Quota Trading and Profitability:

Theoretical Models and Applications to Danish Fisheries

by

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Abstract

Using Data Envelopment Analysis (DEA), we provide a framework to analyze the potential gains from quota trading. We compare the industry profit and structure before and after a free trade reallocation of production quotas. The effects of tradable production quotas depend on several technological and behavioral characteristics, including the ability to learn best practice (catch-up) and the ability to change the input and output composition (mix). To illustrate the usefulness of our approach, we analyze a dataset from the Danish fishery. We study the industry profit and structure under each of four sets of technological and behavioral characteristics.

Keywords

Data Envelopment Analysis (DEA), Individual Transferable Quotas (ITQ), Reallocation, Technical Efficiency, Allocative Efficiency, Fishery.

JEL-classification

C61, L51, Q22, Q28

Acknowledgement

The research was supported by the Center of Fisheries and Aquaculture, Management and Economics (FAME) financed by the Danish Ministry for Food, Agriculture and Fisheries and the Danish Agricultural and Veterinary Research Council.

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Introduction

In theory as well as in practice, *individual transferable (production) rights* are useful to ensure optimal allocation of production. Popular applications are found within environmental and resource economics, where the usage of a resource by one agent implies negative externalities on the other agents. Pioneering work includes Crocker and Dales, and Montgomery gives an early mathematical presentation. In a traditional externality interpretation, the regulator distributes the property right to the good causing the externality among the users of this good. Thereafter they are restricted from using more of the good than they own, but they are allowed to sell and buy these rights.

The fishery is one of the economic sectors, where regulators in many countries use individual transferable rights. Applications are found in for example United States, New Zealand, Canada, Iceland and the Netherlands. Furthermore, several countries, including Denmark, are considering to use this instrument. In fisheries, the individual rights are quotas that define initial allowances to catch a certain amount of fish. In the literature, the rights are therefore referred to as *Individual Transferable Quotas* (ITQ).

Any change in the regulatory framework is costly. Introducing ITQ requires that the regulator and the industry learn about and adapt to the new regime. Before moving from an incumbent regime to one based on ITQs, it is therefore important to estimate the likely gains from the resulting reallocation of the production. The potential gains (in a comparative static sense) should exceed the transition costs.

This paper discusses different ways to model the reallocation of production following the introduction of ITQs. It uses these models to estimate the likely *gains and structural implications* from introducing ITQs in the Danish fishery. The potential gains from ITQs are estimated by comparing the profit under the current system of catch allocation with the profit under the optimal allocation of catches. We presume that the optimal allocation will eventually be realized, if we introduce free quota trade.

Part of the challenge is that the available production data and behavioral patterns are the result of the incumbent regime. The *technological adaptation* and *behavioral responses* are therefore somewhat uncertain. We suggest several alternatives – varying in the extent to which individual fishermen can improve performance and change their catch mix - and use these to estimate a range of likely impacts.

Data Envelopment Analysis (DEA) is useful to model the underlying production structure in a reallocation study. DEA is essentially an activity analysis approach, where actual productions are used as activities. DEA estimates a production frontier from the best practices of the analyzed Decision Making Units (DMU). This frontier can be used to evaluate possible gains from individual learning (catching up) as well as from reallocations among the DMUs. Moreover, by its reliance on *Linear Programming*, it is easy to formulate alternative research questions and to get numerical estimates from large datasets, as we shall demonstrate below.

The outline of the paper is as follows: The next section reviews some related literature. A brief introduction to DEA is given in third section. The fourth section discusses the theoretical framework and the ways in which reallocations can give rise to gains in general terms. The specific sectoral models are presented in the fifth section. In the sixth section, the usage of the framework is demonstrated on a dataset from Danish fisheries. The final section concludes the paper.

Related Literature

There is a large micro-economic literature on the usage of tradable production rights. We shall not cover this here. Rather, we focus on the relatively few papers using DEA to estimate reallocation gains in a manner somewhat similar to our approach. Also, we briefly relate our approach to the usage of (Positive) Mathematical Programming to predict sectoral developments in agriculture and to the iterative multilevel planning problems found in divisionalized firms and planned economies.

Brännlund, Färe, and Grosskopf and Brännlund, Chung, Färe, and Grosskopf study the Swedish pulp and paper industry using a DEA model with some non-discretionary inputs and some unwanted outputs. They use this model to estimate the cost of the existing transmission constraints at the individual units and the gains from reallocation.

A related approach is used in Bogetoft and Wang and Bogetoft, Strange, and Thorsen. In these papers, the potential gains from mergers of consultancy units in the agricultural and forestry industries, respectively, are estimated. The reallocations are restricted to take place among geographical neighbors. Moreover, the gains are decomposed in learning, mix and size effects, and the corresponding organizational changes are identified.

An attractive feature of these studies is the direct investigation of reallocations and the associated *matching problems*. The rights and obligations of the individuals are reallocated in a balanced manner to preserve the sectorwide rights and obligations. This requires the solution of non-trivial matching problems, since a multiplicity of inputs and outputs in the production process must be accounted for.

Also, the explicit formulation of the matching problems is in sharp contrast to the simpler, more naive but widely used production economic approach of measuring allocative efficiency. *Allocative efficiency* is typically defined as cost efficiency divided by technical efficiency. It therefore measures what can be gained by adapting to given prices in a complete and perfect market and it effectively ignores the matching issues in a finite economy.

A potential drawback of these studies, however, is that they all assume that the reallocation takes place at the frontier. This means that all units are assumed to *adapt to the best practice before the reallocation*. Although competition may work to drive out inefficient firms, it may be naive to presume technical efficiency up front. After all, efficiency studies of most sectors, including very competitive ones, have revealed that inefficiency is a persistent phenomenon. Also, even from a theoretical perspective, technical inefficiency may be a rational response as it may help compensate the employees, facilitate rent seeking behavior or improve the result of strategic interactions with other firms on the market place, cf. Bogetoft and Hougaard.

The fact that reallocation and individual efficiency improvement may not go hand in hand was first suggested in Bogetoft and Färe. There, we discuss how to measure allocative efficiency without presuming technical efficiency. Also, we compare the “new approach” with the “traditional approach” of assuming technical efficiency before measuring allocative efficiency. In particular, we develop necessary and sufficient conditions on the technology to ensure consistency between the new and the traditional measures.

In this paper, we extend the traditional approach to allocative efficiency in DEA models by 1) working with genuine and direct reallocation estimates that take into account matching problems and sector wide restrictions and by 2) dispensing with the assumption of technical efficiency when the gains from reallocations are examined. Moreover, we 3) estimate the differences in an actual large-scale application.

It is worthwhile also to relate our approach to the traditional use of mathematical programming in *sector models*. There is a large literature on such usages of mathematical programming in agriculture, cf. e.g. Hazell and Norton. There is also a recent revival of this literature known as *positive mathematical programming*, cf. Howitt, where the calibration to the real world outcome is done using non-linear objectives to avoid “jumpy” behavior.

In the sector models using mathematical programming, the individual firms may be more or less efficient. It basically depends on the activities we use to model their possibilities. Also, genuine reallocation problems may be studied. In this sense, the approach of this paper is certainly in line with the traditional mathematical programming approach to sector models. The way we deviate is primarily by working with a large number of firm types, one for each firm in the sector, and by modeling the individual firms based on an initial DEA based efficiency analysis.

Another line of literature that share many similarities with the present usage of mathematical programming to study reallocations, is the so-called *iterative, multilevel planning literature*, cf. Dirickx and Jennergren, Johansen (1977, 1978), Meijboom, and Obel. The focus of this literature has been the coordination problem in a divisionalized firm or planned economy.

An example involves a headquarters facing the problem of allocating resources among divisions so as to maximize overall profit. The headquarters lacks information about the profit functions of the divisions, i.e. about how the contributions of the divisions depend on allocated resources. Hence, it pays to acquire further information. Full disclosure is typically impossible or prohibitively costly, and iterative planning procedures are therefore considered. In such a procedure, the headquarters asks a sequence of questions about the values of or needs for resources, and hereby gradually learns about the profit functions of the divisions. At some point, the procedure stops and an allocation is chosen. This line of research has been concerned with the design of procedures that exhibit certain desirable properties like convergence, feasibility, monotonicity, and efficient use of information.

The sector and multilevel models share two important properties with the present paper: 1) they solve genuine reallocation problems and 2) the individual firms or divisions may, depending on the way they are modeled, be more or less technically efficient. In this sense, there are important similarities. Moreover, the multilevel literature studies the transition path from an incumbent allocation to a new allocation – and not just the resulting reallocation in a comparative static outcome. In this sense, it extends the previous and present approaches and could be an interesting dynamic supplement to the approach of this paper.

Data Envelopment Analysis

In this section, we provide an introduction to the main ideas and constructs in Data Envelopment Analysis (DEA). DEA is a relatively simple approach to derive the relative efficiency of production units using linear programming. DEA was first introduced in the late seventies by Charnes, Cooper, and Rhodes (1978, 1979). Subsequently, more than a thousand scientific papers have elaborated upon and applied DEA to almost every sector of the economy[1]. A brief introduction should therefore suffice to introduce new readers to this methodology[2].

Consider the case where each of V Decision Making Units (DMUs), $v \in I=\{1,\dots,V\}$, transform N inputs to M outputs. Let $x^v = (x_1^v,\dots,x_N^v) \in \Re_0^N$ be the inputs consumed and $y^v = (y_1^v,\dots,y_M^v) \in \Re_0^M$ the outputs produced in DMU^v, $v \in I$. Also, let T be the underlying production possibility set:

$$T = \{(x,y) \in \Re_0^{N+M} \mid x \text{ can produce } y\} \qquad (1)$$

Some regularity assumptions are usually imposed on T. The classical assumptions are that for all $x', x'' \in \Re_0^N$ and $y', y'' \in \Re_0^M$, we have:

A1 *disposability*: $(x',y') \in T$ and $x'' \geq x'$ and $y'' \leq y' \Rightarrow (x'',y'') \in T$

A2 *convexity*: T convex

A3 *s-return to scale*: $(x', y') \in T \Rightarrow k(x', y') \in T$ for $k \in K(s)$

where s corresponds to either constant (crs), decreasing (drs) or variable (vrs) return to scale, and where $K(crs) = \Re_0$, $K(drs) = [0,1]$, and $K(vrs) = \{1\}$, respectively.

For a given technology, (in)efficiency is the ability to reduce inputs without affecting outputs or to increase outputs without requiring more inputs. In the case of multiple inputs and

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[1] See for instance www.deazone.dk for an updated bibliography. Alternatively, Fried, Lovell, and Schmidt, Charnes, Cooper, Levin, and Seiford give examples of Data Envelopment Analysis applications to different sectors.

[2] For textbook introductions to DEA, see Charnes, Cooper, Lewin, and Seiford; Coelli, Rao, and Battese or Cooper, Seiford, and Tone.

outputs, the efficiency of a DMU, say DMU^v, is often measured by the so-called *Farrell* (1957) *efficiency measures*:

$$E^v = \text{Min } \{E \in \Re_0 \mid (Ex^v, y^v) \in T\} \quad (2)$$

or

$$F^v = \text{Max } \{F \in \Re_0 \mid (x^v, Fy^v) \in T\} \quad (3)$$

where E^v is the maximal radial contraction of all inputs and F^v is the maximal radial expansion of all outputs that are feasible for DMU^v in T. Note that $1-E^v$ is a measure of the (proportion of) inputs wasted on non-productive purposes. DMU^v uses x^v, but in fact $E^v x^v$ would be sufficient. Similarly, F^v-1 is a measure of the proportional waste of output. DMU^v is only producing y^v but could have produced $F^v y^v$.

In many applications, the underlying production possibility set T is unknown. The DEA approach can be used to model and evaluate DMUs in such cases.

Assume that $x^v = (x_1^v, ..., x_N^v) \in \Re_0^N$ are the inputs actually consumed and $y^v = (y_1^v, ..., y_M^v) \in \Re_0^M$ are the outputs actually produced by DMU^v, $v \in I$. The DEA approach estimates T from the observed data points and evaluates the observed productions relative to the estimated technology.

The estimate of T, denoted as the *empirical reference technology* T*, is constructed according to the *minimal extrapolation principle*. T* is the smallest subset of $\Re_0^{N+M}$ that contains (envelop) the actual production plans (x^v, y^v), $v \in I$, and satisfies certain technological assumptions specific to the given approach.

The (relative) efficiency of DMU^v may then be measured in input or output space by using the Farrell measures above, with T* substituted for T.

Different DEA models invoke different assumptions about the technology. Charnes, Cooper and Rhodes (1978, 1979) proposed the original constant returns to scale (*crs*) DEA model assuming A1, A2 and A3(crs). Banker developed the decreasing returns to scale (*drs*) model, while Banker, Charnes and Cooper outlined the (local) variable returns to scale (*vrs*) model using A1, A2 and A3(drs) and A1, A2 and A3(vrs), respectively. It is straightforward to see, cf. the references above, that A1, A2 and A3(s) lead to the empirical reference technology:

$$T^*(s) = \left\{ (x, y) \in \Re_0^{N+M} \middle| \exists \lambda \in \Re_0^V : x \geq \sum_{v=1}^{V} \lambda^v x^v, y \leq \sum_{v=1}^{V} \lambda^v y^v, \lambda \in \Lambda(s) \right\} \quad (4)$$

where $\Lambda(s)$ equals either $\Lambda(crs) = \Re_0^V$, $\Lambda(drs) = \{\lambda \in \Re_0^V \mid \sum_v \lambda^v \leq 1\}$ or $\Lambda(vrs) = \{\lambda \in \Re_0^V \mid \sum_v \lambda^v = 1\}$. Since these are polyhedral convex sets, the Farrell efficiency programs become linear programming problems.

The three classical assumptions A1-A3 have been relaxed in several respects. Deprins, Simar, and Tulkens proposed the free disposability hull (*fdh*) model, which invokes only A1. The structure of T*(fdh) therefore has the structure above with $\Lambda(fdh) = \{\lambda \in \Re_0^V \mid \sum_v \lambda^v = 1, \lambda^v \in \{0, 1\}\ \forall v\}$. The free replicability hull (*frh*) model was briefly proposed in Tulkens. The free replicability hull model invokes A1 and an additivity assumption A4: $(x',y') \in T$ and $(x'',y'') \in T \Rightarrow (x'+x'', y'+y'') \in T$, giving T*(frh) the structure above with $\Lambda(frh) = \{\lambda \in \Re_0^V \mid \lambda^v \in \{0,1,2,3\ldots\}\ \forall v\}$. Partial relaxation of the convexity assumption A2 in DEA models is suggested in Petersen and examined by Bogetoft.

It should be noted that DEA by construction provides an inner approximation of the underlying production possibility set. The efficiency estimates can therefore be over optimistic and the potential input savings and output expansions thus underestimated.

The effects of reallocations

The effects of allowing reallocations within an industry depend on the reactions of the firms. In this section, we first develop a general framework to model the likely reactions and to measure the expected effects. Next, we discuss in more details some important extreme cases that we have implemented in the empirical section.

The first crucial question is what can and what cannot be reallocated? To capture this we assume that inputs and outputs can be sub-divided into *standard (S) goods*, i.e. goods that can be acquired and sold at perfect markets, *regulated (R) goods*, i.e. goods than in principle could be transferred, but which are at present regulated, and *fixed (F) goods*, i.e. non-discretionary goods which must be used and produced locally. In the case of fisheries, fuel is a typical standard good, quota a typical regulated but potentially transferable good, and fixed costs a typical non-discretionary good in the short run. Let the inputs and outputs of DMU^v be split up according to this classification:

$$(x^v, y^v) = (x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) \qquad (5)$$

where x_S^v, x_R^v, x_F^v, y_S^v, y_R^v and y_F^v are N_S-, N_R-, N_F-, M_S-, M_R-, and M_F-dimensional sub-vectors with $N_S + N_R + N_F = N$ and $M_S + M_R + M_F = M$. In a study of the likely consequences of introducing reallocation, the S goods are those that can be reallocated in the incumbent regime, while the S and R goods are those that can be reallocated in the new regime.

Now, assume that the *objectives of the DMUs* are to maximize profit from the standard goods:

$$\pi(x^v, y^v) = \pi(x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) = py_S^v - wx_S^v \tag{6}$$

where p is the price vector for standard outputs and w is the price vector for standard inputs.

With the present regime and the observed inputs and outputs, ($x^{obs\ v}$,$y^{obs\ v}$), v=1,…,V, therefore, *observed industry profit* is:

$$\Pi^{obs} = \sum_{v=1}^{V} \pi\left(x^{obs\,v}, y^{obs\,v}\right) = \sum_{v=1}^{V} \left[py_S^{obs\,v} - wx_S^{obs\,v}\right] \tag{7}$$

Technical *efficiency with non-discretionary variables* can be measured as above, except that there is no contraction or expansion in the non-discretionary dimensions, cf. Golany and Roll and Charnes, Cooper, Levin and Seiford. Therefore, the *observed efficiency* of DMU^v can be calculated as:

$$E^{obs\ v} = \text{Min}\ \{E \in \Re_0 \mid (E\, x_S^{obs\,v}, E\, x_R^{obs\,v}, x_F^{obs\,v}, y^{obs\,v}) \in T\} \tag{8}$$

or

$$F^{obs\ v} = \text{Max}\ \{F \in \Re_0 \mid (x^{obs\,v}, F\, y_S^{obs\,v}, F\, y_R^{obs\,v}, y_F^{obs\,v}) \in T\} \tag{9}$$

If we now allow the regulated goods to be transferred, the *new industry profit* will be:

$$\Pi^{new} = \sum_{v=1}^{V} \pi\left(x^v, y^v\right) = \sum_{v=1}^{V} \left[py_S^v - wx_S^v\right] \tag{10}$$

where (x^v,y^v), v=1,…,V, are the inputs and outputs in the new regime with transferable, regulated goods. The difference ? ^{new}-? ^{obs} thus measures the effects of reallocation.

To calculate the new industry profits and hereby the gains from allowing reallocation, we must predict how the firms will react to the allowed reallocation and thus what the new inputs and outputs of the firms will be. To model this, we assume very generally that the new outcome is determined by solving the following *reallocation problem*:

$$\max_{(x_S,x_R,y_S,y_R,E)}\left[\sum_{v=1}^{V}\left(py_S^v - wx_S^v\right)\right] - \Gamma\left[(x_S,x_R,y_S,y_R,E)\middle|(x_S^{obs},x_R^{obs},y_S^{obs},y_R^{obs},E^{obs})\right] \quad (11)$$

s.t. $(E^v x_S^v, E^v x_R^v, x_F^{obs\,v}, y_S^v, y_R^v, y_F^{obs\,v}) \in T \qquad v = 1,\ldots,V \quad (11.a)$

$1 \geq E^v \geq E^{obs\,v} \qquad v = 1,\ldots,V \quad (11.b)$

$$\sum_{v=1}^{V} x_R^v \leq \sum_{v=1}^{V} x_R^{obs\,v} \quad (11.c)$$

$$\sum_{v=1}^{V} y_R^v \geq \sum_{v=1}^{V} y_R^{obs\,v} \quad (11.d)$$

where G is a penalty function. In this program, we have used (x_S,x_R,y_S,y_R,E) to briefly refer to the standard and regulated inputs and outputs and the efficiency levels of all the units. That is, we stick to the convention of referring to a variable from all the vessels by suppressing the specific vessel numbers *v*.

The interpretation of this program is that it determines reallocated standard and regulated goods and changed efficiency levels, (x_S,x_R,y_S,y_R,E), so as to maximize profit and minimize the penalty Γ. The idea of the penalty function Γ is that it increases with growing distance between the new (x_S,x_R,y_S,y_R,E) and old $(x_S^{obs},x_R^{obs},y_S^{obs},y_R^{obs},E^{obs})$ allocations and efficiency levels. It can therefore be interpreted in two ways. One can think of it as a technical way to calibrate the model in line with the positive mathematical programming tradition. Conversely, one can think of it as reflecting the costs of changing behavior from one regime to another. The more the new allocations and efficiency levels deviate from the presently observed ones, the more complicated the transition.

The constraints in the reallocation problem reflect that the reallocated goods must lead to feasible production plans under the assumed improvements in efficiency levels. Moreover, the reallocations must be balanced in the sense that the industry at large cannot use more of the regulated inputs nor reduce the regulated outputs.

In the reallocation problem above we assumed that improvements in the technical efficiency would work on the input side, in the sense that the proportional (Farrell type) waste of (discretionary) inputs (1-E) will be reduced. Alternatively, one could assume that the technical efficiency improvements work on the output side and lead to a reduction in the waste (F-1) of discretionary outputs. This will result in the following reallocation problem:

$$\max_{(x_S, x_R, y_S, y_R, F)} \left[\sum_{v=1}^{V} \left(p y_S^v - w x_S^v \right) \right] - \Gamma\left[(x_S, x_R, y_S, y_R, F) \middle| (x_S^{obs}, x_R^{obs}, y_S^{obs}, y_R^{obs}, F^{obs}) \right] \quad (12)$$

$$\text{s.t.} \quad (x_S^v, x_R^v, x_F^{obs\,v}, F^v y_S^v, F^v y_R^v, y_F^{obs\,v}) \in T \qquad v = 1,\ldots,V \quad (12.a)$$

$$1 \le F^v \le F^{obs\,v} \qquad v = 1,\ldots,V \quad (12.b)$$

$$\sum_{v=1}^{V} x_R^v \le \sum_{v=1}^{V} x_R^{obs\,v} \quad (12.c)$$

$$\sum_{v=1}^{V} y_R^v \ge \sum_{v=1}^{V} y_R^{obs\,v} \quad (12.d)$$

In the next section, we solve a series of problems like the above. The problems correspond to different and rather extreme specifications of the penalty function G as indicator functions. The penalty is either zero or infinite, i.e. we only look at changes in allocations and efficiency levels that are either costless to introduce or impossible to undertake. The motives for the cases we consider is that some important *determinants of the reactions to an ITQ system* in the case of fisheries will be

- The extent to which the level of technical efficiency can be changed
- The extent to which the output mix can be changed

Numerous articles have investigated the level of technical efficiency for fishing vessels, including which factors influence this level and how it can be improved[3]. It is difficult to determine a priori whether a change in regulation system will give rise to a change in the level of technical efficiency. As a start, it is therefore useful to examine the two extreme situations, where changes in efficiency are either prohibitively costly or entirely costless, i.e. where efficiency can either not be changed or be changed entirely free.

The output mix chosen by a fisherman is influenced by many factors, including the costs of changing the mix and the regulatory possibilities. With respect to costs, some vessels may be able to change their output mix without significant costs, while these may be large for others. The level of costs depends upon factors such as type of fishery conducted (pelagic, demersal or benthic), flexibility to re-rig, experience of the fisherman, etc. Of course the mix will also depend on possible regulatory constraints imposed alongside the quota system. The exact formulation of the quota system (which catches can be exchanged for example), and the way a possible market for reallocating quotas is set up (how often is it possible to reallocate for example) will be important. Again we consider only two extremes below, viz. the case of no mix restrictions and the case of fixed mixes such that a fisherman can only scale his operations up and down without altering the mix.

Our applied framework thus consists of four models defined by the allowed technological and behavioral changes. The models including their acronyms are summarized in Table 1 below.

[3] See for instance Kirkley, Squires and Strand; Sharma and Leung and Pascoe, Andersen and de Wilde.

Table 1 Sector models and their acronyms

	Output mix fixed (MF)	Output mix changeable (MC)
Level of technical efficiency fixed (EF)	Model EF-MF	Model EF-MC
Level of technical efficiency changeable (EC)	Model EC-MF	Model EC-MC

The fisherman's ability to change behavior is thus most restricted in Model EF-MF and least restricted in Model EC-MC. The lowest trade gains are therefore expected in the former and the highest in the latter[4]. The two other models are intermediate and their profits cannot be ranked internally.

We conclude this section by discussing how the reallocation in the different cases can generate improved profits. Three important effects can be identified, i.e. *efficiency effects*, *scale effects* and *mix effects*, respectively. Table 2 below illustrates which of these effects are effective in each of the four models.

Table 2 Reallocation effects

	Efficiency effects	Scale effects	Mix effects
Model EF-MF	X	X	
Model EC-MF		X	
Model EF-MC	X	X	X
Model EC-MC		X	X

The efficiencies of the individual vessels play a role, when they cannot be changed. In such cases, reallocating quota from less efficient to more efficient vessels can generate trade gains. The scale of operations will also be important. If the underlying technology is a variable return to scale technology, it will in general be beneficial to move the vessels closer to the so-called most productive scale size (cf. Banker), where the output per input is maximal. This suggests that gains can be generated by giving more quotas to small units operating under

[4] The partial ranking follows from the principle sometimes referred to as Le Châtelier Principle (cf. Samuelson). It states that gains cannot increase, when an extra restriction is imposed.

increasing return to scale and by taking quota from larger units working above optimal scale size. Finally, if the mix of inputs and outputs can be changed, this can generate improved industry profits. By the convexity of the technology, it always pays to have non-specialized or non-extreme compositions. The mix effect refers to the tradability gains arising from vessels changing their output mix towards a more productive direction of the product space. This effect is therefore only observed in the model where the output mix can be changed. For an extended discussion of efficiency, size and mix gains, see Bogetoft and Wang.

Four sectoral models

The mathematical representations of the model to calculate individual technical efficiencies and the four sectoral models to calculate industry profits under various technological and behavioral assumptions are given in this section. We assume in each model that the production technology is characterized by variable returns to scale on a yearly basis[5].

Using the output-oriented approach described in Section 3, the technical efficiency F of each vessel v' can be calculated by solving the following *technical efficiency program* (c.f. Färe, Grosskopf, and Lovell):

[5] The sectoral models have also been formulated under the assumption of variable returns to scale on a daily basis, but these are not presented here. Further information can be obtained from the authors.

$$\max_{(F^{v'},\lambda^{v'v})} F^{v'} \tag{13}$$

s.t. $\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq F^{v'} \cdot CPY_m^{obs\,v'}$ M = 1,…,M (13.a)

$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{obs\,v'}$ n = 1,…,Ñ (13.b)

$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'}$ n = Ñ+1,…,N (13.c)

$\sum_{v=1}^{V} \lambda^{v'v} = 1, \lambda^{v'v} \geq 0$ v = 1,…,V (13.d)

where *CPY* is the catch per year in weight, *VCPY* is the variable (discretionary) costs per year, *FCPY* is the fixed (non-discretionary) costs per year, and *?* is the intensity variable. As previously, the subscripts are respectively related to the output number (*m*) and the input number (*n*) and the superscript *obs* indicates that the observed values have been used. We use this notation in the forthcoming models as well.

The level of technical efficiency is thus maximized under four individual restrictions for each vessel. The restrictions secure that the analyzed vessel is within the production possibility as estimated by minimal extrapolation from the observed vessels.

Turning attention to the sector problems, each programming problem includes an objective function and a series of restrictions. The objective is to maximize industry profits. The restrictions relate both to the individual vessels and to the entire industry, and they ensure that the reallocated productions are technically feasible.

Given the estimated levels of technical efficiency F^{obs} for each vessel, the industry programming problem related to Model EF-MF can be formulated as follows:

$$\Pi = \max_{(\beta^{v},\lambda^{v'v},VCPY^{v})} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \beta^{v} \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^{v} \right) \qquad (14)$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq \beta^{v'} \cdot CPY_m^{obs\,v'} \qquad m = 1,\ldots,M \qquad (14.a)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \qquad (14.b)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \qquad (14.c)$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1, \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \qquad (14.d)$$

⋮

(14.a,b,c,d) repeated for each v' = 1,…,V

⋮

$$\sum_{v=1}^{V} \beta^{v} \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \qquad (14.e)$$

where *ß* is the output expansion variable, and *P* is the vector of output prices.

Short run industry profits are thus maximized under four individual restrictions for each vessel and one overall industry restriction for each output. The first four restrictions ensure that the new cost-catch profile for each vessel is within the production possibility set estimated from all the vessels. The first restriction allows the output level, but not the output mix, to be changed via modifications in the parameter *ß*. The second restriction tracks the corresponding changes in the variable costs. The changes in output and variable costs are however restricted by the presence of fixed costs as described in the third restriction. Finally, the total output of the industry, i.e. catch being the regulated good, is restricted by the last restriction to be equal or below the total observed output in the dataset. The profit improvements are therefore not generated by exploiting the natural resources more heavily, but come from the way the vessels allocate the use of the fish resources among each other. This unchanged utilization of the resource is also imposed in the subsequent programs. In more advanced applications, this could of course be changed and in particular, one could use the above program to determine the costs of the overall utilization constraints.

By including the level of technical efficiency for each vessel in the industry profit function and the industry output restriction, the gains are generated without any improvements in the individual efficiencies. The idea is that a vessel with an individual score of say 1.25 will always catch only a fraction (1/1.25=0.8) of his potential output.

If vessels are allowed to change their level of technical efficiency, i.e. become technically efficient, the industry problem denoted Model EC-MF becomes:

$$\Pi = \max_{(\beta^v, \lambda^{v'v}, VCPY^v)} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \beta^v \cdot CPY_m^{obs\,v} - \sum_{n=1}^{\tilde{N}} VCPY_n^v \right) \qquad (15)$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq \beta_{v'} \cdot CPY_m^{obs\,v'} \qquad m = 1,\ldots,M \qquad (15.a)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \qquad (15.b)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \qquad (15.c)$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1 \;,\; \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \qquad (15.d)$$

⋮

(15.a,b,c,d) repeated for each v' = 1,…,V

⋮

$$\sum_{v=1}^{V} \beta^v \cdot CPY_m^{obs\,v} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \qquad (15.e)$$

Compared to Model EF-MF, all vessels are assumed to produce on the frontier. This implies that previously non-efficient vessels become more relevant to consider when maximizing industry profits.

Instead of allowing the level of technical efficiency to change, it can be assumed that vessels can change their output mix, i.e. catch composition. The consequences of such an assumption can be analyzed by solving the industry program labeled Model EF -MC:

$$\Pi = \max_{(\lambda^{v'v}, CPY^{v}, VCPY^{v})} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \frac{CPY_m^{v}}{F^{obs\,v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^{v} \right) \quad (16)$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq CPY_m^{v'} \qquad m = 1,\ldots,M \qquad (16.a)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \qquad (16.b)$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \qquad (16.c)$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1 \ , \ \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \qquad (16.d)$$

⋮

(16.a,b,c,d) repeated for each v' = 1,…,V

⋮

$$\sum_{v=1}^{V} \frac{CPY_m^{v}}{F^{obs\,v}} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \qquad (16.e)$$

In the least restrictive model, it is assumed that the level of technical efficiency and the output mix can be changed. The industry problem related to this situation is denoted Model EC-MC and becomes:

$$\Pi = \max_{(\lambda^{v'v}, CPY^{v}, VCPY^{v})} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot CPY_m^{v} - \sum_{n=1}^{\tilde{N}} VCPY_n^{v} \right) \tag{17}$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq CPY_m^{v'} \qquad m = 1,\ldots,M \tag{17.a}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \tag{17.b}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \tag{17.c}$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1 \;,\; \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \tag{17.d}$$

⋮

(17.a,b,c,d) repeated for each v' = 1,…,V

⋮

$$\sum_{v=1}^{V} CPY_m^{v} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \tag{17.e}$$

Four industry models with different assumptions about production technology and behavior have thus been formulated. Depending on the number of observations in the analyzed dataset, the number of equations in each model is equal to $V\times(M+N+1) + M$ and can therefore be substantial.

By varying the assumptions about the flexibility, managers can by estimating these models obtain further insight into the possible gains, when going from one management system to an individual quota system. The expected gains rise with increased flexibility, with respect to behavior and technology.

An application to Danish fisheries

In this section, we illustrate the framework above by estimating the potential gains from implementing an individual quota system in Danish fishery.

A dataset from 2001 covering 288 Danish fishing vessels is utilized[6]. Extensive economic information is available on these vessels, because they are used to develop the yearly account statistics for the Danish fishing fleet published by the Danish Research Institute of Food Economics[7].

The vessels in the dataset differ from each other in several respects. Most notably, the vessels vary from netters and Danish seiners to trawlers and purse seiners. This variation in types affects the catch and cost composition of the vessels. Larger trawlers, for example, are specialized to catch low-priced industrial species (sandeel, sprat etc.), Danish seiners, beam trawlers and netters catch higher priced consumption species (cod, plaice, herring etc.), while other vessels, for instance medium sized trawlers, catch both types of fish depending on the season.

In the reallocation study, we have aggregated the number of outputs[8] to nine output groups defined as: 1) cod, 2) other codfish, 3) plaice, 4) other flatfish, 5) herring, 6) mackerel, 7) lobster and shrimps, 8) other consumption species and 9) industrial species. All costs in the

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[6] A fictitious observation is also included in the dataset with zero catches and costs in order to facilitate vessels to reduce their catches and costs to zero, i.e. lay-up. The actual number of observations is therefore 289.

[7] The statistics only cover the commercial part of the Danish fishing fleet, i.e. vessels with a total catch value above 219,202 DKK (≈21,225US$) in 2001.

[8] The original dataset included 45 species.

dataset have likewise been categorized as either variable or fixed, and thereafter combined into four types of variable costs and two types of fixed costs, respectively. Variable costs are thus considered to be expenses for: 1) fuel and lubricants, 2) ice and provisions, 3) sale and 4) crew, while fixed costs are divided between costs for: 1) maintenance and 2) insurance and different services.

It is assumed that the allocation of catches observed in the dataset corresponds to a feasible allocation under the management system in 2001. The following analysis therefore reflects the gains that could be realized, if the 2001 catches were allocated optimally among the vessels. As above, we have made different assumptions about the production technology. Each model has been programmed and solved in the optimization software General Algebraic Modeling System GAMS (Brooke, Kendrick, Meeraus, and Raman)[9].

Firstly, we estimate the level of technical efficiency for each vessel by solving the technical efficiency program. Table 3 gives the descriptive statistics for the estimated scores.

Table 3 Output-orientated technical efficiency scores

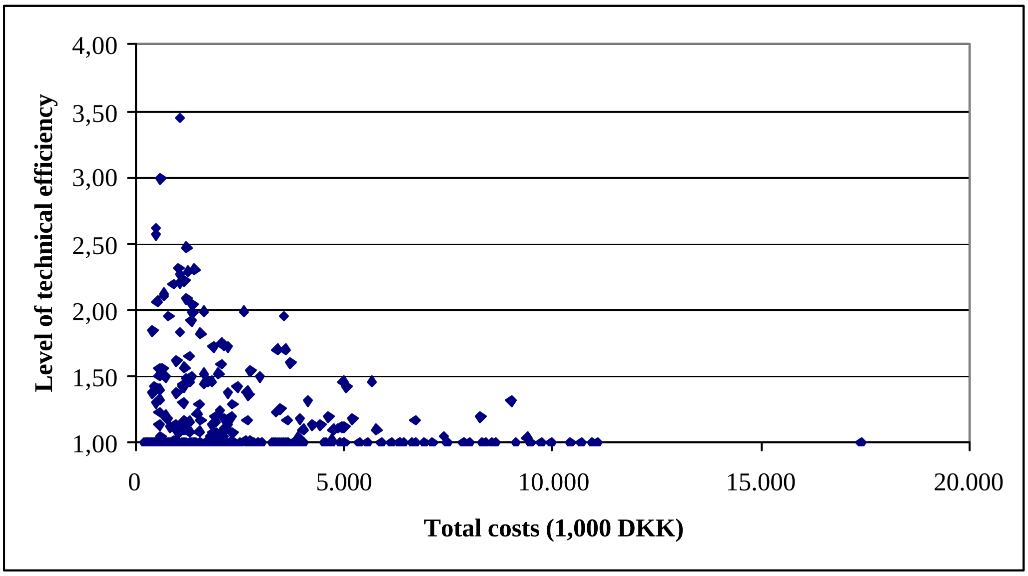
	Mean value	Standard deviation	Maximum value
F	1.22	0.38	3.45

Interpretation of the results in Table 3 indicates that the vessels can increase their output by approximately 20% on average without increasing costs. For some vessels, the increase in output can even be more than three times their present output. The number of 100% technically efficient vessels is estimated to be 143. However, there seems to be a tendency for sample size bias in the estimates as illustrated in Figure 1. The plots of technical efficiency

[9] Each industry model consisted of 4,923 equations, and took around 15 minutes to solve on a Pentium IV (2.4 GHz) processor.

against the total costs suggests that larger vessels may be categorized as technically efficient simply because there is a low number of these vessels.

Figure 1 Technical efficiency as a function of total costs



With this in mind, we now analyze the expected gains and the consequences on the fleet structure from introducing a quota market. Table 4 shows the increase in short run profits or earnings, i.e. catch value minus variable cost. Exclusively reallocating catches without changing the level of technical efficiency and output mix, Model EF-MF estimates that earnings can be increased by 27%. Relaxing each of these assumptions separately implies that earnings can be increased by 38% compared to the earnings in the current regulation system. Thus, despite the obvious differences between allowing mix or efficiency changes, they approximately give rise to the same change in earnings. In the situation with the most flexible production technology, earnings are predicted to increase by 45%, corresponding to 223 million DKK (≈32 million US$).

Table 4 Earnings

	Earnings (1,000 DKK)	Change compared to initial earnings (%)
Initial	494,447	
Model EF-MF	628,582	27.13
Model EC-MF	683,065	38.15
Model EF-MC	685,563	38.65
Model EC-MC	720,515	45.72

If we deduct fixed costs from earnings we get gross profits, i.e. how much is left as rent on the invested capital and any extra payment to the vessel owner. The same pattern can be observed for gross profits as for earnings, cf. Table 5, although the relative changes are higher. In the most flexible situation given by Model EC-MC, gross profits are estimated to increase by 87%, and are thus almost twice as high as in the initial situation.

Table 5 Gross profits

	Gross profits (1,000 DKK)	Change compared to initial gross profits (%)
Initial	260,270	
Model EF-MF	394,404	51.54
Model EC-MF	451,386	73.43
Model EF-MC	448,888	72.47
Model EC-MC	486,338	86.86

For both earnings and gross profits, we observe that over 50% of the gains expected in the most flexible model arises from simply reallocating quotas without allowing technological or behavioral changes. The increases in earnings and gross profits can primarily be related to the fact that catches are reallocated to vessels with lower variable costs, cf. Table 6. Only minor variation in the catch value is observed, as one would expect from the imposed industry restrictions on total catch[10]. Total variable cost is reduced by 30% from an initial level of 752 million DKK to 526 million DKK in the most flexible model, i.e. Model EC-MC.

[10] Reallocation of catches between different vessel types does not alter the catch value, because the price of each species is assumed to be the same for all vessels. This may be an over-simplistic assumption, but is considered acceptable for current illustration purposes.

Table 6 Catch values and variable costs

	Catch value (1,000 DKK)	Variable costs (1,000 DKK)
Initial	1,246,760	752,313
Model EF-MF	1,233,210	604,629
Model EC-MF	1,241,803	556,240
Model EF-MC	1,246,760	563,695
Model EC-MC	1,246,760	526,245

The gains from implementing a system of ITQs would most likely be higher in a long run specification. In the short run, vessels without activity still have to defray the fixed costs, and can therefore only lay-up. In the long run, vessels would be able to decommission, and therefore do not have to pay the fixed costs.

To get an idea of the quota market necessary to support the new allocations, it is interesting to look at the predicted trade patterns. Table 7 depicts the number of vessels that are net-buyers and net-sellers of quota, the total traded amount and the number of vessels ending up with zero catch. A vessel can - on the disaggregate level be - both a buyer and a seller, but here we only focus on the aggregate, net effects.

Table 7 Activity on the quota market

	Number of buying vessels	Number of selling vessels	Number of status quo vessels	Traded amounts (tonnes)	Number of vessels with zero catch
Model EF-MF	124	124	40	112,520	24
Model EC-MF	146	111	31	116,250	14
Model EF-MC	119	169	0	729,066	25
Model EC-MC	98	190	0	841,178	0

We observe an interesting development, when allowing the output mix to change. First of all, every vessel becomes active on the market, i.e. there are no status quo vessels. Also, the number of selling vessels is higher than the number of buying vessels. This could indicate a possible tendency towards concentration on the market, a topic that we will return to in detail later. Last but not least, the possibility to change mix has a dramatic impact on the trade volume. In the two models with output mix fixed, the traded amounts are around 115,000 tonnes, no matter whether technical efficiency is fixed or changeable. Allowing vessels to rearrange their catch composition leads to a factor increase of 6-7 in the trade volume. One interpretation of this is that the economies of scope are very important.

To explore the structural implications and concentration further and the scope effects in particular we have calculated the angle between the output composition of each individual vessel in the dataset and the average vessel in the dataset[11].

Table 8 Output composition angles (degrees)

	Initial	Model EF-MF	Model EC-MF	Model EF-MC	Model EC-MC
Average angle	52.52	52.44	52.11	42.29	45.64

As seen in Table 8, the initial average angle is approximately 52 degrees for the two models with fixed output mix. This is as expected, because the average vessel is only marginally changed. However, allowing the output mix to change results in a significant reduction in the average angle to 42 and 46 degrees, respectively. This can naturally be understood as an exploration of the economies of scope. In a convex production technology like the one modeled by DEA, there are no gains from specialization in the mix, cf. also Bogetoft and Wang for an extended discussion.

[11] The angles have been calculated using $\mathrm{Cos}(\theta_{a,b}) = \left(\vec{a} \cdot \vec{b} \big/ |\vec{a}| \cdot |\vec{b}|\right)$, where *a* and *b* refer to the output vector of the analyzed vessel and the average vessel in the dataset, respectively, and $\theta_{a,b}$ is the angle between them. To reflect the relative importance of the vessels, the average angle is a weighted average using $|\vec{a}|$ as weight. Observe that in multiple dimensions, the average angles can be quite high in the positive orthant. For example, the angle between (1,1,1,1,1,1,1,1,1) and (1,0,0,0,0,0,0,0,0) is 70 degrees.

The tendency for vessels to adjust their size towards the average vessel is also supported by the figures in Table 9. We see that the average catch weight per vessel is approximately unchanged, while the standard deviation and maximum catch weight decrease.

Table 9 Catch weight (tonnes)

	Average	Standard deviation	Maximum	Minimum
Initial	2,157	3,996	21,959	9
Model EF-MF	2,154	4,100	21,959	0
Model EC-MF	2,156	3,992	21,959	0
Model EF-MC	2,157	3,922	20,623	0
Model EC-MC	2,157	2,998	17,662	11

Conclusions

The use of individual transferable quotas is an interesting instrument in the regulator's toolbox. However, before putting it to work, it is valuable to estimate the potential economic gains that can be obtained. After all, changing a current regulatory system to one based upon ITQs will introduce new transaction costs and it may take time before the comparative static effects are realized.

In this paper, we have suggested a framework to estimate the gains that can be expected from implementing an ITQ system. We developed the framework in general terms, making it applicable to any economic sector and any modeling of the production technology. Moreover, we briefly introduced Data Envelopment Analysis and showed how this can be used as one way to operationalize the gains. In the framework, we allowed for different behavioral and technological assumptions regarding the ability to learn best practice and change the output mix. The reasons for reallocation can in these models be related to efficiency, scale and mix effects.

Based on the general framework, we have developed four sectoral models to capture the gains from introducing ITQs in fisheries. These models all seek to maximize profits under individual restrictions for each vessel, while at the same time securing that the pressure upon the harvested resource does not increase.

To illustrate the proposed framework we finally presented an empirical example. We used a dataset of 288 Danish fishing vessels to estimate each of the sectoral models. The analysis reveals that for the included vessels, gross profits may be increased by at least 50%. However, if fishermen are able to change their level of technical efficiency and output mix, the gains may increase by up to 90% compared to the current level. The resulting quota market was briefly characterized. The traded volume – and hereby the amount of reallocations – increased considerably when the output mix was allowed to change. Also, the structural implications were explored. As one would expect after reallocations, the vessels were less specialized suggesting that economies of scope play a significant role, at least when the behavioral and technological flexibility increases.

There are several relevant extensions of the research reported here. In particular, it may be useful to examine the impact of alternative restrictions on the changes in mix and efficiency that are allowed. We have taken a somewhat stylized approach and analyzed only four different and somewhat extreme specifications of the general penalty function.

In the empirical example, we have either frozen the catch composition or we have allowed the vessels to alter their catch composition completely. The latter is an unlikely scenario in most fisheries - at least in the short run. It is unrealistic that a purse seiner, for example, that is highly specialized in catching pelagic species such as mackerel and herring can change to catch demersal species such as codfish. We have used the extreme assumptions to derive an interval of likely effects, but middle of the road assumptions could be introduced as well. As suggested by Korhonen and Syrjänen, this could, be done by allowing the output mix to change with only a certain percentage. Another approach would be to only allow vessels to change their output mix in accordance with the observed output mix of similar vessels.

Alternative restrictions on the possible reallocations can also be derived from the design of the quota system. It may be too costly – or politically unacceptable – to operate a quota system with free trade of all types of catch. The industry implications of alternative designs, however, can be analyzed along the same lines as the technological and behavioral restrictions. It is hereby possible to extend the approach of this paper to analyze the trade-off between political costs, transaction costs and industry profits.

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