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Applications of Dual Theory in Fisheries: A Survey

by

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Abstract: *This paper surveys empirical studies that utilize the theory of the firm and dual theory to reveal economic and technological conditions of fish harvesting firms. 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 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 in public management of resource exploitation by dealing with various regulatory regimes, i.e., input management, output management, and prospects for future regulation. The purpose of this paper is to review theoretical issues and empirical results with respect to fishing gear and regulatory regimes.*

Keywords: Survey, Dual Approach, Production theory, Fish harvesting technology, Multiproduct Firm.

1. Introduction

The public management of marine fisheries is often seen as the only possible means of preventing overexploitation of our fish resources. 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. For the regulator, it is therefore of value to make assessment of the technological and economic conditions before a given policy is imposed.

Detailed knowledge of the technological and economic conditions that apply to fishing firms can be obtained by employing the dual approach. 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 purpose of this paper is to review the different theoretical issues and empirical results across fishing gears as revealed by use of the dual approach to fish harvesting firms. Shumway (1995) and Fox and Kivanda (1994) illustrate the prominent position of the dual approach in revealing production conditions in agriculture. This paper shows that by applying neoclassical production theory on fishery, the dual approach has enabled fishery economics to become a part of applied microeconomics rather than to exist on its own *ad hoc* basis.

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 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, for example by 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, 1987abc, 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, 1998). 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, and Segerson and Squires 1993).

1.1 The dual approach: 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 approach and the dual approach 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.

Campbell (1991), Hannesson (1983), and Robinson and Pascoe (1996) use the primal approach to describe the technological properties in the fish harvesting industry. A problem with using the primal 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).[2] By employing prices as regressors, the dual approach offers a complementary approach that is highly suitable for dealing with the 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 modeling 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 modeling fishing technology, it is crucial that the applied theoretical model should agree with the behavioral hypothesis and market conditions of the firm. Applications of the dual approach in the fishing industry utilize three different sets of behavioral hypotheses and accompanying objective functions to describe firm behavior. These are; profit maximization, input constrained revenue maximization, and output constrained cost minimization.

[2] The Hausmann test can be employed to test variable exogeneity of the regressors (see Hausmann, 1978).

Squires (1987abc), Alam, Ishak and Squires (1996, 2002), and Salvanes and Squires (1995) employ the multiproduct profit function, π(p, w) to describe the profit-maximizing firm expressed by

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

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 respectively by w and p. The regularity properties imply that π(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 behavior 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

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

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 behavioral hypothesis of cost minimization to describe firms operating under output regulation. The output-constrained firm minimizes the cost function,

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

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 behavioral hypothesis correctly specify the features of the multiproduct firm. The profit function is an appropriate specification with which to address the behavior 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 behavior, 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 behavior.

2.1 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

	Gear	Functional Form	Separability[1)]	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 clams and ocean quahogs 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.[3] The survey indicates that the majority of fishing technologies should be modeled in a disaggregated context. Aggregated modeling 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 favor of disaggregated modeling of fishing technologies.

Evidence in favor 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

[3] In the studies of Kirkley and Strand (1988), Campbell and Nicholl (1995), Thunberg, *et al.* (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 modeling 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 (1987ab) indicate 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 output 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 (1987ab) 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.[4]

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[4] Problems encountered by employed the 0.01 values might be discovered by comparing sign and statistical significance to estimates of the nonzero observations.

2.2 Nonjointness in inputs of the multiproduct firm

Fish stock regulation is often done by regulating individual species.[5] 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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[5] This is for example seen in the fishery of the European Community, where the species are mainly regulated in a single species context by applying TACs for each single species. Although multi-species TAC (MSTAC) have been introduced by 3760/92 (See O.J. L 389, 31.12 1992.), the multi-species management has not been widely used.

Table 2. Test for nonjointness in inputs

	Gear	Functional Form	Non-jointness[1)]	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 expect for Dover sole.
Thunberg, Bresnyan 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 on the single output will not affect the profit or the quantities produced of the other outputs. This implies the restriction

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

which is a necessary condition for

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

That is, a price change in the j*th* output will not affect the firm's output supply of the i*th* nonjoint output.

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.[6] This implies that fishing managers need to acknowledge the consequences of TAC regulation on a given species 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 modeling of the transformation in production between different species.

A 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 the

[6] TAC stands for Total Allowable Catches.

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 fishery studied by Weninger, the nonjointess in inputs indicates that these species are harvested independently. This has the policy implication that surf clam and ocean quahog might be regulated independently, because no spillover effect of the regulation of the 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 regulation species individually, although nonjointness in inputs is found in the fishery. The reason for this is that no evidence in favor 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. However, employing biomass regulation would make it difficult to ensure the sustainable development of species that are overexploited.

2.3 Modeling biological conditions constraining the multiproduct firm

Modeling 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, 1994), treating stock abundance as an input factor in the production process like capital, labor 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 modeled as an exogenous component that shifts the level of production. Most applications of the dual approach use annual or seasonal dummy operators to measure fluctuations in resource stocks (see Squires 1987abc, Bjørndal and Gordon 1993, Salvanes and Squires 1995, Campbell and Nicholl 1995, Squires and Kirkley 1996, Diop and Kazmierczak 1996). A few applications employ indices to measure fluctuations in stock abundance (see Bjørndal 1987, Dupont 1990, and Weninger 1998).

On the other hand, given that biological conditions constrain the behavior of the firm, it is not sufficient to employ seasonal dummies in modeling the firm. Instead, insufficient availability of stocks of individual species restricts the supply of this output for the firm. This means that output supply of the particular species cannot be based on exogenous output prices. Although biological conditions restrict the supply of a single species, the assumption of profit or revenue maximization might still be appropriate for the other outputs produced by the firm. The biologically restricted output should be modeled by the restricted quantity in the profit function. On the other hand, if all outputs of the firm are restricted by biological conditions, then it is not appropriate to assume profit- or revenue-maximizing behavior. Instead, the firm is assumed to minimize its production costs for given quantities of the restricted outputs.

3.1 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.

Table 3. Product Supply Elasticities

	Gear	Elasticity with respect to outputs [1)]	Own-price elasticity	Cross-price elasticities	Fishery featured by
Kirkley and Strand (1988)	Trawl	SH	Inelastic	Substitutes, Complements	Flexible catches
Alam, Ishak and Squires (2002)	Trawl	SM	Inelastic	Mainly Complements	Inconclusive[2)]
Salvanes and Squires (1995)	Trawl	SM	Inelastic[3)]	Substitutes, Complements	Flexible catches
Squires (1987b)	Trawl	SM	Inelastic	Not reported	Not reported
Squires (1987c)	Trawl	LM	Elastic, Inelastic[4)]	Substitutes, Complements	Flexible Catches[5)]
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, Bresnyan and Adams (1995)	Gill net	SH	Elastic, Inelastic[6)]	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 by-catch 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 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%.[7] The fairly 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

[7] There are two exceptions. Thunberg, Bresnyan 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 trawlers fishery of New England. The latter confirms that the elasticities are higher in the long run.

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.[8] 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 thereby insignificant parameter estimates.

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).[9] For the gill-net technology, all outputs are produced as complements. Although Thunberg *et al.* (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

[8] Search cost in the form of energy consumption, risk, quality deterioration for some species, and opportunity cost foregone and labors cost.
[9] The Hicksian elasticity measures the pure substitution effect (see Lopez 1984).

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 by-catches.[10, 11]

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 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.

3.2 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 restrict simultaneously all dimensions of fishing effort. Strand, Kirkley and McConnell (1981) demonstrated the multidimensionality of fishing effort though 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.

[10] If there is two "key" species these are produced as complements.
[11] The missing ability to substitute between outputs is also found in the gill net fishery described by Alam, Ishak, and Squires.

Table 4. Factor Demand Elasticities

	Gear	Variable effort items	Functional Form	Elasticity with respect to inputs[1),2)]	Own-price elasticity	Cross-Price elasticities
Alam, Ishak and Squires (2002)	Trawl	Labor, energy	Translog profit	SM, SH	Elastic[3)]	Substitutes
Bjørndal and Gordon (1993)	Purse seine	Fuel	Translog profit	SM	Elastic, Inelastic[4)]	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[5)]	Substitutes, Complements
Squires (1987b)	Trawl	Labor, energy, capital services	Translog Profit	SM	Elastic	Complements
Squires (1987c)	Trawl	Energy and labor	Translog profit	LM	Elastic[6)]	Complements
Weninger (1998)	Surf clams and ocean quahogs 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 and Lopez, 1984).
3) Marshallian elastiticies are elastic expect 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, labor, 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 go in 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.[12], while in the input-regulated fishery studied by Dupont (1991), the- own-price elasticities for the unrestricted inputs were inelastic. 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 1994). In this sense, input regulations will tend to reduce the flexibility (e.g. the 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.[13] Hicksian elasticities will normally be smaller than Marshallian elasticities. This follows because Hicksian elasticities do not incorporate the reduction in production that follows 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.[14] The Hicksian elasticities reported by Squires (1987a) Weninger (1998), Alam, Ishak and Squires (2002) show substitution between input factors.[15] This is not surprising since Hicksian elasticities measure the pure substitution

[12] Bjørndal and Gordon report the own-price elasticity on fuel, which varies on a yearly basis between -0.713 and -1.108.

[13] The Hicksian elasticities or constant output demand function is derived from the cost function.

[14] The Marshallian and Hicksian elasticity of input build respectively on the profit and cost function. Lopez (1984) show how to estimate Hicksian elasticities from the profit function.

[15] 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 elasticity is related by $\sigma_{ij} = \varepsilon_{ij}/s_j$, where ε and σ are respectively the Hicksian and Allen elasticities and s_j is the cost share of the *jth* input. The Allen partial elasticity separates the relative impact of the price changes.

effect between inputs at a given level of output. What is more interesting is to observe that the Marshallian elasticities in Squires (1987bc) 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 labor 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.

3.2.1 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 reveals that restricting the number of fishing days is an effective way to reduce the fishing effort for seiners and gillnet-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, labor, 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

3.3 The cost structure of multiproduct firms

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.

Table 5. The cost structure of the multiproduct firm

	Gear	Functional form	Economies of scope	Multiproduct economies of scale	Product specific economies of scale
Alam, Ishak and Squires (2002)	Trawl	Translog profit	Economics of scope[1)]	Decreasing returns to scale	Both increasing and decreasing [2)]
Bjørndal and Gordon (2000)	Purse seiners, Trawlers, coastal boats	Translog cost	Not reported	Increasing returns to scale for each vessel group[3)]	Not reported
Diop and Kazmierczak (1996)	Trawl	Leontief revenue	Not reported	Not reported	Decreasing and constant[4)]
Segerson and Squires (1993)	Trawl	Leontief Revenue	Not reported	Not reported	Decreasing for all
Squires (1987b)	Trawl	Translog profit	Economies of scope[1)]	Decreasing returns to scale	Both increasing and decreasing[4)]
Squires (1987c)	Trawl	Translog Profit	Diseconomies of scope	Decreasing returns to scale	Both increasing and decreasing[5)]
Squires (1988)	Inshore and offshore trawlers	Translog Profit	Economies of scope[1)]	Decreasing returns to scale for each vessel group	Both increasing and decreasing[6)]
Squires and Kirkley (1991)	Trawl	Leontief Revenue	Economies of scope[1)]	Decreasing returns to scale	Both decreasing and constant[7)]
Weninger (1998)	Surf clams and ocean quahogs vessels	Translog cost	Diseconomies of scope	Increasing returns to scale	Increasing for all[8)]

1) The economies of scope are verified due to weak cost complementary between 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 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 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(.) 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_{y-T} in separate productions results in higher costs than employing a joint production of y_T and

$y_{y\text{-}T}$.[16]

The results of economies of scope for fish-harvesting technologies are ambiguous. Squires (1987b, 1987c, and 1988) indicates 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 clams and ocean quahogs fishery, where fishermen are restricted by output regulation. This result is not surprising, due to the condition of nonjointness in inputs previously reported for this fishery, 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.[17] Moreover, the imposed output regulation might limit the

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[16] The economies of scope are satisfied for one of two reasons, because of fixed costs or due to weak cost complementary. 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 that the sum of costs from two specialized product technologies. Expressed by $F_T + F_{v\text{-}T} > F_v$, where F_T, $F_{v\text{-}T}$ 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 *ith* output will decrease with an increase in the production of the *jth* output. Weak cost complementarity can be expressed by $\delta(\delta C[.]/\delta y_i)/\delta y_j \leq 0$, where C[.] denotes the multiproduct cost function and y_i and y_j denote the production of the *ith* and *jth* outputs.

[17] Still, economies of scope cost could prevail due to sharing fixed costs in the harvesting the two species.

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 by-catch limitation may distort the complementary of jointly harvested species, leading to increased production costs. In this sense, imposed 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. The regulation will thus 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 a given species is harvested under condition 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). But 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 behavior 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 subaddivity of cost, which is expressed in the condition: $C(y) < {}_i\Sigma_k C(y_i)$, where ${}_i\Sigma_k y_i = y$. $C(y)$ measures the cost of the single firm producing y and ${}_i\Sigma_k C(y_i)$ 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.[18]

[18] A sufficient condition for cost subadditivity is the presence transray convexity and ray subadditivity. The transray convexity embodies cost convexity and economies of scope, the conditions imply that when the monopoly changes its output the 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, *et al.* 1982).

Squires (1998), Alam, Ishak and Squires (2002) rejects for the presence of cost subadditivity in trawler fisheries of New England and Malaysian, 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, π, follows as: $\delta^2 C^*[.]/\delta y_i \delta y_j = [\delta^2 \pi[.]/\delta p_i \delta p_j]^{-1}$ $\forall$ i, j ε M. This means that the inverse Hessian matrix of the long-term profit function π 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.

4.1 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 vessel are sources of welfare gains at 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

	Gear	Regulatory regime[1)]	Functional form	Description
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, gillnet troll	Input regulation	Quadratic Profit	Addresses rent dissipation due to input regulation based on Kulatilaka test.
Lipton and Strand (1992)	Surf clam and ocean quahogs 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 clams and ocean quahogs 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 firm behavior under study

Different regulatory regimes are addressed in the applications. Each regulatory regime imposes certain behavioral restrictions on the behavior 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 the 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.[19] On the other hand, inappropriate fleet structures due to nonoptimal fleet composition and reluctant fleet capacity are found in the fishery.[20]

Campbell and Nicholl (1995) address the connection between stock externality and

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[19] The Kulatilaka test is described more carefully in the section that addresses testing of full static equilibrium.

[20] Reluctant fleet capacity is derived based on the TAC in the fishery.

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. 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.[21]

The empirical result indicates 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 allows the vessels to substitute the unregulated species. In contrast, the effort tax will reduce landings of all species thus resulting in lower effort and earnings than under the royalty tax.

4.2 Testing capacity utilization/full static equilibrium of quasi fixed input

Applications of the dual approach mainly outline the firm's short-term behavior, treating vessel capacity as quasi-fixed. The incentive for the 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.

[21] 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.

Table 7. Tests for full static equilibrium/capacity utilization

	Gear	Quasi-fixed input	Functional form	Full static Equilibrium/ Capacity utilization[1)]	Details
Alam, Ishak and Squires (1996)	Gill net	GRT-capacity	Translog Profit	Reject	Conrad and Unger test[2)]
Alam, Ishak and Squires (2002)	Trawl	GRT-capacity	Translog Profit	Reject	Conrad and Unger test[2)]
Bjørndal and Gordon (1993)	Purse seine	GRT-capacity	Translog profit	Reject	Conrad and Unger test[2)]
Dupont (1990)	Seine, troll, gill net, gillnet-troll	GRT-capacity	Quadratic Profit	Accept	Kulatilaka test[3)]
Segerson and Squires (1990)	Trawl	GRT-capacity	Translog cost	Reject, Accept[3, 5)]	Capacity utilization[4)]
Segerson and Squires (1993)	Trawl	GRT-capacity	Leontief revenue	Accept[3)]	Capacity utilization[4)] Kulatilaka test
Squires (1987c)	Trawl	GRT-capacity	Translog Profit	Accept	Capacity utilization[4)] Kulatilaka test[3)]
Squires (1988)	Trawl	GRT-capacity	Translog Profit	Accept	Kulatilaka test[3)]
Squires and Kirkley (1991)	Trawl	GRT-capacity	Leontief Revenue	Accept	Kulatilaka test[3)]

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.[22] The test of the quasi-fixed input is based on the behavior of the firm in the short run, i.e., when vessel capacity is quasi-fixed.[23] 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

[22] The GRT measures the size of the vessel indicating the storage capacity of the vessel.
[23] It is possible to address the situation where several inputs are quasi-fixed.

capacity. If the firm has 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 is also needed 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 vessel 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 troll. 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 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 emphasize the importance of conducting tests on full static equilibrium over several years, and the result reveals 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 fishery have been made. Segerson and Squires (1990) emphasize the straightforwardness in defining the dual measure of the 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.

4.3 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 behavioral 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 behavior of the firm that maximizes revenue during the fishing trip, assuming fixed input composition.

Table 8. Applications using e*x ante* assessment of production quota on firms

	Gear	Functional form	Contribution addressing the impact of trip quota on
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 φ_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.

The 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 for 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 at the expense that they will not 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 sablefish fishery is not fully obtained.[24] On the other hand, if 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.[25]

[24] The gains by introducing ITQ management arise, as firms will reallocate their fishing activity to the most favorable periods of the year. Moreover, economic rent will also arise since the most efficient vessels will purchase quota from less efficient vessels.

[25] Vestergaard (1999) develops the framework to measure welfare effects of individual quotas in multiproduct industries.

5. 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 ability to alter harvesting strategy 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 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 different 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 impose behavioral restrictions on firms. Even so, interesting policy implications result from these applications.

Success of input management hides 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 reluctant capacity means that money is granted 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 <u>no</u> 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, thereby 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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