Adapting the Short-Run Johansen Industry Model for Common-Pool Resources: Planning the Danish Fisheries' Industrial Capacity to Curb Overfishing

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Abstract

The level of capacity in a common-pool industry vis-à-vis a sustainable target level of yield simultaneously indicates the economic state of the industry, the success of its regulation, and the pressure on stocks. The main methods to assess capacity and its utilisation operate at the firm level, but neglect the industry capacity. In this contribution, the Johansen-Färe measure of plant capacity of the firm enters a multi-output and frontier-based version of the short-run Johansen industry model. This model decides on the utilisation of firm capacities such that current industry outputs are maintained while minimising the use of fixed inputs at the industry level and assuming abundant variable inputs. We also provide policy extensions relevant to combat overfishing: tightening quotas; seasonal closures; linking economic and plant capacity; decommissioning schemes and area closures; implementation issues and equity considerations; among others. The empirical results show that there is substantial overcapacity at the level of the Danish fleet, while the resulting fleet structure depends on the precise policy objective and the chosen mix of instruments.

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1. Introduction

The growth of fishing capacity and its biological twin of overfishing are two of the most pressing problems facing many fisheries around the world. Excess capacity develops when an excessive number of vessels enter the fishery and these vessels and their variable inputs are excessively employed to exploit the available fish stocks beyond a sustainable target level of yield. 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.

The level of capacity in a common-pool resource industry is important, because the development of capacity over time vis-à-vis a sustainable target yield indicates the economic state of the industry. Furthermore, the development of capacity indicates 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 excessive utilization of variable inputs, and puts additional pressure on the resource stocks. Management of capacity is often both an instrument and a goal for the regulation of fisheries.

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 sustainable fishing stocks. Indeed, subsidies to build and decommission vessels, tax deductions for investments in fixed inputs and the like actually encourage investments 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-property 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 effectively transformed much of the world's fisheries into an almost centrally planned sector. This paper takes no side in this debate on the optimal mix of policy

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[1] Overviews of the wide range of policy measures that 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 (CDQs), ITQs, and Pigouvian taxes- and their relative merits and failures are found in Merrifield (1999), Squires, Kirkley and Tisdell (1995), Sutinen (1999), and Townsend (1990), among others.

instruments, but simply intends to offer a coherent framework to formulate and refine most of the currently used command-and-control policy instruments.

In recent years, several international organisations have prepared policy plans to respond to this overcapacity crisis and its devastating consequences on fishing stocks. For instance, in the European Union (EU), the Multi Annual Guidance Programme provides figures for reduction in capacity that each state should impose within a given time span (COM (2002) 446 final). The Food and Agriculture Organization (FAO) has formulated an International Plan of Action where each state is bound to come up with a figure for the capacity of its fishing fleet and a plan for dealing with the capacity development (FAO (1999)). Finally, the National Marine Fisheries Service (NMFS) in the USA has developed a program to measure, monitor, and reduce overcapacity in a number of its most important fisheries (NMFS (2002)).

Many studies in the past have been carried out on capacity and capacity utilisation in fishing industries. However, this literature did not demonstrate a uniform and consistent use of capacity concepts (see Kirkley and Squires (1999) for an overview). Recently, several initiatives have contributed to the clarification of issues and led to a coherent framework for analysing the capacity concept. This process (FAO (1999), NMFS (2002)) has so far resulted in several background papers, case studies and articles in which different methods have been applied to the fishing industry (e.g., Dupont et al. (2002), Kirkley et al. (2001), Kirkley, Morrison Paul and Squires (2002), Walden, Kirkley and Kitts (2003)). However, 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) and Tingley and Pascoe (2003) that employ a basic version of the same modelling approach adopted here. One of the primary reasons is that the main methods to assess capacity and capacity utilisation operate at the level of the decision-making unit --usually the vessel. Hence, the issue of industry capacity, which is actually far more important from a policy viewpoint, is not addressed at all by these methods.[2]

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[2] This is not totally correct, since the so-called "peak-to-peak" method also addresses the industry capacity. But, the method is rather ad hoc and therefore unreliable (Christiano (1981)). There are also a number of studies using a linear programming approach to determine overall expected catch and the allocation of this catch over different fleets. Stiegel, Mueller and Rothschild (1979) are an early contribution 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.

The short-run Johansen (1972) sector model allows analysing the industry structure resulting from underlying ex-post firm level production structures. In this approach, investment decisions imply a putty-clay production structure: while ex-ante firms may choose from a catalogue of production options exhibiting smooth substitution possibilities, ex post most face fixed coefficients 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. Historically, this short-run sector model has mainly if not exclusively been applied to various industries. Examples include Hildenbrand's (1981) study of the Norwegian tanker fleet and the U.S. electric power generating industry, the analysis by Førsund and Hjalmarsson (1983) of the Swedish cement industry, and of the same authors and Summa (1996) on the Finnish brewery industry, the empirical chapters in the Førsund and Hjalmarsson (1987) book, among others. In any case, as far as we are aware of, this model has never been applied to a common-pool resource industry.

This paper combines the capacity at the individual and industry levels using a frontier-based version of the short-run Johansen (1972) sector model, a methodological refinement developed in Dervaux, Kerstens and Leleu (2000). The latter authors transformed the original short-run industry model (Johansen (1972)) in two ways: (i) the single-output model was transformed into a multiple-output model, and (ii) the ad hoc estimation of production capacities was replaced by a frontier based estimation method compatible with the Johansen (1968) notion of plant capacity. The alleviation of the single output restriction enlarges the scope of applications beyond traditional industry studies (see above). The frontier nature of firm level production capacities and the short-run industry model allows for a benchmarking perspective when adopting it for social planning purposes (e.g., yardstick competition à la Schleifer (1985)).

This revised short-run Johansen (1972) model basically proceeds in two phases. In a first step, it uses the Johansen-Färe measure of capacity at the individual level to determine capacity production for each firm at the production frontier. Second, this individual firm-level frontier capacity information is employed in the industry model to select the optimal level of activity of firm capacities with the objective of minimising fixed inputs at the industry level given the current total output level and firm-level capacities and conditional upon the current state of the technology. The capacity measure employed in the model is a short-run measure, since it assumes no change in the existing firm-level capacity, and is a technical instead of an economic capacity notion.

The short-run Johansen (1972) sector model has economic relevance for both positive and normative purposes: (i) in a positive way to simulate industry outcomes under decentralised decision-making, or (ii) in normative way to plan the industry in the most efficient way (Førsund and Hjalmarsson (1987: page 141)). This paper explores the normative use of these models to formulate policies that combat overfishing and overcapacity. One of its advantages for developing fishery policies is that it is solely based on input and output information and seeks to optimise production at the industry level given existing capacity and no input or output prices enter into the model. 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 size classes, multi-species production or quotas, and variable input usage.

This paper is the first attempt to extend Johansen's (1972) industry model in such a way that it can be usefully applied to natural resource industries for policy purposes. This modelling approach extends the current focus of policy makers in fisheries on short-run firm-based capacity analysis (see supra) 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 currently conditional upon the current state of the resource stocks and the states of the environment,[3] 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, such as bio-mass targets translated into quotas and equity concerns. The aggregated approach maintained in

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[3] 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 services prices (see Lau (1976)).

traditional natural resource models are important for providing long-term solutions in steady-state, but do not provide the flexible information to tackle heterogeneity in firms, areas, and species confronted by regulators in practice.

To this end, we add some further refinements to the short-run Johansen industry model of Dervaux, Kerstens and Leleu (2000) to analyse policy options in fisheries based solely upon primal information.[4] First, we look at the effects of tightening quota on certain species and within certain fishing areas. Second, seasonal closure policies put limits on the number of fishing days in an effort to control inputs. Third, lower and upper bounds are introduced on the activity vectors to avoid on the one hand economically unviable solutions (lower bound) and on the other hand production at technical capacity levels that are far beyond economic capacity levels (upper bound). This attempt indirectly includes economic information into an otherwise technical production model. Fourth, 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. to protect endangered species such as turtles. Fifth, implementation issues may well 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. Sixth, 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 these completely, although imposing some production discipline via a yardstick benchmarking process may well prove desirable from a normative viewpoint (Andersen and Bogetoft

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[4] Another attempt to tackle environmental and resource economic issues using an industry model based upon price information is the Brännlund et al (1998) article assessing the effect of emission trading on the short-run industry profitability of Swedish paper and pulp industry. Also Färe, Grosskopf and Li (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 maximize aggregate output. In this range of models, the inputs are either constrained at the industry (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.

(2003)). For instance, assuming that technical inefficiency in fisheries is at least partly due to heterogeneity in illegal landings, such a yardstick mechanism could have a favourable effect in terms of making illegal landings more and more difficult given the imposed outputs resulting from an optimal industry model. Finally, we experiment with constraints reflecting concerns of specific equity. Specifically, we look at the impact of privileging the survival of small vessels in the industry.

The purpose of these extensions is to develop a version of the short-run Johansen industry model relevant to developing fishery policies. To illustrate its potential, these refined models are 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 a common-pool resource and it is the first large-scale extension of the model making it suitable for analysing a realistic mixture of environmental policies.[5] The empirical results for the Danish case show substantial overcapacity at the fleet level. The total use of fixed inputs in the industry can be reduced between 15% and 45%, depending on the specific objective and the choice of instruments, while the number of vessels can be reduced by around 14% to 25%. While the reduction in the number of vessels may not seem to vary spectacularly between these various scenarios, the resulting fleet structure is decidedly different.

The paper is organized as follows. In section 2 the empirical methodology, in particular the use of capacity models and the construction of the short-run Johansen (1972) industry model, is developed and special modelling issues related to the fisheries context are discussed along with the presentation of the sample. Section 3 presents the various policy scenarios and presents the empirical results. Section 4 ends with the main conclusions and some suggestions for further work.

2. Firm and Industry Capacity Models: Empirical Methodology

2.1. Basic Firm and Industry Models

Johansen's (1968) notion of plant capacity perfectly adheres to the technical or engineering concept of capacity. He 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. Capacity arises due to fixity of one or more inputs, and is thereby inherently a short-run rather than a

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[5] Färe et al (2001) outline some basic extensions to the Dervaux, Kerstens and Leleu (2000) model, but their empirical application is based on a very small sample of US vessels. Tingley and Pascoe (2003) apply the same industry model to compute the socio-economic impacts of somewhat evolved six scenarios on the Scottish fleet.

long-run concept. Building on this work of Johansen (1968), Färe (1984) formally showed the existence of plant capacity for certain types of production functions. Färe, Grosskopf and Kokkelenberg (1989) made the concept operational by making firm level capacity levels easy to calculate using non-parametric frontier approximations of technology.[6] The approach assumes that firms cannot exceed their use of the fixed factors, but that their use of variable factors is not constrained. Again, a best practice technology is constructed and the current output of each firm is evaluated against the maximum potential output at full capacity utilization, 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 the overcapacity of the industry.

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 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 the fish stocks from overexploitation, constraints are implemented on the activities of the firms, i.e., the sector is regulated with the purpose to sustain the fish stock biomass above a certain critical level, such as by Total Allowable Catch (TAC). Following the approach by Dervaux, Kerstens and Leleu (2000), the optimal industry configuration is found by minimizing 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 upon estimating output-oriented efficiency measures relative to non-parametric, deterministic production frontiers (see Färe, Grosskopf and Lovell (1994)). These efficiency measures are extremum estimators that allow determining the best-practice among production units. These best-

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[6] 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, stochastic frontier functions. For example, Kirkley, Morrison Paul and Squires (2002) review and empirically apply both nonparametric and parametric stochastic frontier functions to evaluate fishing capacity (or Johansen's notion of plant capacity).

practice units are piecewise linearly enveloped to constitute a frontier or reference technology, an inner bound approximation to the true but unknown technology.

To develop the production model formally, the production technology S transforms inputs $x=(x_1,...,x_n)\in R_+^n$ into outputs $u=(u_1,...,u_m)\in R_+^m$ and summarises the set of all feasible input and output vectors: $S=\{(x,y)\in R_+^{n+m}:\ x \text{ can produce } y\}$. 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 capacity utilization (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 (see Färe, Grosskopf and Lovell (1994) or Grosskopf (1986) for details):

$$S^{VRS}=\left\{(x,u)\in R_+^{N+M}:u_{km}\le\sum_{j=1}^{J}z_j u_{jm},\quad m=1,...,M;\right.$$
$$\left.\sum_{j=1}^{J}z_j x_{jn}\le x_{jn},\quad n=1,...,N;\sum_{j=1}^{J}z_j=1,\quad z_j\ge 0,\quad j=1,...,J\right\}. \tag{1}$$

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 or frontier by forming convex combinations of observations forming the best-practice frontier. A short-run version of this same production possibilities set is simply 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:

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

Both of these 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:

$$\max\left\{ \theta_1^j : (x, \theta_1^j u) \in \hat{S}^{VRS} \right\}. \tag{3}$$

To remain consistent with the plant capacity definition of Johansen, in which only the fixed inputs are bounded at their observed level, the variable inputs in the production frontier model are allowed to vary and be fully utilized. 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 m^{th} output is θ_1^{*k} multiplied by actual production u_{km}.[7] Hence capacity utilization based on observed output (hence oo) is:

$$CU_{oo}^{k} = \frac{1}{\theta_1^{*k}}. \tag{4}$$

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.[8]

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

$$\max\left\{ \theta_2^j : (x, \theta_1^j u) \in S^{VRS} \right\}. \tag{5}$$

The technically efficient output vector is θ_2^{*k} multiplied by observed production for each output. Total industry output can simply be found by aggregating the technically efficient output production $\theta_2^{*k} u_k$ of each firm. 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 (hence eo) or unbiased ray measure of capacity utilization is then:

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[7] Note that optimal solutions for decision variables from optimisation problems are denoted by a star (*).

[8] 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 (see Fare *et. al.* (1994)).

$$CU_{eo}^{k} = \frac{\theta_2^{*k}}{\theta_1^{*k}}. \tag{6}$$

The focus is on reallocation of production between vessels by explicitly allowing improvements in technical efficiency and capacity utilization 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:

$$u_{km}^{*} = \sum_{j} z_j^{*k} u_{jm}; \quad x_{kf}^{*} = \sum_{j} z_j^{*k} x_{fj}; \quad x_{kv}^{*} = \sum_{j} z_j^{*k} x_{vj}. \tag{7}$$

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 minimizes 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 both at the firm and 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.:

$$U_m = \sum_{j} u_{jm}, \; X_f = \sum_{j} x_{fj} \text{ and } X_v = \sum_{j} x_{vj}. \tag{8}$$

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

$$\begin{aligned}
&\min_{\theta, z, X_v} \theta \\
\text{s.t.} \quad & \sum_{j} u_{jm}^{*} z_j \geq U_m, && m = 1,..,M, \\
& \sum_{j} x_{fj}^{*} z_j \leq \theta\, X_f, && f = 1,...,F, \\
& -X_v + \sum_{j} x_{vj}^{*} z_j \leq 0, && v = 1,...,V, \\
& 0 \leq z_j \leq 1, \theta \geq 0, && j = 1,...,J.
\end{aligned} \tag{9}$$

Now the *z* variables show which firms, and consequently by how much, the capacity shall be utilized. In the short-run Johansen (1972) industry model, the components of the activity vector *z* are bound above by unity, so that current capacities can never be exceeded. The first constraint secures that the total production by a combination of firm capacities is higher or equal to the current level. In the second constraint, the total use of fixed inputs (right hand side) is higher than the use by a combination of firms. The third constraint calculates the resulting total use of variable inputs. Notice 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.[9]

Geometrically, the short-run industry model is a set consisting of a finite sum of line segments (known as a zonotope (Hildenbrand (1981: 1096)). The activity vector *z* indicates which portions of the line segments representing the firm capacities are effectively used to produce outputs from given inputs. To sum up, 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: Adaptations to the Danish Fisheries Context

These firm and industry models require some adjustments to be applicable to the multiproduct Danish fleet. We therefore first present a description of the sample. Then, we discuss the adjustments necessary to account for specific fisheries and managerial issues.

The sample data set consists of observations for the year 1998 of multiple outputs of different fish species (catches in kilo), two variable inputs (labour and fishing days), and two fixed inputs (gross registered tonnes (Grt.) and horse power (hp)) for individual vessels. These data are available for each of the 5 fishing areas. This data set covers in reality about 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 1805 observations, i.e. on average each vessel fishes in about 2 areas. Descriptive statistics for the fixed and variable inputs are reported in Table 1. The main gear type is trawlers. While trawlers and combination vessels vary in size, Danish seiners, purse-seiners and gillnetters are more uniform in size. The fixed inputs were subsequently transformed into flow variables by multiplying them by the number of fishing days.

The use of the variable input crew differs only between purse-seiners and other vessels. Purse-seiners use, on average, 11 crewmembers, while the other vessels use between 2 and 4 crewmembers

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[9] Note that we disregard any difficult questions about the 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, Dervaux and Leleu (2003), for instance, have begun to tackle some of these issues.

on average. The number of fishing days in an area indicates the importance of the area for the firm. Trawlers, gillnetters and Danish seiners have, on average, the North Sea as their most important catch area, while purse-seiners have other waters, and combination vessels have the Baltic Sea as their prime fishing destinations.

<TABLE 1 ABOUT HERE>

Finally, total catch per species and area is used as the basic output in the model. Table 2 reports the total catches of each species in each area. 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;[10] while the rest of the species have been aggregated together into three combined outputs using the Divisia index (these groups are: other roundfish, pelagic and other fish).

<TABLE 2 ABOUT HERE>

This aggregation of outputs is partly necessary to escape the curse of dimensionality that is inherent to nonparametric methodologies. Intuitively stated, it is clear that at the completely disaggregated level the analysis would detect little inefficiencies (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 test procedure available telling how exactly to reduce the number of outputs and inputs.

Since the catch of some of species in certain areas is very small and therefore of no importance to the fishermen (i.e., pure by-catch), we decided to set the current total catch of these species to zero. This implies that the output constraints of these species do not have an impact on the scenarios. The concerned species are (i) cod, other roundfish and other fish in the Other areas and (ii) sole and lobster in the Baltic Sea area.

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, i.e., 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 of

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[10] The species are cod, plaice, sole, lobster, shrimp and the group of industrial species.

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.

Second, the models have to deal with the fact that vessels are fishing in different 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.[11]

Third, another modification to the basic model comes from the fact that different gear technologies are applied. Each vessel uses a specific gear type, so that the set of vessels can be partitioned into different gear types. 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 second and third modifications imply that the individual firm-level models (1) and (2) are applied for a given area and a given gear type. This means that the efficiency of each vessel is evaluated relative to one of the potentially 25 different technologies (5 areas times 5 gear types). However, since not all gear-types are present in all areas, there are only 20 technologies. Some of these technologies consist of only a few similar observations, which may potentially lead to biases in the estimation of firm plant capacity due to lack of comparable production units. The capacity outputs and inputs (see 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 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:

$$\sum_j u^*_{jma} z_{ja} \geq U_{ma}, \qquad m = 1,..,M, \quad a = 1,..,A \tag{10}$$

where a is an index for area.

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[11] The idea of geographically specific technologies is also found in Dervaux, Kerstens and Leleu (2000).

Second, the industry consists of vessels fishing in different areas. According to the above 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:

$$\sum_{j,a} x^*_{fja} z_{ja} \leq \theta\, X_f, \qquad f = 1,\ldots,F, \tag{11}$$

Third, the constraints on the variable inputs are:

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

Remembering that the amount 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 type of practical impossibility can be avoided by adding 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

The short-run industry model can be easily extended to accommodate various policy concerns. We briefly focus on seven issues: the first concerns the tightening of quotas at either the species level, or at the area level; the second concerns seasonal closures putting limits on fishing days; the third involves the link between economic and plant capacity; the fourth is connected with modelling decommissioning schemes and area closures; the fifth concerns implementation issues due to monitoring problems; the sixth deals with partially tolerating technical inefficiencies; and the final one is related to equity considerations.

First, while current industry outputs may well reflect prevailing quotas, it is straightforward to compute the impact of tightening these quotas at: either 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:

$$\sum_{a} U_{ma} \leq \overline{U}_m, \qquad m = 1,..,M \tag{13}$$

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

$$U_{ma} \leq \overline{U}_{ma}, \qquad m = 1,..,M, \quad a = 1,..,A \tag{14}$$

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

Second, to constrain working time within normal limits we impose the additional constraint that firms can only harvest a total number of fishing days less than the number available in a normal fishing year. Normally, 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. But, constraining working time may also be part of seasonal closure policies that aim at controlling 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 yearly number of fishing days at $FD_{\max}$ common to all vessels. This can be simply represented as follows:

$$\sum_{a} x^{*}_{jva} z_{ja} \le FD_{\max}, \qquad j = 1,\ldots,J, \quad v = 1, \tag{15}$$

given that the fishing days are indexed by v equal to 1 (i.e., the first variable input). 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 contribution.

Third, 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 (e.g., Morrison (1985), Nelson (1989)). Depending on the exact economic capacity notion adopted, economic capacity outputs are situated below plant capacity outputs. 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 to produce below full plant capacity.

These considerations may lead to formulating both lower and upper bounds on the activity or intensity vector (z_{ja}). To start with the upper bound (*UB*), if one would like to avoid imposing production at plant capacity outputs well beyond economic capacity levels, it is straightforward to implement upper bound constraints on the activity levels. Assume it could be established that for the average vessel economic capacity would be situated at about 85% of plant capacity, then it would suffice to add the following constraint to the industry model: $z_{ja} \le 0.85.$ To continue with the lower bound (*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 (z_{ja}). This could imply maintaining vessels in operation for such a small production that it cannot be economically viable (for instance, because fixed cost cannot be covered). Assuming that for the average vessel economic viability requires it to be used for at least about 35% of its plant capacity, then one can add the following constraint to the industry model: $0.35 \leq z_{ja}$. However, this would force all vessels to be used at this lower bound at the optimum.

Assuming the purpose is to impose the lower and upper bound 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 (z_{ja}). This allows defining a set of weak mutual exclusivity constraints: (i) any number of vessels (J) can enter into the optimal solution and (ii) each vessel can fish in any of the areas (A); or formally:

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

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:

$$LB \cdot k_{ja} \leq z_{ja} \leq UB \cdot k_{ja}, \qquad \forall j \text{ and } a. \tag{17}$$

In this way, when k_{ja}=0 then also z_{ja}=0, and when k_{ja}=1 then z_{ja} can take any value within the interval defined by the lower (LB) and upper bounds (UB).

Fourth, notice that the above weak mutual exclusivity constraints (16) have initially no bite, but they can be easily turned into policy tools by directly constraining the maximum number of vessels or areas that can enter into an optimal solution. The first constraint can be meaningful as a tool to implement a decommissioning scheme. For instance, one could easily compute the impact of decommissioning 10% of the current fleet by fixing the right-hand side to 90% times J (e.g, $\sum_j k_{ja} \leq 0.9 \cdot J$). 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 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.

For an example of an area closure policy, assume that 2 of the 5 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 3), without forbidding access to any specific area.

Fifth, the fact that the basic industry model distinguishes between vessels operating in several areas may cause quite some difficulties when implementing the planning solution. To avoid deviations from the model solutions, it may be required to set up extensive control operations at the level of the individual vessels. Monitoring individual fishing trips within each area may well prove costly and such policy probably leads to an imperfectly monitored solution at best. Therefore, it may be wise to impose that a vessel should be used identically within all areas to simplify the monitoring process:

$$z_{j1} = \ldots = z_{j5}\,. \qquad (18)$$

Thus, this constraint makes the industry model focus on vessels instead of trips to particular areas.

Sixth, when it is impossible to push vessels immediately to technical efficiency, it may well be useful to allow for a correction of capacity outputs for (partial) technical inefficiencies. In the spirit of Andersen and Bogetoft (2003), this is straightforwardly modelled by adjusting the technically efficient capacity output downwards. Since from a normative economics point of view 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 adjust 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:

$$\hat{u}^*_{jma} = u^*_{jma} \big/ \max\left\{1, \alpha\theta^*_1\right\}. \qquad (19)$$

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 (α=0). As the efficiency improvement imperative (α) moves away from unity, vessels are forced to produce more and more technically efficient and thus close to their maximal capacity. When vessels are engaged in illegal landings, they will have more and more difficulty to continue these illegal activities because otherwise the divergence between their official landings and their optimal outputs in the industry model may become too wide to remain unnoticed.

Finally, 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 (see Athanassopoulos (1995) or Golany and Tamir (1995) for details). 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 therefore model this desire to preserve the smaller vessels by forcing all vessels below a certain size into the optimal solution. This can be simply achieved 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:

$$\sum_l k_{la} = L. \qquad (20)$$

At this point, it is useful to summarise the industry model and its extensions developed so far:

$$
\begin{aligned}
& \min_{\theta, z, X_v, k} \theta \\
s.t. \quad & \sum_j \hat{u}^*_{jma} z_{ja} \geq U_{ma}, \quad m = 1,..,M, \quad a = 1,..,A && (21.1) \\
& \sum_{j,a} x^*_{fj} z_{ja} \leq \theta \, X_f, \quad f = 1,...,F && (21.2) \\
& -X_v + \sum_{j,a} x^*_{vj} z_{ja} \leq 0, \quad v = 1,...,V, && (21.3) \\
& 0 \leq z_{ja} \leq 1, && (21.4) \\
& \sum_a U_{ma} \leq \overline{U}_m, && (21.5) \\
& U_{ma} \leq \overline{U}_{ma}, && (21.6) \\
& \sum_a x^*_{vja} z_{ja} \leq FD_{\max}, \quad v = 1, && (21.7) \\
& LB \cdot k_{ja} \leq z_{ja} \leq UB \cdot k_{ja}, && (21.8) \\
& \sum_j k_{ja} \leq J, && (21.9) \\
& \sum_a k_{ja} \leq A, && (21.10) \\
& z_{ja} = ... = z_{jA}, && (21.11) \\
& \sum_{l'} k_{l'a} = L, && (21.12) \\
& \theta \geq 0, k_{ja} \in \{0,1\}, \hat{u}^*_{jma} = u^*_{jma} \big/ \max\{1, \alpha\theta^*_1\} \quad j = 1,...,J, \quad a = 1,..,A.
\end{aligned}
\tag{21}
$$

It may well be possible that the combinations of certain constraint sets yield infeasible solutions. As mentioned earlier, this infeasibility may only be logical (e.g., when the total number of working days exceeds the civil year) or practical in nature (e.g., when the total number of working days exceeds a certain threshold deemed normal among fisheries specialists). But, also mathematical programming infeasibilities may occur when some of the policy constraints cannot be satisfied simultaneously. This is part and parcel 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 program is restored.[12]

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[12] For instance, for some of the technologies based on gear types with only few observations, actually all observations must enter the solution when imposing the upper bound 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.

3. Policy Scenarios for Danish Fisheries: Empirical Results

3.1. Policy Scenarios: Formulation and Implementation

One of the main purposes of the paper is to test the implications of the various combinations of the extensions to the basic Dervaux, Kerstens and Leleu (2000) model in a fisheries context. Therefore, apart from the basic model, it is useful to define a series of scenarios 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. All of these scenarios are summarized in Table 3.

The basic scenario is the basic industry model defined over the various areas (constraints 21.1-21.4 and 21.7). Remark that constraint (21.7) is included to secure solutions within a normal working year: to be precise, $FD_{\max}$ is fixed at 275 days. A first scenario considers the effect of lowering the catch quotas for all species (constraints 21.5-21.6) by 10%. The second scenario 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 (i.e., $FD_{\max}=200$) each year, which is about a 30% reduction compared to the normal working year. The third scenario looks at the impact of lower and upper bounds on the activity or intensity vector (constraint 21.8). The lower bound (*LB*) was set equal to 0.35, while the upper bound (*UB*) was fixed at 0.90.[13] The fourth scenario considers decommissioning schemes and reduction in number of allowed areas (constraints 21.9-21.10). The total number of vessels was reduced by 10%, while the number of allowed areas was set to 3. A fifth scenario looks at implementation issues by imposing equality of the activity vector over all areas (constraint 21.11). The sixth scenario allows for technical inefficiencies, but already imposes an improvement imperative of 10% (thus, $\alpha = 0.90$). A seventh scenario 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.

Turning to the policy-oriented scenarios, a first policy scenario focuses on the implications on fishing capacity of using a detailed regulation scheme to control fishing power with the purpose to

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[13] A too tight upper bound can make the problem infeasible. In fact, since nearly all catches in the areas Baltic Sea and Other are generated by just a few combination respectively purse-seiners vessels that are operating at full plant capacity, it is impossible to impose the upper bound on the activity vector for these vessels (i.e., their upper bound is 1). See also the final paragraph of subsection 2.3.

implement a lower TAC for an over-fished stock. This kind of approach is commonly used around the world (Sutinen (1999)). One ultimate version of this approach can be very short seasons with a large fleet overcapacity as a result (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 implemented a limited amount of fishing days for each vessel in order to reduce fishing power and hence the catches of cod. We analyse this kind of regulation scheme by reducing the TAC for cod in the North Sea and Skagerrak by 20% and at the same time also reduce the amount of fishing days for vessels fishing cod to 200 per civil year.

The second policy scenario 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 U.S. fishery management councils. This scenario is applied in the model by requiring an equal reduction in the five different gear-types.

<TABLE 3 ABOUT HERE>

3.2. Empirical Results

The first step is to characterize the current situation by using the firm-level model. For each firm, the capacity output is computed for all nine outputs categories. We first report on the capacity outputs, then we comment on the optimal fixed and variable inputs corresponding to this full plant capacity. It should be remembered that 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 4 shows the aggregated vessel capacity outputs (first part of table) and the excess capacity (second part of table) as percentage of the current total production of each output (Table 2). At full capacity production of each vessel, the total production of each species could be increased between 25 and 67%. For example, the production for some of the main species could be raised by 24% (cod, North Sea), 26% (industrial, North Sea), 37% (pelagic, Skagerrak) and 52% (cod, Baltic Sea).

<TABLE 4 ABOUT HERE>

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. It may seem surprising that the use of variable inputs is lower in some of the categories, because individual vessel capacity is determined without restrictions on the use of variable inputs. The use of less than current variable inputs at plant capacity shows that the reference vessels at the capacity frontier are not the vessels with the highest use of variable inputs. In brief, once inefficiencies have been removed, variable inputs may decrease below current levels to produce at full plant capacity.[14]

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 are listed in Table 5 and following. Before embarking on a detailed discussion of the empirical industry analysis, two remarks are to be made. First, notice that we also report aggregate results at the industry level. However, the industry model generates optimal activity vectors defining the optimal outputs, variable and fixed inputs for all vessels individually. This detailed information is suppressed, but clearly has enormous potential when utilising these models for planning purposes. Second, remark that the basic scenario is just a point of reference. Strictly speaking, since all vessels in the sample are subjected to the same existing Danish and European regulations, the utilisation of 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 observed 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 solely relying 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 5 reports (1) the aggregate efficiency measure, which indicates the potential reduction in the use of fixed inputs, (2) the number of non-zero activity variables (i.e., the vessels figuring in the optimal solution) and (3) their average value for both the total fleet as well as the five areas. The basic scenario reduces the use of fixed inputs by about 36%. This leads to a corresponding reduction of the

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[14] These results are in an Appendix that is available from the authors upon simple request.

number of active vessels by 20%. The other scenarios are compared to this basic scenario to assess their quantitative and qualitative impact on efficiency measures, number of vessels in the fleet and the fleet structure formulated in terms of its geographical composition over the areas. 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 by about 45%: the efficiency measure is 0.55 compared to 0.64 in the basic scenario. The reduction in the number of active vessels now amounts to about 25%. A seasonal closure policy (scenario 2) reducing the number of fishing days yields an efficiency measure of 0.65 and reduces the number of active vessels by about 17%, which is less than the basic scenario. Imposing lower and upper bounds on the activity variables to guarantee economic viability (scenario 3) only yields a slightly higher efficiency measure (0.67). Not surprisingly, a significantly higher proportion of vessels remain active in the fleet (86% compared to 81%), but each of these vessels operates at an, on average, slightly lower activity level. Decommissioning 10% of the current fleet and limiting access to 3 areas of choice (scenario 4) generates an efficiency measure of about 0.65 and reduces the number of active vessels by about 21%. Scenario 5, which accounts for implementation problems, indicates 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%, while the industry efficiency measure is a relatively high 0.79 leading to a relatively low reduction in use of fixed inputs. Equity concerns expressed in terms of keeping the Baltic fleet active (scenario 7) only allow obtaining an efficiency measure of about 0.72 and decreases the number of active vessels by approximately 15%. This indicates that equity concerns are similar to technical inefficiency allowances in terms of mitigating the impact of the planning model on the number of vessels.

The first policy scenario, implementing a reduced TAC for cod and limiting the number of fishing days, leads to an efficiency measure of 0.64 and reduces the amount of active vessels by about 22%. Compared to the basic scenario, the main difference is the larger reduction in the number of gillnetters fishing in area North Sea, 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. The second policy scenario with equal reduction in the gear-types produces an efficiency measure of about 0.85 and reduces the number of active vessels by 25%. While the number of vessels is lower than in the basic scenario, the average size of the vessels is larger in terms of Tonnage and HP.

<TABLE 5 ABOUT HERE>

From a policy viewpoint, it is important to assess these different scenarios also in terms of their impact on the fleet structure. Tables 6 and 7 show 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 and areas. 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 1346 and 1459 vessels out of a total number of 1805 current vessels. However, while the optimal size of the fleet remains rather stable, the fleet structure is not the same in the three scenarios. The number of vessels in the Baltic Sea suffers the largest reduction, while the reduction for the North Sea area is relatively small. The average vessel size is lower than the current average size for the three scenarios in all areas, while the number of fishing days is around the same. This indicates that relatively speaking more of the larger vessels become obsolete at the optimal fleet structure.

<TABLES 6-7 ABOUT HERE>

In general, for all gear-types the average vessel size declines in the basic and first policy scenario. In policy scenario 2, the average size is also slightly lower, but it is close to the current level. However, comparing policy scenario 2 with the basic scenario shows that both the average vessel size and average number of fishing days are higher, while the number of vessels is lower. The relatively largest overcapacities are located 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.

To sum up, 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 is not as much reduced when the focus is on an equal reduction over gear-types (policy scenario 2). The conclusion is that the resulting fleet structure depends very much on the choice of policy instruments. The basic reason for the differences in resulting fleet structures relies in the constraints on gear-types that restrict the reallocation of catches and inputs between vessels at the industry level.

Since the models are deterministic in nature, concerns may be raised about the stability of the solutions obtained. Therefore, the robustness of the solution has been tested with respect to changes in the level of TACs. For the main species (cod), the TAC has been reduced by 10%. 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 main policy issue over the last decades due to widespread overfishing and excess use of economic resources. In many cases, the pressure on the biomass is so high that maintaining current 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.

Nonparametric deterministic frontier technologies can be used to estimate the industry capacity starting from a firm-level plant capacity notion. These firm-level capacities are entered as parameters into a short-run industry model (Johansen (1972)) to determine an ideal industry configuration while minimising the deployment of fixed inputs. The utilisation of a sub-vector radial input efficiency measure that has a fixed cost interpretation at the industry level allows to compare 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 to evaluate regulatory policies for common-pool resource industries, where one of 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 current firm-level Johansen (1968) model of plant capacity (which is used by FAO and others) and its flexibility in disaggregating from 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.

Application to the Danish fleet shows that vessel numbers can be reduced by around 14% to 25% and the use of fixed inputs between 15% and 45%, 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 program 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 programs are often designed in such a way that they remain voluntary for the fishermen to participate. Therefore, general fleet reduction programs 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 programs can be targeted towards the thus determined redundant parts of the fleet. Indeed, the main advantage of this industry model from a policy viewpoint is that information about the optimal fleet structure follows suit 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 can be adjusted when needed as a result of these revisions. As in many other applications, it must be emphasized that it is more important to move slowly in the right direction than to move fast in the wrong direction.

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Table 1. Descriptive Statistics of the Inputs

	Areas	North Sea	Baltic Sea	Kattegat	Skagerrak	Other
Gillnetters	No of vessels	153	23	27	69	0[1]
	Tonnage	31	18	17	18	0
	HP	185	139	131	133	0
	Crew-days	439	214	97	128	0
	Fishing days	117	79	34	44	0
Trawlers	No of vessels	307	306	236	338	37
	Tonnage	231	63	30	93	532
	HP	555	268	219	385	998
	Crew-days	471	233	131	227	169
	Fishing days	114	87	57	71	33
Danish Seiners	No of vessels	64	36	31	53	0
	Tonnage	49	36	20	38	0
	HP	181	169	133	184	0
	Crew-days	369	112	116	224	0
	Fishing days	108	39	52	74	0
Combination	No of vessels	20	33	21	18	0
	Tonnage	65	18	23	36	0
	HP	218	141	157	150	0
	Crew-days	197	216	80	173	0
	Fishing days	67	108	38	62	0
Purse-seiners	No of vessels	11	0	0	11	11
	Tonnage	817	0	0	768	793
	HP	1454	0	0	1452	1511
	Crew-days	505	0	0	109	694
	Fishing days	46	0	0	10	62

[1] 0 indicates that there is no observation, because no vessel from this gear type fishes in the area.

Table 2. Current Total Catches (Tonnes or Index)

	North Sea	Baltic Sea	Kattegat	Skagerrak	Other	Total
Cod	20814	19555	3205	10202	0	53776
Other roundfish	2972	59	67	2415	0	5519
Plaice	9393	578	1109	5174	0	16254
Sole	467	0	215	101	0	789
Pelagic	31836	27917	7678	21569	28522	117522
Lobster	1365	0	1349	1905	0	4622
Shrimp	2919	4054	30	2886	0	9890
Other fish	1621	104125	391	2407	0	108546
Industrial	852713	5232	13419	35709	103575	1010648

Table 3. Description of Scenarios in Terms of the Industry Model

Scenarios	Constraints of Formulation (18) 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: $LB = 0.3$ & $UB = 0.9$)
Scenario 4	(21.1: $\alpha = 0$)-(21.4); (21.7: $FD_{\max} = 275$); (21.9: $0.90 \cdot J$) & (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 in solution)
Policy Scenario 1	(21.1: $\alpha = 0$)-(21.4); (21.7: $FD_{\max} = 200$ for cod fishing vessels); (21.5)-(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)-(21.12): equal reduction over gear-types

Table 4. Aggregated Vessel Capacity (Tonnes or Index) and Excess Capacity (%)

Aggregate vessel capacity output

	North Sea	Baltic Sea	Kattegat	Skagerrak	Other	Total
Cod	25848	29811	4413	14166	0	74238
Other roundfish	3689	111	103	3279	0	7190
Plaice	11986	859	1476	6389	0	20710
Sole	665	0	352	135	0	1161
Pelagic	39370	36159	10110	29593	31062	146294
Lobster	1637	0	1986	2637	0	6265
Shrimp	3385	8922	43	3330	0	15680
Other fish	2265	175137	548	3180	0	181132
Industrial	1071165	5418	18014	44334	123596	1262527

Excess capacity (%)

	North Sea	Baltic Sea	Kattegat	Skagerrak	Other	Total
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

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

Table 5. Industry Model Scenarios: Efficiency Measure and Activity Vectors (Total & Per Area)

Scenarios	Eff. Measure # non-0 z_{ja} Mean z_{ja}	Skagerrak # non-0 z_{ja} Mean z_{ja}	Kattegat # non-0 z_{ja} Mean z_{ja}	Baltic Sea # non-0 z_{ja} Mean z_{ja}	North Sea # non-0 z_{ja} Mean z_{ja}	Other # non-0 z_{ja} Mean z_{ja}
Act. # vessels	1805	489	315	398	555	48
Basic Scenario	0.64 1459 0.796	404 0.815	244 0.754	282 0.700	488 0.867	41 0.849
Scenario 1	0.55 1361 0.744	386 0.776	229 0.708	256 0.639	451 0.805	39 0.789
Scenario 2	0.648 1511 0.790	422 0.817	245 0.746	305 0.687	498 0.860	41 0.845
Scenario 3	0.67 1556 0.763	433 0.782	261 0.729	301 0.676	516 0.826	45 0.813
Scenario 4	0.65 1436 0.796	404 0.826	231 0.733	278 0.698	482 0.868	41 0.854
Scenario 5	0.68 1465 0.788	419 0.826	244 0.758	288 0.710	471 0.820	43 0.873
Scenario 6	0.79 1521 0.843	428 0.874	233 0.739	316 0.795	500 0.900	45 0.930
Scenario 7	0.72 1551 0.859	404 0.826	236 0.749	398 1.0	471 0.849	42 0.875
Policy Scenario 1	0.644 1400 0.776	405 0.829	230 0.732	272 0.684	451 0.813	41 0.845
Policy Scenario 2	0.847 1346 0.731	381 0.756	212 0.658	261 0.651	450 0.799	42 0.854

Table 6. Number of Vessels, Fixed Input and Fishing Days per Vessel for Each Area

	North Sea	Baltic Sea	Kattegat	Skagerrak	Other
Current situation					
No of vessels	555	398	315	489	48
Tonnage	154	54	28	80	626
HP	406	244	203	332	1182
Fishing days	111	84	53	66	39
Basic scenario					
No of vessels	481	279	238	399	41
Tonnage	120	36	23	58	555
HP	315	194	175	260	1033
Fishing days	111	78	48	67	38
Policy scenario 1					
No of vessels	451	272	230	405	41
Tonnage	130	37	23	58	553
HP	332	201	179	268	1034
Fishing days	111	80	49	67	38
Policy scenario 2					
No of vessels	449	262	207	368	39
Tonnage	140	41	24	73	574
HP	353	216	193	315	1102
Fishing days	116	85	57	71	42

Table 7. Number of Vessels, Fixed Input and Fishing Days per Vessel for Each Vessel Type

	Gillnetters	Trawlers	Danish seiners	Combination	Purse seiners
Current situation					
No of vessels	272	1224	184	92	33
Tonnage	28	130	41	31	800
HP	173	398	175	160	1484
Fishing days	87	82	75	74	39
Basic scenario					
No of vessels	201	992	167	52	24
Tonnage	22	105	34	18	696
HP	143	318	148	144	1442
Fishing days	89	79	81	60	40
Policy scenario 1					
No of vessels	178	982	164	52	24
Tonnage	22	107	34	20	694
HP	144	326	152	147	1443
Fishing days	84	81	82	60	39
Policy scenario 2					
No of vessels	194	891	118	65	21
Tonnage	27	122	36	28	762
HP	164	364	152	157	1468
Fishing days	90	88	85	70	43