factor,  $q_i$ . This tells us that profit is the difference between revenue and cost of production. Observed profits are often taken as an estimate of realised rent in a fishery (Dupont, 1990).

In open access or regulated open access fisheries, resource rents will be dissipated by the common property nature of the fishery and profits, defined by the above equation, are zero. However, with individual vessel quotas fishing vessels are ensured a share of the resource, so that profits can be positive, representing resource rent.

In many empirical applications, the above equation is modified to account for restrictions in the actual harvesting process. Often capital (the vessel) is treated as a fixed factor in harvesting, recognising that regulations prevent adjustment or that second hand markets often are limited and adjustment costs accordingly high (Squires, 1988; Dupont, 1991, Bjørndal and Gordon, 1993). Under this scenario, a restricted profit function is specified where the fishing vessel is assumed to maximise profits by choosing inputs and harvest level subject to the size of the vessel used in harvesting. Total profit can be calculated from the restricted profit function,  $\Pi^R(p, w; z)$ , by accounting for the cost of the vessel or

$$\Pi(p, w, w_z) = \Pi^R(p, w; z) - w_z z$$

where  $w_z$  is the user price for purchasing capital stock (i.e., the vessel), and  $z$  represents the size of the vessel. Since this equation defines the long-run profit relationship, resource rents can be measured in the same manner as in the previous equation.

The equation can also be used to derive the optimal level of the fixed factor by maximising it with respect to the fixed factor(s) (Lau, 1976; Brown and Christensen, 1981). This was utilised by Dupont (1990), who noted that by finding the optimal level of the fixed factor, one can compute potential rent for a vessel if the regulatory system allows this factor to be adjusted to its optimal level. Hence, the revised equation can be used both to compute actual rents harvested under a regulatory system and the potential rents if the system is changed so that a (quasi-) fixed factor is allowed to adjust to its optimal level. Moreover, the fish stock or the TAC is in most cases given, and total catch cannot be increased. If vessels are to operate optimally, the number of vessels in the fleet has to be reduced. Dupont (1990) shows that this can be used to calculate optimal fleet size and potential rents obtainable with an optimal fleet.

With individual vessel quotas harvest is an exogenous or restricted factor. For price taking fishermen, the optimization problem is to maximize profits for a given catch level or equivalently, to minimize the cost of harvesting the given quota, assuming the quota is the only fixed factor. With these modifications the total profit for a fisherman under an IVQ scheme can be written as

$$\Pi(p, w) = Yp - C(w; Y)$$

where  $C(w; Y)$  represents the cost function where the individual fishermen decide the mix of input quantities for a given quota. The cost function contains all the choice variables for the fishermen under an IVQ scheme. Moreover, these variables will contain all information about behaviour from the observed data. It is well known that a cost function is a special form of a restricted profit function with (output quantity) harvest level treated as a fixed factor (Lau, 1976). Therefore, the structure of this

equation is the same as for the previous equation with the restricted profit function. The only difference is due to different decision variables for the fishermen because of the different regulatory schemes.

This provides total profits, and observed profits can therefore be regarded as actual or realised rents. However, in contrast to the problem considered by Dupont (1990), the regulatory scheme now restricts the output. One can find the optimal output level by finding the cost minimizing output (Weninger, 1999), giving  $Y^*(p,w)$ . This can be done either by finding the output level associated with constant returns to scale, or by maximizing the unit quota value using the virtual price approach of Fulginiti and Perrin (1993).<sup>34</sup> Furthermore, if one knows the TAC and assumes that the data set is representative, one can find how many vessels are necessary to take the TAC with the current technology. This will then be a measure of optimal fleet size. The total profits of these vessels will then be the potential rent in the fishery with the observed type of vessels. This is important information in fisheries managed with IVQs, as it will provide information about the extent to which one has been able to collect the resource rent and how much resource rent is dissipated due to overcapacity in the fishery.

#### **5.4 Fisheries where individual quotas are present for some outputs**

Society are increasingly concerned with the effects of a firm's activity that are consequences of but not a part of the firm's economic decision problem. Regulating the quantity that a firm can produce of a specific output is a commonly employed regulatory tool employed by the society to enforce its preferences. Hence, multioutput

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<sup>34</sup> This condition will then also implicitly define the demand for quota (Arnason, 1990).

firms increasingly face restrictions on some of its outputs. However, this is not to any extent reflected in the way we model firm behaviour. In this chapter we will therefore address modelling of multioutput firms that face regulations on some of its outputs. Furthermore, the impacts of the regulations are of interest and we therefore investigate elasticities of intensity, separability, jointness and economies of scope in this context.

Following Beamol, Panzar and Willig's (1982) seminal work, substantial interest was focused on the impact of regulations in multioutput industries. However, the analyses were typically conducted assuming either that all outputs are fixed or variable. Hence, a cost minimization framework was used e.g. by Kim (1987?), assuming that the regulations applied for all outputs. Squires (1987) and Squires and Kirkley (1991) used respectively profit and revenue function specifications, conducting the analysis prior to the implementation of the restrictions. However, to our knowledge the case when restrictions have been imposed on some but not all of the multioutput firms outputs have not received much attention. This is important as such regulations are in operation in a number of industries. Examples are firms with pollution quotas, fishermen for which some species are regulated by quota, and farmers that face restrictions on some outputs (e.g. milk quotas). Econometrically, when modelling firm behaviour, it is important to not model (quasi-) fixed factors as variable and vice versa if one are to avoid inconsistent parameter estimates, tests and elasticities (Brown and Christensen, 1981). Hence, modelling all outputs as either as variable or fixed as in profit or cost functions are not good alternatives for industries with this structure.

The theory necessary for our analysis has largely been developed by Lau (1976). In particular, he provides a framework where distinctions between inputs and outputs are unnecessary, and hence where cost functions, revenue functions and any other representation of the firm's problem where some factors are treated as fixed are special cases of a restricted profit function. He also anticipates profit functions where some but not all outputs are treated as fixed naming pollution quotas as an example, and also raises the possibility of a negative output prices, which will be the case if the quota is traded. Our contribution is to provide specification usable for empirical analysis, and to provide measures of the impact of the regulations through using elasticities of intensity, jointness, separability and economies of scope in this context.<sup>35</sup>

Let  $y$  be a vector of outputs and  $x$  a vector of inputs. The technology of a firm can then be represented by a transformation function

$$F(y,x)=0$$

We assume that standard regulatory conditions apply for the transformation function.<sup>36</sup>

Let the vector of output prices associated with all but one element of the output vector be denoted  $p$ , input prices  $w$ , and let there be a fixed output be denoted as  $\bar{y}$ . Following Lau (1976), the firm's optimisation problem can then be represented with a restricted profit function, but where it is a group of outputs that are treated as fixed,  $\pi^R(p, \bar{y}, w)$ .

Associated with this restricted profit function are a set of supply functions  $y_i=f(p, \bar{y}, w)$

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<sup>35</sup> Lau (1978) provides a good discussion of separability and jointness with respect to a profit function.

<sup>36</sup> See e.g. Lau (1976) or McFadden (1978) for a discussion of regulatory conditions for the transformation function.

for the variable outputs, a marginal cost equation for the fixed output  $MC_k=g(p, \bar{y}, w)$  and a set of input demand equations  $x_m=h(p, \bar{y}, w)$ . The discussion here is easily extended to cases where also some input factors are regarded as fixed.

The first measure we are interested in is the effect of relaxing the quota. This can be found by deriving what Diewert (1974) refers to as elasticities of intensity, which was used by Dupont (1991) when evaluating the effect of changing regulations for restricted outputs. These are given as

$$e_{ik} = \frac{\partial \ln y_i}{\partial \ln \bar{y}_k} \text{ and}$$

$$e_{mk} = \frac{\partial \ln x_m}{\partial \ln \bar{y}_k}$$

The  $e_{ik}$  elasticity gives the percentage change in the  $i$ th output due to a one percent increase in the quota, while  $e_{mk}$  gives the percentage increase in the use of input  $m$  due to a one percent increase in the quota. The  $e_{ik}$  elasticities are of particular interest in natural resource industries like fisheries, as a negative elasticity indicates that fishing pressure on the unregulated species will increase if the quota is reduced, while it will be reduced if the elasticity is positive. In addition, one will of course compute standard price elasticities, which then will be conditional on the fixed output.

Input-output separability indicates that one can regard the technology as having one aggregate output and one aggregate input. As discussed in chapter 3.3, for profit functions with only variable netputs, this implies that the profit function can be written as  $\pi(p, w) = \pi(f(p), g(w))$  and a cost function can be written as  $C(w; y) = C(h(w), i(y))$  (Lau, 1978; Denny and Pinto, 1978). This implies that the



composition of inputs is not influenced by the composition of outputs. Squires (1987) indicates that one then can regulate the outputs efficiently with a total quota for all outputs. In the restricted profit function, input-output separability implies that the restricted profit function can be written as  $\pi^R(p, w; \bar{y}) = \pi^R(f(p; \bar{y}), g(w))$ .

Lower levels of aggregation, and hence separability is also of interest as it allows more precise targeting of regulations (Squires, 1987). Weak separability among a subset of outputs (inputs) implies that the marginal rate of transformation (substitution) between variables within the subset is independent of the composition of other variables. This allows separate regulation of the variables within this subgroup(s). This is in our case of interest if considers regulating more than one output.

Another important possible structure of the technology is nonjointness. If the technology is nonjoint in inputs, there is a separate production function for each output (Lau, 1972). This implies that one can efficiently regulate the industry output by output. Similarly, in a profit (cost) function setting it implies that there is a separate profit (cost) function for each output. With our special form of a profit function it implies that there are separate profit functions for each of the unregulated outputs, while there is a separate cost function for the regulated output. It follows from Lau (1972; 1978) that

this is the case if and only if<sup>37</sup>

$$\frac{\partial^2 \Pi^R}{\partial p_i \partial p_j} = 0, \quad \forall i \neq j \quad \text{and} \quad \frac{\partial^2 \Pi^R}{\partial p_i \partial \bar{y}_k} = 0, \quad \forall i$$

If the technology is joint, a regulator should also consider if there are economies of scope to design efficient regulations. Economies of scope can arise from two sources, weak cost complementarities and fixed costs. A sufficient condition for weak cost complementarities is: (Gormon, 1985)

$$\frac{\partial^2 C}{\partial y_i \partial y_j} \leq 0$$

That is, there are cost complementarities if increased production of one output reduces the marginal cost for another. Squires (1987) utilize a result from Sakai (1974), that  $\partial^2 C / \partial y_i \partial y_j = [\partial^2 \pi / \partial p_i \partial p_j]^{-1}$ . Hence, one can also find whether there are weak cost complementarities for a profit function, although this is not a statistical test. In our case we will use the results of Squires (1987) for the variable outputs. In addition, we need to investigate whether increased production of variable outputs reduce marginal cost for the regulated output. This implies that

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<sup>37</sup> An alternative procedure used by Squires (1988) in the context of a restricted profit function is to first derive the long-run profit function from the restricted profit function, and then test hypotheses about the technological structure on the long-run profit function. This is certainly the best procedure if one are interested in the long-run, which seems to be the best perspective when inputs are treated as fixed because of slow adjustment rather than regulations. However, as also pointed out by Squires, when modelling outputs as variable as in a profit function one ensures that one are on the firms supply schedules, while in cost function specifications the firm can deviate from its supply schedules. As the regulations are likely to make the firm deviate from its long-run supply for the restricted output, we think that in this case it is appropriate to use the restricted profit function for the tests. An alternative can also be to derive the firms cost function using the results of Lau (1976).

$$\frac{\partial^2 \pi^R}{\partial \bar{y}_k \partial p_i} \leq 0$$

Since the Hessian of the restricted profit function is symmetric, weak cost complementarities implies that an increased quota for the regulated output will reduce costs for the unregulated output.

To consider the issue of optimal outputs in this scenario, let  $y$  be a vector of netputs where an element is positive if it is an output and negative if it is an input, and similarly  $z$  is a vector of fixed netputs that include the fixed output. Denote  $p$  as the price of variable netputs and  $r$  as the price of fixed netputs. In this scenario, a restricted profit function is specified where the fishing vessel is assumed to maximise profits by choosing some inputs and harvest levels subject to the quotas on other species and the fixed inputs (e.g. vessel). Total profit can be calculated from this restricted profit function,  $\Pi^R(p, z)$ , by accounting for the cost of the vessel or

$$\Pi(p, r) = \Pi^R(p, z) + rz$$

From this expression, the optimal levels of fixed netputs can be estimated in the same fashion as in Squires and Kirkly (1996), using virtual prices that take the resource rent per unit of catch into account.

## 6. Summary

The survey shows that the dual approach is very suitable for providing knowledge of the disaggregated production structures in fisheries based on a positive analysis and the theory of the firm. The dual approach reveals information about various aspects of fish harvesting such as the firm's supply and transformation between outputs, input demand and substitution between inputs, long-run investment intentions, and the estimation of welfare gains by introducing ITQ management in fisheries.

In general, caution should be expressed when drawing inference based on case studies across different harvesting technologies and fishing regions. This follows because technological conditions are critically dependent on the specific characteristics of fishing gear, fishing areas, harvesting conditions, range of species, etc. Bearing this in mind, however, some general technological features of various gear types and regulatory regimes, based on the present survey, are outlined.

Most applications are devoted to analyses of the technological conditions in trawl fisheries. The applications reveal that the trawl is a highly flexible gear because trawlers have the ability to alter harvesting strategy in order to cope with different species. Most trawl gear embodies jointness in inputs and economies of scope, the latter meaning that cost complementarity exists in harvesting several species. On the other hand, multiproduct economies of scale are seldom found for trawl gear. In a management setting, the consequences of output regulation are not easy to assess because trawlers are capable of altering their harvest composition. In this sense, it is beneficial for the regulator to assess the spillover effects that regulating a single species will have on

other species. A certain degree of success of input management in reducing the fishing effort of trawlers is indicated because complementarity in the use of individual input components is found. On the other hand, input-output separability implies that input management induces trawlers to alter their harvest composition.

The few studies of gill net fisheries find that the technology is rather inflexible. This is first and foremost because of a lack of ability to switch between species. Gill netters harvest a variety of species, but individual species are harvested as complements or in fixed scale output. Therefore, output management of individual species will not cause significant problems of external increases in the gill netters' catches of other species. Discarding regulated species is a natural reaction of gill netters in coping with output management. However in general, gill netters are vulnerable to output management, because this form of regulation might require them to reduce fishing effort to satisfy output regulations, resulting in significant economic losses.

Most applications address technological conditions in fisheries, where input or output management imposes behavioural restrictions on firms. Even so, interesting policy implications result from these applications.

Success of input management builds on whether firms, through the disaggregated structure of fishing effort, have the ability to increase the use of unregulated inputs or not. The survey indicates that for many technologies, complementary relationships between inputs are found, thereby offering some hope of reducing fishing mortality through input management. However, some obstacles to effective input management do

exist. For example, productivity growth and technological refinements mean that input management should currently be adjusted to take dynamic developments in technology into account. Moreover, decommissioning schemes are often suggested as a good means of reducing fishing capacity. The success of the schemes depends on whether the fishing capacity is being fully exploited or not. Addressing incentives for adjustment of capacity by means of a test of capacity utilization might, therefore, be useful. This follows because it is important to avoid that incomplete capacity utilization (at the firm level) means that decommissioning funds are granted (to reduce the number of vessels) without any reduction in fishing mortality being obtained. In addition, significant welfare losses due to the inefficient composition of fishing fleets are indicated by the dual applications.

Assessment of output regulation on specialized technologies is relatively easy to make. This is because separate production functions are employed for different species, so that there are no spillover effects of regulation between species. However, most technologies such as trawling, gill netting, and seiners are multispecies fishing gears. This means that output regulation on individual species will have spillover effects on other species, implying external effects on fleet segments that exploit these other species. Moreover, it is emphasized in dual applications that output regulation impacts the cost conditions of the harvesting firms. In this sense, imposed output regulation might distort the economies of scope, thereby leading to cost inefficiency in the fishery.

Dual applications show that significant efficiency gains can be obtained by a transition from unregulated or limited-access fishery to ITQ-managed fishery. The transformation

is most easily performed in the management of single species that are exploited by specialized firms, where production is nonjoint in inputs and diseconomies of scope offer no cost advantages in harvesting several species. However, as this survey indicates, most technologies are devoted to multispecies production characterized by jointness in inputs. This means that imposing ITQ management on individual species requires firms to minimize harvesting costs, and the presence of economies of scope implies that firms also have incentives to harvest other species. As a result, the option of imposing ITQ management of several species simultaneously is addressed. Various applications suggest that efficiency gains in introducing ITQ management of several species might also be obtained.

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