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A short-run Johansen industry model for common-pool resources: planning a fishery's industrial capacity to curb overfishing

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Summary

Current methods for assessing capacity and its utilisation in fisheries operate at the firm-level, but neglect industry capacity. Here, we introduce the Johansen-Färe measure of plant capacity of the firm into a multi-output, frontier-based version of the short-run Johansen industry model. The model determines firm capacity utilisation such that current industry outputs are maintained, while minimising the use of fixed inputs at industry level and assuming abundant variable inputs. Policy extensions relevant to combating overfishing include tightening quotas, seasonal closures, linking economic and plant capacity, decommissioning schemes and area closures, implementation issues and equity considerations. The application to the Danish fisheries reveals substantial overcapacity in the Danish fleet.

Keywords: plant capacity, Danish vessels, industry, planning, efficiency

JEL classification: L52, Q22, Q28

1. Introduction

The growth of fishing capacity and its consequence, overfishing, are two of the most pressing problems facing many fisheries around the world. Excess capacity occurs when a too high number of vessels enter the fishery, and these vessels and their variable inputs are employed to exploit the available fish stocks beyond a target level of yield (whether the latter is sustainable or not). The absence or ineffectiveness of regulation and the lack of fully specified property rights of either private or common property are fundamental to this overcapacity problem.

In a common-pool resource industry, the development of capacity over time vis-à-vis a target yield indicates the economic state of the industry as well as the relative success of its regulation. Capacity fluctuations also provide a measure of the exploitation pressure on the available fishing stocks. Excess capacity entails overinvestment in the capital stock and overuse of variable inputs, which exert additional pressure on the resource stocks and create economic waste. Management of capacity is often both an instrument and a goal of fisheries regulation.

Persistent excess capacity and the overfishing crisis can be seen as a consequence of relying on command-and-control instruments in an effort to manage fishing stocks. Indeed, subsidies to build and decommission vessels, tax deductions for investments in fixed inputs and the like actually encourage investment in capacity, and the excess capacity crisis then just signals rent dissipation. Thus, many economists have criticised the use of input control measures and output quotas because they fail to address the basic externality of exploiting a renewable common-pool resource. The use of economic instruments, e.g. under the form of individual transferable quotas (ITQs), is therefore widely regarded as an indispensable part of a long-term solution to this excess capacity and overfishing crisis.[1]

Nevertheless, one cannot but observe that authorities worldwide continue to rely on command-and-control instruments that have transformed much of the world's fisheries into an almost centrally planned sector. This paper takes no side in the debate on the optimal mix of policy instruments, but simply intends to offer a coherent framework to formulate and refine most of the currently used command-and-control policy instruments. Indeed, this contribution formulates a central planning model of capacity utilisation (CU) at the industry level given a variety of concerns expressed in current fishery policies. Ideally, the advantages of this framework should be weighed against the cost of its implementation, the latter forming part of the cost of regulation.

Various international organisations have prepared policy responses to the overcapacity crisis and its devastating consequences for fishing stocks. For instance, in the European Union (EU), the Multi Annual Guidance Programme sets targets for capacity reductions for each member state (European Commission, 2002). The Food and Agriculture Organisation (FAO) has formulated an International Plan of Action where each state is bound to assess the capacity of its fishing fleet and develop a plan for dealing with capacity development (FAO, 1999).

Many studies have been conducted on capacity and CU in fisheries, but a uniform and consistent use of capacity concepts was often lacking (see

1 A wide range of policy measures have been implemented in practice, including gear restrictions, area and seasonal closures, entry restrictions under various forms (license moratorium, license and vessel buyback schemes), community development quotas, ITQs and Pigovian taxes. Their relative merits and failures are reviewed in Merrifield (1999), Squires *et al.* (1995), Sutinen (1999) and Townsend (1990), among others.

Kirkley and Squires, 1999). While most studies have focused on capacity at the individual vessel level, we are unaware of studies on the capacity at the industry level, except the unpublished work by Färe *et al*. (2001), which used a basic version of the same modelling approach adopted here. A primary reason is that the main methods to assess capacity and CU operate at the level of the decision-making unit. Hence, the issue of industry capacity, which is actually far more important from a policy viewpoint, is not addressed by these methods.[2]

The short-run Johansen (1972) sector model analyses the industry structure resulting from underlying *ex post* firm-level production structures. Investment decisions imply a putty-clay production structure: while firms may choose *ex ante* from a catalogue of production options exhibiting smooth substitution possibilities, most face fixed coefficients *ex post* and have a capacity that is entirely conditioned by the investment decision made. The short-run industry model nevertheless exhibits substitution possibilities when inputs and outputs can be reallocated across the units composing the industry. Over time, substitution and technical change can be traced via shifts in successive short-run industry models. As far as we are aware, this model has never been applied to a common-pool resource industry.

This paper combines the plant capacity notion (Johansen, 1968) at the individual and industry levels using a multiple-output and frontier-based version of the short-run Johansen (1972) sector model, a methodological refinement developed in Dervaux *et al.* (2000). Relaxing the single-output restriction enlarges the scope of application beyond the historically almost exclusive focus on industry studies.[3] The frontier nature allows for a benchmarking perspective when adopting it for social planning purposes (e.g. yardstick competition à la Schleifer, 1985).

The short-run Johansen (1972) sector model has economic relevance for both positive and normative purposes: (i) positive: to simulate industry outcomes under decentralised decision-making or (ii) normative: to plan the industry in the most efficient way (Førsund and Hjalmarsson, 1987: 141). This paper explores the normative use of these models to formulate policies that combat overfishing and overcapacity. An advantage for developing fishery policies is that it is based solely on input and output information when prices are unavailable. This is important in industries like fisheries, where price information is either incomplete or lacking altogether. A second advantage is that such a disaggregated industry model provides detailed information about the optimal industry structure in terms of, for example, vessel

2 Except for the so-called 'peak-to-peak' method, which also addresses industry capacity. But the method is rather *ad hoc* and therefore unreliable (Christiano, 1981). There are also studies using a linear programming approach to determine overall expected catch and the allocation of this catch over different fleets, e.g. Siegel *et al.* (1979), where the expected catch in a multi-species fishery is found given different physical constraints at the industry level. However, these constraints are specified in a rather *ad hoc* way.

3 Examples include Hildenbrand's (1981) study of the Norwegian tanker fleet and the US electric power-generating industry, the analysis by Førsund and Hjalmarsson (1983) of the Swedish cement industry and by Førsund *et al.* (1996) on the Finnish brewery industry, the empirical chapters in Førsund and Hjalmarsson (1987), among others.

size classes, multi-species production or quotas and variable input usage necessary to implement the social plan.

Our modelling approach extends the current focus of policy makers in fisheries on short-run, firm-based capacity analysis by looking for an optimal, in terms of plant capacity, capital stock or other quasi-fixed and fixed factors at the industry level. This approach may reveal the existence of excess capacities at the firm level when certain target levels of outputs, due to quotas, are formulated at the industry level. The Johansen industry approach is presently conditional upon the current state of the resource stocks and the states of the environment and technology,[4] but future research is warranted in this area.

This industry approach allows relaxation of several assumptions normally maintained in natural resource models, such as the existence of an aggregate output and/or an aggregate input (see Squires, 1987). Relaxing these assumptions allows for the determination of an optimal industry structure for heterogeneous firms (where heterogeneity is defined in terms of firm (i.e. vessel) sizes, technologies (gear and vessel types), areas, etc.), while simultaneously taking into account other criteria like bio-mass targets (translated into quotas) and equity concerns. The aggregate approach maintained in traditional natural resource models is important for providing long-term solutions in the steady state, but does not provide the information for tackling heterogeneity in firms, areas and species confronted by regulators in practice. Regulators place considerable weight on issues like distribution and heterogeneity, a critically under-researched area in fisheries economics.

The purpose of this paper is to develop a version of the short-run Johansen industry model that can guide fishery policy choices. To illustrate its potential, our model is applied to a large sample of the Danish fishery in 1998, covering almost the entire fleet. This is the first large-scale empirical application of the short-run Johansen industry model to fisheries and it is the first large-scale extension of the model making it suitable for analysing a realistic mixture of traditional fishery policies in this sector.[5] The empirical results show substantial overcapacity at the fleet level. The total use of fixed inputs in the industry can be reduced between 15 and 45 per cent, depending on the specific objective and the choice of instruments, while the number of vessels can be reduced by 14–25 per cent. Although the reduction in the number of vessels seems not to vary greatly between the various scenarios, the resulting fleet structure is decidedly different.

The paper is organised as follows. In Section 2, the empirical methodology is developed and modelling issues related to the fisheries context are discussed along with the presentation of the sample. Section 3 presents the various policy scenarios and the empirical results. Section 4 ends with the main conclusions and suggestions for further work.

4 This approach is analogous to duality approaches where a short-run profit or cost function is econometrically estimated in the first stage, and in the second stage optimal fixed factors are determined by setting their shadow prices equal to their rental or service prices (see Lau, 1976).

5 Färe *et al.* (2001) outlined some basic extensions to the Dervaux *et al.* (2000) model, but their empirical application was based on a very small sample of US vessels.

2. Firm and industry capacity models: empirical methodology

2.1. Basic firm and industry models

The revised short-run Johansen (1972) model proceeds in two phases. In a first step, the Johansen–Färe capacity measure determines capacity production for each individual firm at the production frontier using information collected by official bodies. Second, this firm-level capacity information is employed in the industry model by the central planner to select the level of activity at which individual firm capacities are utilised with the objective of minimising fixed industry inputs given total outputs and capacities and the current state of technology. This capacity measure is short-run, since it assumes no change in the existing firm-level capacity, and it is a technical rather than an economic capacity notion. Note that, when appropriate price information is available, one can replace the technical optimisation (in terms of primal or quantity based aspects) in both stages of the short-run Johansen industry model by alternative economic capacity notions in the first stage and economic objective functions (e.g. industry cost functions as in Førsund and Hjalmarsson (1983) or industry revenue or profit functions) in the second stage.[6]

Johansen (1968) defined plant capacity as the maximal amount of output that can be produced per unit of time with existing plant and equipment without restrictions on the availability of variable inputs. This derives from a technical or engineering capacity concept. Capacity arises due to fixity of one or more inputs and is thereby inherently a short-run rather than a long-run concept. Färe (1984) formally showed the existence of plant capacity for certain types of production functions. Färe *et al.* (1989) made the concept operational by making firm-level capacity levels easy to calculate using non-parametric frontier approximations of technology.[7] The approach assumes that firms cannot exceed their use of the fixed factors, but that their use of variable factors is not constrained. A best-practice technology is constructed and the current output of each firm is evaluated against the maximum potential output at full CU, called ‘capacity output’. Summing these firm-level capacity outputs across firms gives an estimate of aggregate industry capacity output. Comparing this aggregate industry capacity output to current industry output provides a measure of overcapacity at the industry level.

However, this plant capacity measure does not allow reallocation of inputs and outputs across firms, precluding insight into the optimal restructuring and configuration of the industry. The plant capacity measure indeed implicitly

6 See Dervaux *et al.* (2000: 139–142) for numerical examples of both stages in our modelling approach.

7 The Johansen industry model is not necessarily limited to activity analysis, since the first stage determination of capacities can also be implemented by econometric estimation of parametric frontiers. Kirkley *et al.* (2002) reviewed and applied both non-parametric and parametric frontier functions to evaluate fishing capacity.

assumes that production of capacity output is feasible and that the necessary variable inputs are available. In fisheries, this is normally not the case, since total production of the sector is constrained by the productivity of the fish stocks. To protect fish stocks from overexploitation, constraints (such as Total Allowable Catch (TAC) limits) are imposed on the firms' activities. Following Dervaux *et al.* (2000), the optimal industry configuration is found by minimising the total use of fixed inputs given that each firm cannot increase its use of fixed inputs and the production of the industry is at least at the TAC level. The output level of each firm in this type of model is the capacity output estimated from the firm-level capacity model.

Turning from the general principles to the particulars of the firm models, the empirical methodology is based on estimating output-oriented efficiency measures relative to non-parametric, deterministic production frontiers (see Färe *et al.*, 1994). These efficiency measures are extremum estimators, which determine the best practice among observed production units by a piecewise linear envelopment to constitute a frontier or reference technology, an inner bound approximation to the true but unknown technology.[8]

To develop these production models formally, the production technology S transforms inputs $x = (x_1, \ldots, x_n) \in R^n_+$ into outputs $u = (u_1, \ldots, u_m) \in R^m_+$ and summarises the set of all feasible input and output vectors: $S = \{(x, u) \in R^{n+m}_+ : x \text{ can produce } u\}$. Let J be the number of firms/units. The n-dimensional input vector x is partitioned into fixed factors (indexed by f) and variable factors (indexed by v): $x = (x_v, x_f)$. To determine the capacity output and CU, a radial output-oriented efficiency measure is computed relative to a frontier technology providing the potential output given the current use of inputs: $E^0(x, y) = \max\{\theta : (x, \theta y) \in S\}$.

Assuming strong disposal of inputs and outputs and variable returns to scale, a non-parametric inner-bound approximation of the true technology can be represented by the following set of production possibilities (Färe *et al.*, 1994):

$$S^{\text{VRS}} = \left\{ (x, u) \in R^{N+M}_+ : u_{jm} \leq \sum_{j=1}^{J} z_j u_{jm}, \quad m = 1, \ldots, M; \right.$$

8 Being extremum estimators, these efficiency estimates are sensitive to outliers. Recently, substantial progress has been made in determining the statistical properties of these estimators. Indeed, the limiting distributions of some efficiency estimators have been obtained and one can sometimes estimate their bias and build confidence intervals (Simar and Wilson, 2000). Alternatively, the bootstrap is perhaps the only (computationally burdensome but practical) way of making inference for multivariate efficiency estimators. The intuition is to approximate the sampling distributions of interest by simulating the underlying data generating process (Simar and Wilson, 2000). Our analysis in two stages, one based on firms and another on the industry, would seriously complicate the use of these recent bootstrapping methodologies. Henceforth, this problem is noted and left for future work. Examples of 3D-visualisations of these production frontiers can be found in Ali and Seiford (1993).

$$\left.\sum_{j=1}^{J} z_j x_{jn} \le x_{jn}, \quad n = 1, \ldots, N; \quad \sum_{j=1}^{J} z_j = 1, z_j \ge 0,\ j = 1, \ldots, J\right\} \tag{1}$$

Following the activity analysis tradition, the vector of intensity or activity variables z indicates the intensity at which a particular activity is employed in constructing the reference technology by forming convex combinations of observations constituting the best-practice frontier. The specific constraint that the sum of activity vectors equals unity reflects a variable returns to scale hypothesis. A short-run version of this same technology is defined by dropping the constraints on the variable input factors to translate Johansen's definition of plant capacity whereby the availability of variable factors is not restricted:

$$\hat{S}^{\text{VRS}} = \left\{ (x, u) \in R_{+}^{N+M} : u_{jm} \le \sum_{j=1}^{J} z_j\, u_{jm}, \quad m = 1, \ldots, M; \right.$$
$$\sum_{j=1}^{J} z_j\, x_{jf} \le x_{jf}, \quad f = 1, \ldots, F;$$
$$\left. \sum_{j=1}^{J} z_j = 1, \quad z_j \ge 0,\ j = 1, \ldots, J \right\}. \tag{2}$$

Both technologies are, geometrically speaking, convex monotonic hulls enveloping all observations.

The output-oriented efficiency measure θ_1 is found by solving the following linear programming problem for each firm $j = 1, 2, \ldots, J$ relative to the short-run production possibilities set:

$$\max_{\theta_1^j, z_j} \{\theta_1^j : (x, \theta_1^j\, u) \in \hat{S}^{\text{VRS}}\}. \tag{3}$$

To remain consistent with the plant capacity definition, in which only the fixed inputs are bounded at their observed level, the variable inputs in the production model are allowed to vary and be fully utilised. The outcome of the production frontier model is a scalar θ_1 showing by how much the production of each output of each firm can be increased. In particular, capacity output for firm k of the mth output is θ_1^{*k} multiplied by actual production u_{km}.[9] Hence, capacity utilisation based on observed output (subscripted 'oo') is:

$$\text{CU}^k_{\text{oo}} = \frac{1}{\theta_1^{*k}}. \tag{4}$$

9 Note that optimal solutions for decision variables from optimisation problems are denoted by an asterisk (*).

This approach provides a ray measure of capacity output and CU, in which the multiple outputs are maintained in fixed proportions when they are expanded (see Segerson and Squires (1990) in a parametric context). This ray measure corresponds to the Farrell (1957) measure of output-oriented technical efficiency, due to the radial nature of the output expansion.[10]

Färe *et al.* (1994) noted that this ray CU measure may be biased downwards, because there is no guarantee that the observed outputs are produced in a technically efficient way. Another technical efficiency measure can be obtained by evaluating each firm $j = 1,2, \ldots, J$ relative to the production possibility set S^{VRS}. The outcome (θ_2) shows by how much production can be increased using the technically efficient inputs:

$$\max_{\theta_2^j, z_j}\{\theta_2^j : (x, \theta_1^j\ u) \in\ S^{\text{VRS}}\}. \tag{5}$$

The technically efficient output vector is θ_2^{*k} multiplied by observed production for each output. Total industry output can be found by aggregating the firm-level technically efficient output $\theta_2^{*k}u_k$ over firms. Likewise, the aggregate industry capacity output can be found as the sum of firm-level capacity outputs ($\theta_1^{*k}u_k$).

The technically efficient output (subscripted 'eo'), or unbiased ray measure of capacity utilisation, is then:

$$\text{CU}^k_{\text{eo}} = \frac{\theta_2^{*\,k}}{\theta_1^{*\,k}}. \tag{6}$$

The focus is on reallocation of production between vessels by explicitly allowing improvements in technical efficiency and capacity utilisation rates. The model is developed in two steps as follows. In the first step, from model (3), an optimal activity vector z^{*k} is provided for firm k and hence capacity output and its optimal use of fixed and variable inputs can be computed:

$$u^*_{km} = \sum_j z_j^{*\,k} u_{jm} - s^{*\,k}_{jm}; \quad x^*_{kf} = \sum_j z_j^{*\,k} x_{jf} + s^{*\,k}_{jf}; \quad x^*_{kv} = \sum_j z_j^{*\,k} x_{jv}, \tag{7}$$

where s_{jm}^{*k} and s_{jf}^{*k} are the optimal surplus and slack variables corresponding to the output, respectively, fixed input dimensions.

10 A non-radial expansion of outputs corresponds to Koopmans' (1951) notion of technical efficiency that focuses on projections onto the efficient subset rather than the isoquant of the frontier technology. This approach requires different, non-radial efficiency measures (Fare *et al.*, 1994).

In a second step, these ‘optimal’ frontier figures (capacity output and capacity variable and fixed inputs) at the firm level are used as parameters in the industry model. In particular, the industry model minimises the industry use of fixed inputs in a radial way such that the total production is at least at the current total level (or at a quota level in the model extension developed below) by a reallocation of production between firms. Reallocation is allowed, based on frontier production and input use of each firm. In the short run, it is assumed that current capacities cannot be exceeded either at the firm or industry level. Define U_m as the industry output level of output m and X_{f} (X_{v}) as the aggregate fixed (variable) inputs available to the sector of factor f (v), i.e.:

$$U_m = \sum_j u_{jm}, \quad X_{\mathrm{f}} = \sum_j x_{fj} \text{ and } \quad X_{\mathrm{v}} = \sum_j x_{vj}. \tag{8}$$

The formulation of the multi-output and frontier-based short-run Johansen (1972) industry model can then be specified as:

$$\begin{aligned} &\min_{\theta,w,X_v} \ \theta \\ &\text{s.t.} \sum_j u^*_{jm} w_j \geq U_m, \quad m = 1, \ldots, M, \\ &\sum_j x^*_{fj} w_j \leq \theta X_{\mathrm{f}}, \quad f = 1, \ldots, F, \\ &-X_{\mathrm{v}} + \sum_j x^*_{vj} w_j \leq 0, \quad v = 1, \ldots, V, \\ &0 \leq w_j \leq 1, \theta \geq 0, \quad j = 1, \ldots, J. \end{aligned} \tag{9}$$

Rather than reflecting a returns-to-scale hypothesis, the w variables now indicate which firms’ capacity shall be utilised and by how much. The components of the activity vector w are bounded above at unity, so that current capacities can never be exceeded. The first constraint prevents total production by a combination of firm capacities from falling below the current level. The second constraint means that the total use of fixed inputs (right-hand side) cannot be less than the use by a combination of firms. The third constraint calculates the resulting total use of variable inputs. Note that the total amount of variable inputs is a decision variable. The objective function is a radial input efficiency measure focusing on the fixed inputs solely. This input efficiency measure has a fixed-cost interpretation at the industry level.[11]

Geometrically, the short-run industry model is a set consisting of a finite sum of line segments, or *zonotopes* (Hildenbrand, 1981: 1096). The activity vector w indicates which portions of the line segments representing the firm capacities are

11 We sidestep the issue of aggregation of firm and industry capacities and efficiency measures (e.g. whether industry capacity could be formulated in a way similar to expression (8) and its relation to the underlying firm capacities). Recently, Briec *et al.* (2003) and Färe and Grosskopf (2004) began to analyse this issue. Notice that these aggregation problems for measures of capacity and technical efficiency might be further complicated by the fact that the fishing industry is subject to technological externalities.

effectively used to produce outputs from given inputs. The optimal solution to this simple LP gives the combination of firms that can produce the same or more outputs with less or the same use of fixed inputs in aggregate.

2.2. Extensions of firm and industry models: adaptation to the fisheries context

The sample data consist of observations for the year 1998 on catches of different fish species (kilograms), two variable inputs (labour and fishing days) and two fixed inputs (gross registered tons (Grt) and horse power (HP)) for individual vessels.[12] These data are available for each of the five fishing areas and cover effectively the whole Danish fleet, since only very small vessels or vessels with very low catches are excluded. In total, 923 vessels are included in the sample with 1,805 observations, i.e. on average each vessel fishes in about two areas.

Descriptive statistics for each area are reported in Table 1. These aggregate figures hide some variation across vessels.[13] The number of fishing days in an area indicates the importance of the area for the firm.

Finally, total catch per species and area is used as the basic output in the model. The number of observed outputs (caught species) has been reduced from 25 to 9, which is then either species or group of species. Six of the main species have been selected,[14] while the rest have been aggregated together into three combined outputs using a Divisia index (these groups are: other roundfish, pelagic and other fish).[15] This aggregation of outputs is partly necessary to escape the curse of dimensionality that is inherent to non-parametric methodologies. Intuitively, it is clear that at the completely disaggregated level the analysis would detect little inefficiency (Tauer and Hanchar, 1995; Thrall, 1989) and little scope would be left for reductions of fixed inputs at the industry level. Unfortunately, there is no standard procedure for how to reduce the number of outputs and inputs.

The models described in the previous subsection require some adjustment to take into account specific fisheries and managerial issues. We specify some general principles and indicate whether they apply to the individual technologies (1) and (2), to the industry model (9) or to both individual technologies and the industry model.

First, we decided to specify the use of fixed inputs as flow variables, so the fixed input variables (Grt and HP) are both multiplied by the number of fishing days. This specification guarantees a more balanced picture of the efficiency of fishing firms, because firms are rather heterogeneous in terms

12 Weather may influence the number of fishing days and affect the yield. Ignoring weather variations can distort the capacity measures. While in principle it is possible to include an exogenous weather variable, a meaningful empirical measure of weather across all regions and relevant across an aggregated time period was not possible.

13 Descriptive statistics across vessel types reported are available upon request.

14 The species are cod, plaice, sole, lobster, shrimp and the group of industrial species.

15 Since the catch of some of species in certain areas is very small and/or not subject to a quota, and furthermore a pure by-catch, we decided to set the current total catch of these species to zero.

Table 1. Sample size and average inputs and current total catches by area

	Areas					Total
	North Sea	Baltic Sea	Kattegat	Skagerrak	Other	
Number of vessels	555	398	315	489	48	1,805
Gillnetters	153	23	27	69	0	272
Trawlers	307	306	236	338	37	1,224
Danish seiners	64	36	31	53	0	184
Combinations	20	33	21	18	0	92
Purse-seiners	11	0	0	11	11	33
Average per vessel						
Tonnage	129	75	30	96	504	101
Horsepower (HP)	367	278	207	329	962	325
Crew size (number)	4	3	2	3	6	3
Fishing days	111	84	53	66	39	81
Cod[a]	20,814	19,555	3,205	10,202	0	53,776
Other roundfish[b]	2,972	59	67	2,415	0	5,519
Plaice[a]	9,393	578	1,109	5,174	0	16,254
Sole[a]	467	0	215	101	0	789
Pelagic[b]	31,836	27,917	7,678	21,569	28,522	117,522
Lobster[a]	1,365	0	1,349	1,905	0	4,622
Shrimp[a]	2,919	4,054	30	2,886	0	9,890
Other fish[b]	1,621	104,125	391	2,407	0	108,546
Industrial[a]	852,713	5,232	13,419	35,709	103,575	1,010,648

[a]Tons.
[b]Index.

of their fishing effort and service flow, i.e. the number of fishing days varies substantially. Traditionally, production models in other industries assume that firms operate in a similar environment during normal working time (depending on how this is defined). This principle applies to all models. This transformation complicates the interpretation of the optimal value of the efficiency measure in model (9). It necessitates dividing the optimal scalar reduction of the fixed inputs by the optimal value of the number of fishing days (i.e. $\theta^* \ X_f/X_v^*$).

Second, the models have to deal with the fact that vessels are fishing in areas that differ in terms of stock conditions. Therefore, if we assume that the stock conditions are part of the technological constraints, then the search for more efficient combinations of production plans has to be restricted to combinations of vessels fishing in the same area. This principle applies to all models.[16]

Third, another modification to the basic model comes from the fact that each vessel uses a specific gear type, so that the set of vessels can be partitioned

16 The idea of geographically specific technologies is also found in Dervaux *et al.* (2000).

according to different gear technologies. Therefore, when finding the frontier production output and the optimal input usage of the firm, the reference technology can be limited to include only firms using the same gear technology. This principle applies to the individual technologies (1) and (2).

These last two modifications imply that the individual firm-level models (1) and (2) are applied for a given area and a given gear type. Thus, the efficiency of each vessel is evaluated relative to one of the potentially 25 different technologies (five areas by five gear types). In fact, since not all gear types are present in all areas, there are only 20 technologies, some of which consist of only a few similar observations, which may lead to biases in the estimation of firm plant capacity due to lack of comparable production units. The capacity outputs and inputs (equation (7)) are then calculated for each firm using the plant capacity reference technology provided by model (2). Indeed, the firm-level capacity outputs and inputs given by equation (7) are indexed by area and gear type and enter as parameters into the industry model (9) in the second stage.

Having summarised the implications for the individual technologies, we turn to the second-stage industry model (9). First, following the second modification above, the constraints for each output dimension have to reflect the fact that production may take place in different areas. This means there are M output constraints (species) for each of the A areas:

$$\sum_{j} u^{*}_{jma} w_{ja} \geq U_{ma}, \quad m = 1, \ldots, M, \; a = 1, \ldots, A, \tag{10}$$

where a is an index for area.

Second, the industry consists of vessels fishing in different areas. According to the second modification, the constraints for each of the total fixed inputs can be formulated in a most general way in terms of constraints indexed by area:

$$\sum_{j,a} x^{*}_{fja} w_{ja} \leq \theta X_{\mathrm{f}}, \quad f = 1, \ldots, F. \tag{11}$$

Third, the constraints on the variable inputs are:

$$-X_v + \sum_{j,a} x^{*}_{vja} \, w_{ja} \leq 0, \quad v = 1, \ldots, V. \tag{12}$$

Since the quantity of variable inputs at the industry level is a decision variable, the resulting solution may well imply that vessels are supposed to fish more days than available in a civil year. This can be avoided by an additional constraint on the number of fishing days. This leads us to consider the more general issue of formulating a series of additional constraints representing potential policy variables in fisheries.

2.3. Extensions of firm and industry models: policies in a fisheries context

To offer a menu of current and potential conservation and distributional policies in a social plan for fisheries based solely upon primal information, we add some further refinements to the short-run industry model of Dervaux *et al.* (2000).[17] We briefly focus on seven issues: (i) tightening quotas at either species or area level, (ii) seasonal closures, putting limits on fishing days, (iii) the link between economic and plant capacity, (iv) decommissioning schemes and area closures, (v) implementation issues due to monitoring problems, (vi) partial tolerance of technical inefficiencies and (vii) equity considerations.

(i) Tightening quota. While current industry outputs may well reflect prevailing quotas, it is straightforward to compute the impact of tightening these quotas either at the level of the species over all the areas or at the species level and specific per area. In the first case, we simply add the constraint:

$$\sum_a U_{ma} \leq \bar{U}_m, \quad m = 1, \ldots, M, \tag{13}$$

where $\bar{U}_m$ denotes the overall quota for species m. In the second case, the constraint is simply:

$$U_{ma} \leq \bar{U}_{ma}, \quad m = 1, \ldots, M, \;\; a = 1, \ldots, A, \tag{14}$$

where $\bar{U}_{ma}$ denotes the overall quota for species m in area a.

(ii) Seasonal closure policies limit the number of fishing days in an effort to control inputs. To limit the amount of variable inputs that appear in the model as an aggregate decision variable, we fix a constraint on the total annual fishing days at $\text{FD}_{\max}$ common to all vessels. This can be simply represented as follows:

$$\sum_a x^*_{jva}\, w_{ja} \leq \text{FD}_{\max}, \quad j = 1, \ldots, J, \;\; v = 1, \tag{15}$$

17 Another attempt at tackling environmental and resource economic issues using an industry model based upon price information is by Brännlund *et al.* (1998), which assesses the effect of emission trading on the short-run industry profitability of Swedish paper and pulp industry. Färe *et al.* (1992) developed models of industry performance using firm-level data employing output-oriented efficiency measures, whereby reallocations of some or all of the inputs across firms are allowed to maximise aggregate output. In such models, inputs are either constrained at the industry level (if reallocatable) or at the firm level (if not reallocatable) to their current use and comparing maximum potential industry output with current aggregate output provides a measure of the industry performance. These authors did not, however, address the issue of capacity limitations (hence these models are long run) nor were their models ever applied in resource economics.

given that the fishing days are indexed by v equal to 1 (i.e. the first variable input).[18] Of course, it is possible to refine this constraint by conditioning seasonal closures per gear type or per area, but these latter options are not considered in this paper.

(iii) Lower (LB) and upper bounds (UB) are introduced on the activity vectors to avoid, on the one hand, economically unviable solutions (LB) and, on the other hand, production at technical capacity levels that are beyond economic capacity levels (UB). This indirectly includes economic information into an otherwise technical production model. Indeed, it is important to recognise that the industry model is based upon a technical or engineering notion of capacity. It is unlikely that it is ever economical in terms of cost minimisation, revenue or profit maximisation to produce at maximal plant capacity (Morrison, 1985; Nelson, 1989). Depending on the exact economic capacity notion adopted, economic capacity outputs are below plant capacity outputs.[19] Implementing the conclusions from the short-run industry model based upon plant capacity outputs will therefore normally lead to lower industry output levels than computed in the industry model, since individual firms have an obvious interest in producing below full plant capacity.

These considerations may lead to formulating both LB and UB on the activity or intensity vector (w_{ja}). To start with the UB, to avoid imposing production at plant capacity outputs well beyond economic capacity levels, one can implement UB constraints on the activity levels. Suppose it could be established that, for the average vessel, economic capacity is at about 85 per cent of plant capacity, then it would suffice to add the constraint $w_{ja} \leq 0.85$ to the industry model. To continue with the LB, it may be useful to avoid solutions of the short-run Johansen sector model that yield very small values of the activity or intensity vector (w_{ja}) that could imply maintaining vessels in operation or low output levels that are not economically viable (for instance, because fixed cost are not covered). Assuming that, for the average vessel, the required threshold for economic viability is at least 35 per cent of plant capacity, then the constraint $0.35 \leq w_{ja}$ can be added to the industry model. However, this would force all vessels in the optimum solution to satisfy this LB.

If the purpose is to impose LB and UB on plant capacity simultaneously, this last problem can be avoided as follows. First, one defines a set of auxiliary binary decision variables (k_{ja}) corresponding to the number of activity variables (w_{ja}), which can be used to define a set of weak mutual exclusivity constraints: (i) any number of vessels (J) can enter into the optimal solution and

18 Since fishing days is a variable input whose optimal value is determined by the model, it may be necessary to impose the constraint that firms can only harvest a total number of fishing days less than the number available in a normal fishing year. This constraint is only active when the number of fishing days in different areas yields an unrealistic aggregate number of fishing days in a year and when no additional seasonal closure policy is implemented.

19 However, the technical plant capacity notion is estimated using empirical data that at least partially reflect changes in economic conditions. Therefore, the difference between technical and economic notions of capacity may well be much smaller in practice than imagined.

(ii) each vessel can fish in any of the areas (A), or formally:

$$\sum_j k_{ja} \leq J, \;\; \forall\, a, \quad \sum_a k_{ja} \leq A, \;\; \forall\, j, \text{ and } k_{ja} \in \{0, 1\}. \tag{16}$$

Then, one links these binary decision variables and the activity variables via a constraint making the bounds on the activity variable contingent on the binary decision to enter the vessel into the optimal solution:

$$\text{LB} \cdot \; k_{ja} \leq w_{ja} \leq \text{UB} \cdot \; k_{ja}, \quad \forall\, j \;\text{ and } a. \tag{17}$$

In this way, when $k_{ja} = 0$ then also $w_{ja} = 0$, and when $k_{ja} = 1$ then w_{ja} can take any value within the interval defined by the *LB* and *UB*.

(iv) Decommissioning schemes and area closures are modelled to address some of the key contemporary policy issues, such as marine reserves, separation of commercial and artisanal fishers in developing countries and ecosystem concerns e.g. protecting endangered species such as turtles. The weak mutual exclusivity constraints (16) have initially no bite, but can easily be turned into policy tools by directly constraining the maximum number of vessels or areas. The first constraint can be meaningful as a tool for implementing a decommissioning scheme. For instance, one could easily compute the impact of decommissioning 10 per cent of the current fleet by fixing the right-hand side to 90 per cent of J ($\sum_J k_{ja} \leq 0.9\, J$). The second constraint can be meaningful in combination with area closure considerations or if one wishes to reduce vessel mobility (i.e. the number of areas that vessels can operate in without closing down specific areas). The reason for the latter is that there is a negative open-access externality that arises when vessels can freely enter into any area. Reducing the number of areas where vessels can operate can mitigate this negative externality.

As an example of an area closure policy, assume that two of the five areas' fishing stocks are deemed vulnerable, then it is straightforward to tighten the second constraint by setting A smaller or equal to 3 (i.e. $\sum_a k_{ja} \leq 3$) in combination with imposing zero activity variables for the two specific vulnerable areas. Or, if limited access would suffice in both vulnerable areas, one could set A smaller or equal to 4 together with a mutual exclusivity constraint allowing access to one of both vulnerable areas. Another example aimed at reducing vessel mobility is implemented by setting A equal to the number of areas vessels can fish in (for instance, three), without forbidding access to any specific area.

(v) Implementation issues may arise due to monitoring problems keeping track of vessels across different areas over the year. Requiring the activity level in each area to be identical alleviates this information problem. Since the industry model distinguishes between vessels operating in several areas, this may cause difficulties when implementing the planning solution. To avoid deviations from the model solutions, it requires setting up extensive control operations at the individual vessel level. Monitoring fishing trips within each area may well prove costly and such a policy probably leads to an imperfectly monitored solution at best. Therefore, we can impose that a vessel should be used identically within all areas to simplify the monitoring process (e.g. counting the number of days a vessel has left the harbour rather than monitoring its destination):

$$w_{j1} = \cdots = w_{j5}. \tag{18}$$

(vi) The frontier nature of the underlying technologies may push things too far in that it is practically impossible to require vessels to adjust immediately to technically efficient production plans. While technical efficiency is a condition for any social optimum, realistic planning procedures may for informational and political reasons require tolerating technical inefficiency (even increased technical inefficiency) for part of this path (Peters, 1985). We do not trace an optimal path to the social optimum, but take a static and more pragmatic perspective. Given the widespread prevalence of technical inefficiencies, it may well be impossible to eradicate them completely, although imposing some production discipline via a yardstick benchmarking process may well be desirable from a normative viewpoint (Andersen and Bogetoft, 2003).

Thus, it may be useful to correct capacity outputs for (partial) technical inefficiencies. In the spirit of Andersen and Bogetoft (2003), this is modelled by adjusting the technically efficient capacity output downwards. Since, from a normative economics viewpoint, it is hard to tolerate such technical inefficiencies, one can imagine that currently observed technical inefficiencies are only partially accepted. This can be modelled by adjusting the capacity output entering the second stage industry model by its current observed technical inefficiency eventually corrected by an efficiency improvement imperative (α). Of course, currently technically efficient firms need no such adjustment. Hence, assuming this correction factor is smaller or equal to unity ($\alpha \leq 1$), the adjustment of the second stage capacity output could take the following form when technical inefficiency is (partially) accepted:

$$\hat{u}^*_{jma} = \frac{u^*_{jma}}{\max\{1, \alpha\theta^*_1\}}. \tag{19}$$

When inefficiencies are (partially) tolerated, capacity outputs are lower and more vessels are needed within the industry. When no adjustment for technical inefficiency is accepted, then the correction factor simply equals zero ($\alpha = 0$). As the efficiency improvement imperative (α) moves away from unity, vessels are forced to move towards their maximal capacity. For instance, assuming that technical inefficiency in fisheries is at least partly due to heterogeneity in illegal landings, such a yardstick mechanism makes it more and more difficult to continue illegal activities, because otherwise the divergence between official landings and optimal outputs in the industry model may become too wide to remain unnoticed.

(vii) The equity of certain solutions may be questioned in that redundant vessels may well be concentrated in certain regions or even among specific small fishing communities (e.g. situated on remote islands). Equity concerns may be general in nature (e.g. related to the distribution of resources within a population) or specific in nature (e.g. related to the distribution of resources within certain subsets within the population). First, it is perfectly possible to account for general equity concerns in the distribution of specific inputs or outputs by imposing a certain inequality aversion in terms of a Gini-coefficient (Athanassopoulos, 1995; Golany and Tamir, 1995). Concerns about special equity can equally be accommodated by forcing certain subsets of the activity vector in the optimal solution (or by forcing them into the solution above certain minimal levels supposed to guarantee sufficient revenues). For instance, it is clear that official Danish fishery policies have been deeply influenced by the concern for the survival of smaller vessels in the fleet. This reflects specific distributional concerns for the weakest economic firms in the sector.

We model this desire to preserve the smaller vessels by forcing all vessels below a certain size into the optimal solution by defining a mutual exclusivity constraint over the subset of binary decision variables k_l representing the relevant number of vessels (L) within this category:

$$\sum_l k_{la} = L. \tag{20}$$

At this point, it is useful to summarise the industry model and its extensions developed so far. Starting off from the basic formulation of the industry model in equation (9) and the extensions developed in Sections 2.2 (equations (10)–(12)) and 2.3 (equations (13)–(20)), we end up with the following formulation of the short-run Johansen (1972) industry model suitable to analyse a wide variety of fishery policy options:

$$\min_{\theta, w, X_v, k} \theta$$

$$\text{s.t.} \sum_j \hat{u}^*_{jma} w_{ja} \geq U_{ma}, \quad m = 1, \ldots, M, \quad a = 1, \ldots, A \tag{21.1}$$

$$\sum_{j,a} x^*_{fj} w_{ja} \leq \theta X_{\text{f}}, \quad f = 1, \ldots, F \tag{21.2}$$

$$-X_{\text{v}} + \sum_{j,a} x^*_{vj} w_{ja} \leq 0, \quad v = 1, \ldots, V, \tag{21.3}$$

$$0 \leq w_{ja} \leq 1, \tag{21.4}$$

$$\sum_a U_{ma} \le \bar{U}_m, \tag{21.5}$$

$$U_{ma} \le \bar{U}_{ma}, \tag{21.6}$$

$$\sum_a x^*_{vja} w_{ja} \le \mathrm{FD}_{\max}, \quad v = 1, \tag{21.7}$$

$$\mathrm{LB} \cdot k_{ja} \le w_{ja} \le \mathrm{UB} \cdot k_{ja}, \tag{21.8}$$

$$\sum_j k_{ja} \le J, \tag{21.9}$$

$$\sum_a k_{ja} \le A, \tag{21.10}$$

$$w_{ja} = \cdots = w_{jA}, \tag{21.11}$$

$$\sum_{l'} k_{l'a} = L, \tag{21.12}$$

$$\theta \ge 0, k_{ja} \in \{0, 1\}, \hat{u}^*_{jma} = \frac{u^*_{jma}}{\max\{1, \alpha\theta^*_1\}}$$

$$j = 1, \ldots, J, \quad a = 1, \ldots, A.$$

It may well be possible that the combinations of certain constraint sets yield infeasible solutions of a logical or practical nature (e.g. when the total number of working days exceeds the civil year or a certain threshold deemed normal among fisheries specialists). Mathematical programming infeasibilities may also occur when some of the policy constraints cannot be satisfied simultaneously. This is part of a standard learning process when formulating coherent planning models using mathematical programming. It simply requires the judicious adjustment of some of the policy parameters until the feasibility of the mathematical programme is restored.[20]

3. Policy scenarios for fisheries: empirical illustrations

3.1. Policy scenarios: formulation and implementation

A major purpose of the paper is to test the implications of the various combinations of the extensions to the basic Dervaux *et al.* (2000) model in a fisheries context. Therefore, apart from the basic model, we define a series of scenarios

20 For instance, for some of the gear technologies with only a few observations, actually all observations must enter the solution when imposing the UB on the activity variable (equation (17)) to guarantee feasibility. Combined with very small catches of certain species in some areas (Baltic Sea and other area), this leads to infeasibility in the scenario where the activity vector is constrained to be less than 1.

Table 2. Description of scenarios in terms of the industry model

Scenarios	Constraints of formulation (21) involved
Basic scenario	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$)
Scenario 1	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.5)–(21.6): 90% of current outputs
Scenario 2	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 200$)
Scenario 3	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.8: LB = 0.3 and UB = 0.9)
Scenario 4	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.9: $0.90{\cdot}J$) and (21.10: $A \leq 3$)
Scenario 5	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.11)
Scenario 6	(21.1: $\alpha = 0.90$)–(21.4); (21.7: $FD_{max} = 275$)
Scenario 7	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.12: Baltic Sea vessels forced into the solution)
Policy Scenario 1	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 200$ for cod fishing vessels); (21.5) and (21.6): 80% of current cod outputs in North Sea and Skagerrak
Policy Scenario 2	(21.1: $\alpha = 0$)–(21.4); (21.7: $FD_{max} = 275$); (21.11) and (21.12): equal reduction over gear types

systematically testing the impact of some of the additional constraints to end up with a few policy-oriented scenarios combining several constraints at the same time and therefore having a flavour of realism. These scenarios are summarised in Table 2.

The basic scenario is the basic industry model defined over the various areas (constraints 21.1–21.4 and 21.7). Constraint (21.7) is included to secure solutions within a normal working year: to be precise, FD_{max} is fixed at 275 days. Scenario 1 considers the effect of lowering the catch quotas for all species (constraints 21.5–21.6) by 10 per cent. Scenario 2 imposes a seasonal closure policy (constraint 21.7). As an example, we implement a moderate general seasonal closure policy limiting the number of fishing days to 200 each year, which is about a 30 per cent reduction compared to the normal working year. Scenario 3 looks at the impact of LB and UB on the activity or intensity vector (constraint 21.8). The LB was set equal to 0.35, while the UB was fixed at 0.90.[21] Scenario 4 considers decommissioning schemes and reduction in the number of allowed areas (constraints 21.9–21.10). The total number of vessels was reduced by 10 per cent, while the number of allowed areas was set to 3. Scenario 5 looks at implementation issues by imposing equality of the activity vector over all areas (constraint 21.11). Scenario 6 allows for technical inefficiencies, but already imposes an improvement

21 A too tight UB can make the problem infeasible. In fact, since nearly all catches in the areas Baltic Sea and other are generated by just a few combinations, respectively, of purse-seiner vessels that are operating at full plant capacity, it is impossible to impose the UB on the activity vector for these vessels (i.e. their UB is 1). See also the final paragraph of Section 2.3.

imperative of 10 per cent (thus, $\alpha = 0.90$). Scenario 7 models the equity concern as expressed in terms of constraint (21.12) by considering a major issue in Denmark, namely the fleet fishing in the inner Danish waters (i.e. Baltic Sea area). This concern is expressed by forcing all binary variables corresponding to these vessels operating in the Baltic Sea to be unity.

Policy Scenario 1 explores the implications for fishing capacity of using a detailed regulation scheme to control fishing power or productivity in order to implement a lower TAC for an over-fished stock. This kind of approach is commonly used around the world (Sutinen, 1999). An extreme version of this approach can result in very short seasons with large fleet overcapacity (Homans and Wilen, 1999). Implementation of the lower TAC is often followed by a detailed regulation to control fishing power. An actual example is the cod fishery in the North Sea, where the EU has limited the number of fishing days per vessel in order to reduce fishing power and hence catches of cod. We analyse this kind of regulation scheme by reducing the TAC for cod in the North Sea and Skagerrak by 20 per cent and at the same time also reduce fishing days for vessels fishing cod to 200 per civil year.

Policy Scenario 2 focuses on measures aimed at reducing fleet capacity taking policy requirements into account. In many cases, different nations and different gear types are participating in the same fishery. Given the lack of well-defined institutions to handle this situation, substantial overcapacity is the result. Therefore, the reduction in fishing capacity often leads to an agreement where the reduction is uniformly distributed among the different fleets. Examples of this are the multi-annual guidance programme in the EU and the concerns of equity in the US fishery management councils. This scenario is applied in the model by requiring an equal reduction in the five different gear types.

3.2. Empirical results

The first step is to characterise the current situation by using the firm-level model. For each firm, capacity output is computed for all nine output categories. We only report aggregate results, even though the models generate optimal capacity outputs, variable and fixed inputs (see expression (7)) for each and every individual vessel that could be used for planning purposes.

Table 3 shows the excess capacity as a percentage of the current total production of each output. At full capacity production of each vessel, the total production of each species could be increased between 25 and 67 per cent. When looking at the aggregated use of fixed inputs at vessel capacity the results show that the inefficiencies are mainly found among vessels fishing in the Baltic Sea. The use of crew and the number of fishing days are reduced slightly compared to actual crew utilisation for combination and purse-seiners, while trawlers, Danish seiners and gillnetters increase their use.[22]

Turning from the analysis of firm-level capacity to the short-run Johansen industry model, results for the basic scenarios as well as the policy scenarios

22 These results are available from the authors on request.

Table 3. Aggregated vessel excess capacity (%)

	Areas					Total
	North Sea	Baltic Sea	Kattegat	Skagerrak	Other	
Cod	24	52	38	39	0	38
Other roundfish	24	90	55	36	0	30
Plaice	28	49	33	23	0	27
Sole	43	0	63	33	0	47
Pelagic	24	30	32	37	9	24
Lobster	20	0	47	38	0	36
Shrimp	16	120	41	15	0	59
Other fish	40	68	40	32	0	67
Industrial	26	4	34	24	19	25

Note: Excess capacity is the difference between aggregate vessel capacity and current total catches as per cent of current total catches.

are listed in Tables 4 and 5. Two initial remarks are in order. First, the industry model generates optimal activity vectors defining the optimal outputs, variable and fixed inputs for all vessels individually. This detailed information is not reported here, but clearly has enormous potential when utilising these models for planning purposes. Since the model accounts for technological heterogeneity (distinguishing between vessel types and gear types), a wealth of information is available. For instance, one can imagine that some fishing days of purse-seiners have effectively been transferred to trawlers operating in another area.

Second, the basic scenario is just a point of reference. Strictly speaking, since all vessels in the sample are subject to the same Danish and European regulations, optimisation models based on 'regulated' data can never represent a regulation-free situation. Rather, the basic scenario indicates the optimum that could be obtained starting from the current situation (including the regulatory mix) if the industry could be geared towards minimising its fixed inputs given its current outputs and firm-level capacities. The first six scenarios show the effect of relying solely on one type of policy instrument rather than another when optimising the industry starting from the current situation. The interpretation of the results from the policy scenarios is subject to the same remark.

Table 4 reports the aggregate efficiency measure, which indicates the potential reduction in fixed input use, the number of non-zero activity variables (i.e. the vessels figuring in the optimal solution) and their average value for the total fleet and the five areas. The basic scenario reduces the use of fixed inputs by 36 per cent, leading to a reduction in the number of active vessels by 19 per cent. Since the efficiency measure represents industry fixed costs, it is possible to interpret the alternative scenarios in terms of opportunity costs relative to the basic scenario.

Imposing additional quotas (Scenario 1) further reduces the use of the total available fixed inputs (the efficiency measure is 0.55 compared to 0.64 in the basic scenario) and the total reduction in the number of active vessels is

Table 4. Industry model scenarios: efficiency measure and activity vectors (total and per area)

Scenarios	All areas Efficiency Number of non-0 w_{ja} Mean w_{ja}	Skagerrak Number of non-0 w_{ja} Mean w_{ja}	Kattegat Number of non-0 w_{ja} Mean w_{ja}	Baltic Sea Number of non-0 w_{ja} Mean w_{ja}	North Sea Number of non-0 w_{ja} Mean w_{ja}	Other Number of non-0 w_{ja} Mean w_{ja}
Actual number of vessels	1,805	489	315	398	555	48
Basic scenario	0.64					
	1,459	404	244	282	488	41
	0.796	0.815	0.754	0.700	0.867	0.849
Scenario 1	0.55					
	1,361	386	229	256	451	39
	0.744	0.776	0.708	0.639	0.805	0.789
Scenario 2	0.648					
	1,511	422	245	305	498	41
	0.790	0.817	0.746	0.687	0.860	0.845
Scenario 3	0.67					
	1,556	433	261	301	516	45
	0.763	0.782	0.729	0.676	0.826	0.813
Scenario 4	0.65					
	1,436	404	231	278	482	41
	0.796	0.826	0.733	0.698	0.868	0.854
Scenario 5	0.68					
	1,465	419	244	288	471	43
	0.788	0.826	0.758	0.710	0.820	0.873

(*continued on next page*)

Table 4. (*continued*)

Scenarios	All areas Efficiency Number of non-0 w_{ja} Mean w_{ja}	Skagerrak Number of non-0 w_{ja} Mean w_{ja}	Kattegat Number of non-0 w_{ja} Mean w_{ja}	Baltic Sea Number of non-0 w_{ja} Mean w_{ja}	North Sea Number of non-0 w_{ja} Mean w_{ja}	Other Number of non-0 w_{ja} Mean w_{ja}
Scenario 6	0.79					
	1,521	428	233	316	500	45
	0.843	0.874	0.739	0.795	0.900	0.930
Scenario 7	0.72					
	1,551	404	236	398	471	42
	0.859	0.826	0.749	1.0	0.849	0.875
Policy	0.644					
Scenario 1	1,400	405	230	272	451	41
	0.776	0.829	0.732	0.684	0.813	0.845
Policy	0.847					
Scenario 2	1,346	381	212	261	450	42
	0.731	0.756	0.658	0.651	0.799	0.854

Table 5. Number of vessels, fixed input and fishing days per vessel for each vessel type

	Gillnetters	Trawlers	Danish seiners	Combination	Purse-seiners
Current situation					
Number of vessels	272	1,224	184	92	33
Tonnage	28	130	41	31	800
HP	173	398	175	160	1,484
Fishing days	87	82	75	74	39
Basic scenario					
Number of vessels	201	992	167	52	24
Tonnage	22	105	34	18	696
HP	143	318	148	144	1,442
Fishing days	89	79	81	60	40
Policy Scenario 1					
Number of vessels	178	982	164	52	24
Tonnage	22	107	34	20	694
HP	144	326	152	147	1,443
Fishing days	84	81	82	60	39
Policy Scenario 2					
Number of vessels	194	891	118	65	21
Tonnage	27	122	36	28	762
HP	164	364	152	157	1,468
Fishing days	90	88	85	70	43

25 per cent. A seasonal closure policy (Scenario 2) yields an efficiency measure of 0.65 and reduces the number of active vessels by about 17 per cent, which is less than the basic scenario. Imposing LB and UB on the activity variables to guarantee economic viability (Scenario 3) yields only a slightly higher efficiency measure (0.67), but not surprisingly, a significantly higher proportion of vessels remain active in the fleet (86 compared to 81 per cent), although these vessels operate on average at a slightly lower activity level. Decommissioning 10 per cent of the current fleet and limiting access to three areas of choice (Scenario 4) generates an efficiency measure of about 0.65 and reduces the number of active vessels by 20 per cent. Scenario 5 shows that the cost of imposing equality between activity variables over all areas is rather low, both in terms of the increase in the efficiency measure and the number of active vessels. Allowing for partial technical inefficiency (Scenario 6) reduces the number of active vessels by only 16 per cent, with a relatively low reduction in use of fixed inputs. Respecting equity concerns (expressed in terms of keeping the Baltic fleet active) (Scenario 7) involves a greater reduction in fixed inputs than partially tolerating inefficiency, but a smaller reduction in the number of vessels.

Compared to the basic scenario, the main difference in Policy Scenario 1 is the larger reduction in the number of gillnetters fishing in the North Sea area, while for Skagerrak there is a small reduction in the number of trawlers.

However, the impact on the fleets in the other areas is minimal, meaning that the spillover effect to other fisheries in terms of the optimal industry capacity is small. Policy Scenario 2 (equal reduction in gear types) results in fewer vessels than the basic scenario, although the average size of the vessels is larger in terms of tonnage and HP.

From a policy viewpoint, it is important to assess these different scenarios also in terms of their impact on the fleet structure. Table 5 shows the fleet structure in terms of the number of vessels, the per vessel use of fishing days and the average size in terms of tonnage and HP over the different gear types.[23] To gain focus, the basic scenario and the two policy scenarios are compared to the current situation. The total number of vessels that remain active in the three scenarios varies between 1,346 and 1,459 vessels out of a total number of 1,805 current vessels. However, while the optimal size of the fleet remains rather stable, the fleet structure is not the same in the three scenarios.

In general, for all gear types, the average vessel size declines in the basic and first policy scenarios relative to current levels. In Policy Scenario 2, average vessel size is also slightly lower, but it is close to the current level. However, compared with the basic scenario, Policy Scenario 2 involves larger vessels and more fishing days, whereas the number of vessels is lower. The largest relative overcapacities are found in the fleets of combination vessels and gillnetters. As expected, the basic scenario allows for the largest reduction in the use of fixed inputs, while the more refined scenarios yield slightly less drastic results.

In short, focusing on reducing the total use of fixed inputs leaves space for more smaller-sized vessels (basic scenario and Policy Scenario 1), while the number of larger vessels less reduced by an equal reduction over gear types (Policy Scenario 2). Thus, the resulting fleet structure depends very much on the choice of policy instruments. The basic reason for the differences in resulting fleet structures lies in the constraints on gear types that restrict the reallocation of catches and inputs between vessels at the industry level.

The robustness of the solution was tested with respect to changes in the level of TACs. For the main species (cod), the TAC was reduced by 10 per cent. The results are very robust in the sense that the resulting fleet structure does not change very much or that the changes are as can be expected. For example, for cod in the North Sea, the changes in the number of vessels are situated among gillnetters, which are the vessels most intensively fishing for cod (in accordance with the results from Scenario 1).

4. Conclusions

The assessment of industry capacity in fishing and its relation to the productivity of the fish stock has been a major policy issue in recent decades due to widespread overfishing and excessive use of economic resources. In many cases, the pressure on the biomass is so high that maintaining current

23 Detailed results for areas are available on request.

policies is not sustainable in the longer run. Therefore, new policy tools are needed to formulate and implement more drastic policies aimed at constraining industry capacities in relation to sustainable fish stocks.

Non-parametric deterministic frontier technologies can be used to estimate the industry capacity starting from a firm-level plant capacity notion. These firm-level capacities are used as parameters in a short-run industry model (Johansen, 1972) to determine an ideal industry configuration while minimising fixed input use. Using a sub-vector radial input efficiency measure that has a fixed-cost interpretation at the industry level allows comparison of the basic scenario with more elaborate policy scenarios adopting a mixture of instruments: the impact of these alternatives shows up in terms of possible fixed-cost reductions foregone. The short-run Johansen industry model provides an important framework for evaluating regulatory policies for common-pool resource industries, where one of the primary policy issues is excess capacity due to the associated economic waste of fixed and variable inputs and to the resulting exploitation pressures on resource stocks (which are typically overfished). The short-run Johansen (1972) industry model extends the firm-level Johansen (1968) model of plant capacity (which is used by FAO and others). Its flexibility in breaking down aggregated output and aggregated input into multiple outputs and multiple variable and fixed inputs offers the detailed information and policy flexibility not otherwise provided by traditional approaches to analysing industries that exploit common-pool resource stocks.

An empirical application to the Danish fleet shows that vessel numbers can be reduced by 14–25 per cent and the use of fixed inputs by 15–45 per cent, depending on the specific objective and policy mix. The method also generates information on the resulting fleet structure. Hence, the planner can target a fleet-reduction programme towards the relevant vessels groups or assess the impact of alternative policy mixes on the fleet structure, which more aggregated models do not allow.

Fleet-reduction programmes are often designed in such a way that participation by fishermen is voluntary. Therefore, general fleet-reduction programmes often run the risk that the wrong fishermen (read: vessels) leave the fleet. The industry model is a planning tool to determine the unnecessary vessels within an ideal industry configuration and the implementation of fleet-reduction programmes can be targeted towards those parts of the fleet identified as redundant. Indeed, the main advantage of this industry model from a policy viewpoint is that information about the optimal fleet structure follows from the optimisation exercise.

To provide even more solid recommendations, it could be useful to compute the model on data for several years. Indeed, the model could be applied either on a year-by-year basis or on average data computed over a certain time period. This approach would reduce the impact of special features arising in a given year on the optimal fleet structure. Once they are well established and validated, these kinds of models can be easily updated when new data become available. Consequently, any capacity reduction policies could be adjusted when needed as a result of these revisions.

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