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PRODUCTION ECONOMIC MODELS OF FISHERIES:

VESSEL AND INDUSTRY ANALYSIS

PhD Thesis by Jesper Levring Andersen

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Production Economic Models of Fisheries:

Vessel and Industry Analysis

PhD Thesis by Jesper Levring Andersen

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Preface

This PhD thesis has been written in the period from May 2001 to December 2004 during which I have been employed as a research analyst at the Food and Resource Economics Institute.

It has been three years of hard work, and I would probably not do it again. However, despite the many challenges, it has been an enjoyable time and a great experience for me academically and personally, which I would not have been done without. Unfortunately, I did not have the opportunity to go abroad for a longer period, but this has in my mind to a large extent been offset by the many interesting discussions I have had during the period with researchers, regulators and fishermen at conferences and other events both here in Denmark and abroad.

I owe a number of people many thanks for their contributions to this thesis, some of who need to be mentioned in particular.

First of all, I want to thank my supervisor Peter Bogetoft for his excellent supervision. Working together with him has been a great pleasure and a tremendous learning experience for me, which I gratefully appreciate. It is most likely that the contents of this thesis would have been rather different without his creativity and experience.

I am also grateful to Hans Frost for being my co-supervisor, for sharing his great knowledge within fisheries economics with me through many discussions and for reading several of the included papers.

Erik Lindebo also needs thanks for his efforts towards correcting my written English besides for being a colleague and a very good friend. Without his many comments and corrections, this thesis would for sure be a lot more difficult to read.

Furthermore, I would like to acknowledge Jørgen Løkkegaard and the rest of my colleagues in the Fisheries Economics and Management Division at the Food and Resource Economics Institute, for making the place an inspiring and fun place to be.

Finally, I am indebted to the financial support from the Food and Resource Economics Institute and The Centre 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.

Copenhagen, December 2004

Jesper Levring Andersen

English summary

The overall purpose of this PhD thesis is to investigate different aspects of fishermen's behaviour using production economic models at the individual and industry levels.

Three parts make up this thesis. The first part provides an overview of the thesis. The second part consists of four papers analysing efficiency at the vessel level and factors influencing this. The third part consists of two papers and presents industry level analyses and focuses in particular on the likely impacts of implementing individual transferable quotas. The models are able to allow for changes in fishermen's behaviour via individual learning and adjustments in output mix.

All the papers included in *Part II: Modelling and Evaluating Fishermen's Behaviour* consider factors influencing fishermen's behaviour. Knowledge about these factors is important to give a correct description of fishermen's behaviour. However, including all relevant factors in specific analyses is impossible, and it is therefore important to be aware of the most essential ones.

As demonstrated in the literature review of Paper 1, a large number of factors may significantly influence fishermen's short run behaviour, i.e. choice of gear type or fishing location. Behaviour can be viewed as being determined by the fishermen's objectives subject to different restrictions, given by physical resources, time, mental capacity and information, and institutions. The review of the extensive literature gives reasonable support to the neoclassical assumption of utility maximisation through profit maximisation. Furthermore, the literature has demonstrated the importance of physical restrictions and time. The emphasis on these may of course be a consequence of the relatively easy access to such data.

In the following three papers, specific aspects of fishermen's behaviour are analysed. In Paper 2, technical efficiency and reasons for inefficiency are estimated using the Stochastic Production Frontier Approach. The results suggest that the level of technical efficiency is not influenced by the choice of revenue or weight as the output measure. Also, it has no profound impact whether inputs are measured by including fishing power and fishing time separately or as a composite measure. However, the output elasticities are influenced by these choices. Furthermore, vessel size, employment status and experience is found to influence inefficiency.

Paper 3 considers how to include fish stocks in efficiency analyses. The biological developments are important in relation to fisheries, because fish stocks are one of the primary components in the production process. It is worthwhile to evaluate whether different methods of including fish stocks give rise to different conclusions. Three methods are investigated as possible ways to include fish stocks. The first method is based on catch data, while the two other methods are based on independent stock measures. It is shown that estimations based on the former give different results from the ones based on the latter. This conclusion is independent of the choice of time horizon and choice of other input/output measures.

Paper 4 considers fishermen's behaviour to counteract uncertainty. When performing efficiency evaluations, this is done on ex post data. However, in relation to fisheries such an approach may be too harsh, because the fishermen are operating in an uncertain environment with variations in fish stocks, weather, etc. Fishermen therefore seek in their ex ante decisions to cope with uncertainty. If the conditions are better than expected, this may result in some inputs not being used. In ex post efficiency evaluation, this is interpreted as inefficiency, although it was - in an ex ante perception - rational to bring the inputs along. This type of inefficiency can be denoted rational inefficiency. By further developing the method from Bogetoft and Hougaard (2003), an evaluation of 308 Danish fishing vessels is performed. The results indicate that these vessels seek to insure themselves against uncertainty by allowing for the highest flexibility in crew payments, followed by fuel costs, sales costs and costs for ice/provisions respectively.

Accounting for changes in fishermen's behaviour at the industry level is investigated in *Part III: Industry Models of Fishermen's Behaviour and Individual Transferable Quotas*. Many bioeconomic models have been set-up through time to evaluate such changes, but none of these have to the author's knowledge allowed for the behavioural flexibilities, as included in the modelling framework presented here.

The starting point for Paper 5 is the fact that management changes will most likely result in different behaviour by the fishermen. It is necessary to account for these changes, when evaluating the expected gains to be derived. Based on the Data Envelopment Analysis approach, a framework to calculate these gains is provided. The gains are calculated by comparing industry profits in the initial management system with industry profits in a management system based on Individual Transferable Quotas (ITQs). Two types of behavioural flexibility are allowed in the system. They concern the ability to learn best-practice (catch-up) and the ability to change the input and output composition (mix). The framework is then adapted to a dataset from the Danish fishery. Not surprisingly, the gains rise with increased behavioural flexibility. Under the most restrictive assumptions, reallocation of the ITQs will alone result in a 50% increase in gross profits, while this level increases to 87% in the most flexible situation.

The final Paper 6 provides an extension of the framework developed in Paper 5. A complex of restrictions is included to obtain more realistic estimations of the potential reallocations gains, when applied to specific fisheries. The restrictions relate to the determination of best-practice, possible levels of individual learning and changes in output composition. By using a dataset covering the entire Danish commercial fishery, we obtain estimates of the plausible tradability gains if Danish fisheries had been regulated by ITQs in 2002. In the most flexible (optimistic) situation, a 92% increase in gross profits can be expected, but this level is significantly reduced if vessel behaviour is restricted. Furthermore, a series of policy implications are considered in relation to an ITQ system, including concentration, specialisation, market activity and price changes. Finally, plausible consequences of exogenous chocks and changes in management practice in the form of mesh size increases are considered.

Dansk sammendrag

Formålet med denne ph.d. afhandling er at undersøge forskellige aspekter af fiskeres adfærd ved anvendelse af produktions økonomiske modeller på individ- og industriniveau.

Afhandlingen består af tre dele. Den første del giver en oversigt over afhandlingen. Den anden del består af fire papirer, som analyserer efficiens på fartøjsniveau og faktorer som påvirker efficiens. Den tredje del består af to papirer, hvor der gennemføres analyse på industriniveau og fokuseres specielt på konsekvenserne af at indføre individuelle omsættelige kvoter. De opstillede modeller tillader ændringer i fiskernes adfærd via individuel læring og tilpasninger i sammensætningen af output.

Alle papirerne inkluderet i *Del II: Modellering og Evaluering af Fiskeres Adfærd* betragter faktorer, der påvirker fiskeres adfærd. Kendskab til disse er vigtige for at give en korrekt beskrivelse af fiskernes adfærd. Inkludering af alle faktorer i specifikke analyser er dog umuligt, hvorfor det er vigtig at være opmærksom på de mest betydende af faktorer.

Som fremstillet i litteraturgennemgangen i Papir 1 kan en lang række af faktorer påvirke fiskernes kortsigtede adfærd, det vil sige valg af redskab og fiskeområde. Adfærd kan opfattes som værende bestemt af fiskernes målsætninger underlagt en række forskellige restriktioner i form af fysiske ressourcer, tid, mental kapacitet og information, samt institutionelle forhold. Gennemgangen af den omfattende litteratur giver støtte til den neoklassiske antagelse om nyttemaksimering via profit maksimering. Derudover viser litteraturen betydningen af de fysiske ressourcer og tid, hvilket dog i noget omfang kan tilskrives den relativt nemmere adgang til sådanne oplysninger.

I de efterfølgende tre papirer analyseres specifikke forhold af fiskeres adfærd. I Papir 2 estimeres teknisk efficiens og årsager til inefficiens ved anvendelse af den såkaldte Stokastisk Front-metode. Resultaterne viser, at niveauet af teknisk efficiens ikke påvirkes af, om fangstværdi eller vægt anvendes som outputmål. Det har heller ikke nogen afgørende betydning om input måles ved at inkludere ”fishing power” og tid på havet separat eller som et kombineret mål. Disse valg har dog betydning for de beregnede output elasticiteter. Derudover er det fundet, at inefficiensen påvirkes af fartøjsstørrelsen, fiskernes erhvervsstatus og deres erfaring.

Papir 3 analyserer, hvorledes fiskebestanden kan inkluderes i efficiensanalyse. Den biologiske udvikling er vigtig i relation til fiskeriet, idet bestandene er en af de primære komponenter i produktionsprocessen. Det er derfor værdifuldt at evaluere, om forskellige metoder for inkludering af bestandene giver anledning til forskellige konklusioner. Tre mulige metoder undersøges. Den første metode er baseret på fangstdata, mens de to andre metoder er baseret på uafhængige bestandsestimater. Det vises, at estimationer på grundlag af den førstnævnte metode ikke er sammenlignelige med dem opnået ved anvendelse af de to sidste metoder. Denne konklusion er uafhængig af valget af tidshorisont og valg af input/output mål.

Papir 4 analyserer fiskeres adfærd til at modvirke usikkerhed. Når efficiensanalyser udføres, sker dette på ex post data. I relation til fiskeriet er dette dog muligvis for hård en tilgang, idet fiskerne opererer i et miljø præget af usikkerhed som følge af variationer i fiskebestande, vejrforhold osv. Fiskerne søger derfor i deres ex ante beslutninger at forholde sig til usikkerheden. Hvis forholdene er bedre end forventet, kan dette resultere i at nogle inputs ikke anvendes. I ex post efficiensanalyse vil dette blive fortolket som inefficiens, selvom det - i en ex ante opfattelse - var rationelt at tage disse inputs med. Denne type af inefficiens kan betegnes som rationel inefficiens. Ved at videreudvikle metoden fra Bogetoft og Hougaard (2003) udføres en evaluering af 308 danske fiskefartøjer. Resultaterne indikerer, at disse fartøjer søger at forsikre dem selv mod usikkerhed ved at have størst fleksibilitet i besætningsaflønningen efterfulgt af omkostninger til henholdsvis brændstof, salg og is/proviant.

Hensyntagen til ændringer i fiskernes adfærd på industriniveau er undersøgt i *Del III: Industrimodeller for Fiskeres Adfærd og Individuelle Omsættelige Kvoter*. Mange bioøkonomiske modeller er blevet opstillet gennem tiderne til at evaluere sådanne adfærdsændringer, men ingen af disse tillader til forfatternes kendskab den adfærdsfleksibilitet, som modellerne i denne afhandling.

Udgangspunktet i Papir 5 er det faktum, at ændringer i regulering ofte vil resultere i en ændret fiskeradfærd. Det er nødvendigt at tage hensyn til sådanne ændringer, når de forventede gevinster beregnes. Ved anvendelse af Data Envelopment Analyse metoden opstilles en ramme til beregning af disse gevinster. Gevinsterne er beregnet ved at sammenligne industriprofitten under det initiale reguleringssystem med den under et reguleringssystem baseret på Individuelle Omsættelige Kvoter (IOK'er). To typer af adfærdsfleksibilitet tillades i form af muligheden for at lære den bedste metode og muligheden for at ændre sammensætningen af inputs og outputs. Den opstillede ramme anvendes efterfølgende på et datasæt for dansk fiskeri. Ikke overraskende vises gevinsterne at stige med øget adfærdsfleksibilitet. Under de mest restriktive adfærdsantagelser vil alene en reallokering af IOK'erne resultere i en stigning i bruttooverskuddet på 50 %, mens denne stiger til 87 % i den mest fleksible situation.

Det sidste Papir 6 udbygger rammen opstillet i Papir 5. Et kompleks af begrænsninger inkluderes, således at mere realistiske estimationer af de potentielle gevinster ved reallokering kan opnås, når rammen anvendes på specifikke fiskerier. Begrænsningerne relaterer sig til bestemmelsen af den bedste metode, muligheden for individuel læring og ændringer i fangstsammensætningen. Ved at anvende et datasæt, som dækker hele det danske kommercielle fiskeri, estimeres de potentielle gevinster, hvis dansk fiskeri havde været reguleret med IOK'er i 2002. I den mest fleksible (optimistiske) situation kan en stigning på 92 % i bruttooverskuddet forventes, men dette niveau reduceres betydeligt, når fartøjernes adfærdsfleksibilitet begrænses. Yderligere en række forhold inddrages i form af koncentration, specialisering, aktivitet på markedet og prisændringer. Slutteligt analyseres de forventelige konsekvenser af eksogene chok og ændringer i reguleringen i form øget maskestørrelser.

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Part I

Introduction

Production Economic Models of Fisheries: Vessel and Industry Analysis

by Jesper Levring Andersen

Abstract

This introductory section of my PhD thesis presents the background, objectives and structure of the thesis. Six papers comprise the thesis. The first four papers use modern production economic models to investigate individual fishermen's behavioural patterns. The last two papers combine the individual fishermen models into an industry model, and use this to investigate the impact of different management systems.

Introduction

Investigation of human behaviour has been performed since ancient times and is the focus of an almost infinite number of studies. Restricting ourselves to social sciences, plausible models have been proposed by psychologists, sociologists, anthropologists and economists. However, the approaches have different advantages and for instance, Frey (1999, p. 11) mentions that "*economics seems to be better equipped to explain changes in human behaviour, while sociology seems to be better equipped to explain historically existing levels*".

Investigation of fishermen's behavioural patterns has also been an important area within fisheries research. The importance hereof for both biologists and economists is - as mentioned by Holland and Sutinen (1999, p. 253) - that "*failure to anticipate and respond to fishers increasing or decreasing and redistributing their effort among fisheries may reduce economic benefits and can result in severe declines or collapse of fish stocks*". With this in mind, it is necessary to find an acceptable method to investigate fishermen behaviour. Carlson (1975, p. 84) calls attention to the fact that "*the behavioural model of interest for fishermen is most likely an economic model*". The economic methodology can thus be seen as a preferable method to investigate fishermen's behaviour, and will therefore be utilised in this PhD thesis.

Economists have since the seminal paper by the Danish economist Jens Warming in 1911, cf. Andersen (1983), participated in the behavioural analyses of fishermen. The behavioural patterns are of course dependent upon the type of decisions to be taken. For instance, is the fisherman choosing where to fish? What to fish? Or is the decision related to possible investments in a new vessel? It is not necessarily the same factors that are important to these different types of decisions. For example, the interest rate will most likely influence the fishermen's investment choices, but it does not necessarily influence the choice of a location to fish in.

1. Purposes

It is a complicated task to describe behaviour due to the large number of factors which can potentially influence this behaviour. Vessel size, skipper qualifications, fish prices, regulations, weather, stock situations, and many other factors may potentially influence the behaviour and may vary between specific fisheries and fishermen.

The first purpose of this PhD thesis has therefore been to focus on some of the important but to some extent less investigated factors influencing fishermen's behaviour. The thesis focuses on three aspects, namely 1) estimation of fishermen's level of technical efficiency and the factors influencing this level, 2) how to account for stock levels in efficiency estimations and 3) how fishermen seek to account for uncertainty.

To make optimal management decisions at the system level, it is important to be able to make ex ante evaluations of the plausible costs and gains from changing management. Setting up models to analyse the consequences of management changes in fisheries requires a flexible modelling framework, which is able to account for behavioural changes, given that fishermen seek to maximise profits. Under the current regulations, fishermen choose a behavioural pattern that maximises their profit. However, changes in regulations are likely to result in a behavioural shift to maximise profit in the new regime.

The second purpose of this PhD thesis has therefore been to set up a flexible framework which can easily account for different behavioural changes that can be expected following a change in management. The focus has been put on individual learning and the possibility to change catch composition.

2. Structure

The first part consists of four papers. In Paper 1, an extensive literature review is performed to illustrate the array of factors influencing fishermen's short/medium run behaviour. The following three papers investigate different aspects of fishermen's behaviour. An analysis of technical efficiency is undertaken in the Paper 2 with focus on how to measure inputs and outputs, and it is further investigated which factors influence the level of technical efficiency. In Paper 3, an empirical study is performed focusing on the consequences of using different approaches to include fish stocks in productivity analysis of fishermen. Paper 4 investigates the possibility to interpret ex post inefficiency as an ex ante rational decision by the fishermen that counteracts the uncertainties that naturally embrace this type of production.

The second part consists of two papers. In Paper 5, individual fishermen's production possibilities are included in industry linear programming problems, which can then be used to analyse the consequences of management changes. Furthermore the framework is able to account for plausible behavioural changes by the fishermen. Paper 6 extends the framework derived in Paper 5 to make this more compliant with real life fishing activities. In addition to

the theoretical issues covered in both papers, empirical estimations are performed. They give indications of the likely gains to be expected if Danish fisheries were to be regulated by individual transferable quotas, instead of the current management regime.

3. Approaches

Behaviour at the vessel level is analysed in Part II. Besides the review conducted in Paper 1, the other three papers consider selected issues using the primal approach contrary to the dual approach. The *primal approach* estimates the technical relationship between the inputs and outputs, while the *dual approach* estimates the economic relationship between inputs and outputs in the form of revenue, cost or profit functions. In the dual approach, it is assumed that input and output prices are determined exogenously and that input and output use is determined in order to maximise profit, maximise revenue or minimise costs. For further insight, readers are referred to Chambers (1988).

Based on the primal approach, two methods are applied. Both methods estimate production frontiers illustrating best-practice behaviour, as opposed to traditional production estimations reflecting "average" behaviour. The applied methods are Stochastic Production Frontier and Data Envelopment Analysis. These methods are described within the respective papers, but readers seeking more general introductions may consult books like Kumbahkar and Lovell (2000) on Stochastic Production Frontier, Cooper, Seiford and Tone (2000) on Data Envelopment Analysis, and Coelli, Rao and Battese (1999) on both approaches.

The industry level models in Part III also use the primal approach. The industry models set up in this section are optimisation models. Here behavioural changes are allowed in an attempt to maximise profits given some explicit restrictions about production structures and catch possibilities. This type of model is thus able to answer "*what's best*" questions, cf. Conrad (1999). The most obvious alternative to optimisation models is simulation models, where "*what if*" questions are addressed. In simulation models, behaviour is specified by the parameters in the equations, and restrictions and objectives are included in these equations. Further insight into these models can for instance be found in Pascoe (2000).

To sum up, an overview of the different levels of analyses and methods utilised in the included papers, excluding the general review in Paper 1, is given in the table below.

	Vessel level	**Industry level**
Stochastic Production Frontier	Paper 2	
Data Envelopment Analysis	Papers 3 and 4	Papers 5 and 6

The PhD thesis can thus be divided into two general parts, namely *Modelling and Evaluating Fishermen's Behaviour* and *Industry Models of Fishermen's Behaviour and Individual Transferable Quotas*, respectively.

4. Abstracts of the included papers

In the following section, an abstract of each paper comprising this PhD thesis is provided.

Paper 1:
Determinants of fishermen's behaviour
by Jesper Levring Andersen

Abstract
In economic theory it is generally assumed that agents seek to maximise utility being derived from one measure (for instance profits) or several measures (for instance profits and adventure). The behaviour is however influenced by restrictions, which limit the solutions that are possible to obtain. This approach is also used in fisheries economics, where the fishermen's behaviour is influenced by many different factors such as weather, tradition and regulation. Considering that it is almost impossible to identify and model all the possible factors, it is important to include at least the most influential ones in a specific analysis to obtain the best possible description of fishermen's behaviour.

The purpose of this paper is to describe the objectives and restrictions that influence fishermen's short run behaviour based on a review of the extensive literature within fisheries economics. Initially, a framework for the review of fishermen's behaviour is derived from the economic theory about human behaviour. Based on this, fishermen's behaviour is investigated with respect to possible objectives and restrictions, classified into physical resources, time, mental capacity and information, and institutions.

In general, the literature supports the neoclassic assumption that fishermen are maximising their utility through profit maximisation. Furthermore, the focus has primarily been on restrictions related to physical resources and time due to their relatively straightforward measurement. However, some papers have also investigated other restrictions in different contexts.

Status
The paper is forthcoming as a working paper published by the Food and Resource Economics Institute.

Paper 2:
Using different inputs and outputs to estimate technical efficiency in fisheries: An application to Danish seiners in the North Sea and Skagerrak
by Jesper Levring Andersen

Abstract
The number of articles analysing technical efficiency in fisheries has risen considerably in the last couple of years, and many different measures of inputs and outputs have been. At

present, however, no consensus has been established about which measures to use in such an analysis. In order to give some insight into which measures to choose, this paper estimates technical efficiency using three different output measures and two different input measures. The estimations are performed assuming that the functional form of the estimated production frontier can be represented by the flexible translog function. Furthermore, inefficiency models are estimated in order to explain why some vessels do not behave as best practice. The dataset used covers the Danish seiner fleet fishing in the North Sea and Skagerrak in the period 1987 to 1999.

The results show that it is not highly important whether output is measured in catch weight or catch revenue with respect to level of technical efficiency and estimation of the inefficiency model, at least for the dataset used. However, using revenue-weighted catch weight as the output measure generally gives other results. Looking at output elasticities, the results are not as decisive. The choice of input measure also has little influence on technical efficiency, but the level of output scale elasticity is affected. Results from the estimated inefficiency models indicate that inefficiency decreases with increases in size, that full-time fishermen are more efficient than other types of fishermen, and that experience with the primary fishing area reduces inefficiency.

Status
An earlier draft of this paper has been published as working paper no. 10/2002 at the Food and Resource Economics Institute. It has also been presented at the 14th annual conference of the European Association of Fisheries Economists in Faro, Portugal, 25-27 March 2002.

Paper 3:
Inclusion of stocks in multi-species fisheries: The case of Danish seiners
by Jesper Levring Andersen

Abstract
Efficiency analysis in fisheries has become an area of increased research. However, setting up models to perform such analyses is complicated and several important modelling issues, including choice of inputs and outputs, level of aggregation and inclusion of stock indices, have only briefly been addressed in the literature. Using data on Danish seiners and Data Envelopment Analysis to estimate efficiency, the latter issue is addressed in this paper. Production in fisheries is obviously dependent on the fish stocks. Comparing vessels efficiency therefore needs to account for stock developments. Three methods to include fish stock are analysed. It is shown that estimations based on Catch Per Unit Effort stock measure gives other results than the estimations based on independent stock measures, and that this is independent of the choice of time horizon and choice of input/output measures.

Status
The paper is published in *Marine Resource Economics* 2005, vol. 20, no. 2, pp. 163-184.

Paper 4:
Rational Inefficiency in Fisheries
by Jesper Levring Andersen and Peter Bogetoft

Abstract
Efficiency evaluations of Decision Making Units (DMUs) are usually done ex post and not ex ante. This may be a too harsh approach, especially if the DMUs are operating under significant uncertainty. Fishermen are often considered to operate in such an environment. The output arising from using given inputs is seldom known with certainty, because external factors such as availability of fish, equipment performance and weather may have a significant influence. Thus, when fishermen decide the inputs to bring on a trip, they try to be in the best possible position to handle the expected uncertainty. This may result in bringing excess inputs that are not used or strictly needed. This situation will usually be interpreted as inefficiency in ex post analyses despite of the fact that it may have been rational to bring them in the first place. One can denote such inefficiency as rational inefficiency.

In this paper, we investigate the allocation of inefficiency on the different input factors and we use this to infer which factors are most useful to insure against the ex ante risk. More specifically, we use the method from Bogetoft and Hougaard (2003) to find the allocation of slack that is consistent with rational behaviour. Based on data from 308 Danish vessels, we show that fishermen tend to allow for the highest flexibility in crew payments, followed by fuel costs. Sales costs and ice/provision costs seem to be the least flexible. Based upon specific utility functional forms, we find support for these conclusions.

Status
The paper is work in progress. A previous version has been presented at the 16th annual conference of the European Association of Fisheries Economists in Rome, Italy, 5-7 April 2004.

Paper 5:
Quota Trading and Profitability: Theoretical Models and Applications to Danish Fisheries
by Jesper Levring Andersen and Peter Bogetoft

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 behavioural 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 potential gains to the industry from tradable quota under each of four sets of technological and behavioural characteristics.

Status
The paper is accepted for publication in European Journal of Agricultural Economics. It has also been selected and presented at the 15th annual conference of the European Association of Fisheries Economists in Brest, France 14-16 May 2003 and the 8th European Workshop on Efficiency and Productivity Analysis in Oviedo, Spain, 24-27 September 2003.

Paper 6:
Potential gains from using Individual Transferable Quotas to regulate Danish fisheries
by Jesper Levring Andersen and Peter Bogetoft

Abstract
Previous articles have shown that there are significant gains to be expected from implementing an Individual Transferable Quota system within fisheries. Andersen and Bogetoft (2003) developed a new approach to calculate expected tradability gains in such systems. Using Data Envelopment Analysis, linear programming problems were formulated to capture reallocation gains under two behavioural restrictions. This considers the ability to learn best-practice and to change output composition. In this paper, we extend the proposed method by focusing on a complex of restrictions, which can be included in order to obtain more realistic estimations, when applied to specific fisheries.

In order to illustrate the applicability, a dataset covering the entire Danish commercial fishery is utilised. Based on this, we estimate the tradability gains in the most flexible situation to be an increase in gross profits of around 90%. However, we also show that the potential gains are significantly reduced, if the flexibility in vessel behaviour is restricted. A series of policy implications is analysed including concentration, specialisation, market activity, price changes, etc. Attention has often been drawn to these effects when the implementation of Individual Transferable Quotas in fisheries is discussed. Finally, we analyse the consequences of exogenous chocks and changes in management practice in form of mesh size increases.

Status
The paper has been presented at different workshops including 'Efficiency Evaluations and Allocations in Time and Space' in Copenhagen, Denmark, 10th June, 2004. Furthermore has parts of this paper been published in the journal Fisk & Hav 2005, vol. 59, pp. 12-21 (in Danish).

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Part II

Modelling and Evaluating Fishermen's Behaviour

Determinants of fishermen's behaviour

by Jesper Levring Andersen

Abstract

In economic theory it is generally assumed that agents seek to maximise utility being derived from one measure (for instance profits) or several measures (for instance profits and adventure). The behaviour is however influenced by restrictions, which limit the solutions that are possible to obtain. This approach is also used in fisheries economics, where fishermen's behaviour is influenced by many different factors such as weather, tradition and regulation. Considering that it is almost impossible to identify and model all the possible factors, it is important to include at least the most influential ones in a specific analysis to obtain the best possible description of fishermen's behaviour.

The purpose of this paper is to describe the objectives and restrictions that influence fishermen's short run behaviour based on a review of the extensive literature within fisheries economics. Initially, a framework for the review of fishermen's behaviour is derived from the economic theory about human behaviour. Based on this, fishermen's behaviour is investigated with respect to possible objectives and restrictions, classified into physical resources, time, mental capacity and information, and institutions.

In general, the literature supports the neoclassic assumption that fishermen are maximising their utility through profit maximisation. Furthermore, the focus has primarily been on restrictions related to physical resources and time due to their relatively straightforward measurement. However, some papers have also investigated other restrictions in different contexts.

Keywords

Fishermen, behaviour, short run, objectives, restrictions

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Introduction

Many different types of analyses within social science have been performed historically for fisheries. However, no matter the type of analysis, detailed knowledge about the fishermen's behaviour is required in order to obtain realistic research results. For instance, in setting up bioeconomic models that combine both economic and biological considerations in fisheries, one of the primary parts is related to the behaviour of fishermen. Despite the purpose of the bioeconomic model, the assumptions about fishermen's behaviour are critical for the results, and thus conclusions, reached as noted in Wilen (1979). Wrong assumptions about the behaviour may/will implement results that are very different to the true results. This can have considerable consequences as phrased by Bockstael and Opaluch (1983, p. 126): "*without detailed and accurate prediction of firms' response to policies, regulation can have unexpected and adverse results*".

An encyclopaedia definition of human behaviour describes it as the collection of activities influenced by culture, attitude, emotions, values, ethics, authority, rapport, hypnosis, persuasion and coercion. A significant number of factors can thus have an effect on behaviour, but considering all these in specific analyses is often not possible due to measurement problems and estimation practicalities. However, in order to obtain a reasonable level of realism, it is important to include the most essential ones and be aware of how the excluded factors can influence the derived results.

From an economic point of view, fishermen's behaviour can principally be described as one seeking to compose the use of production inputs, including fish stocks, in such a way that profits are maximised. It is however important to initially be aware that the behavioural model may depend on the type of fishermen being analysed. A distinction between commercial and non-commercial fishermen hence seems obvious.

Commercial fishermen fish to make a living, and run their activities as firm-like as possible with recognition of the special features characterising fisheries. The most plausible behavioural model of a commercial fisherman is therefore an economic model, as noted by Carlson (1975). However, describing the behaviour of fishermen (and human behaviour in general) by using an economic model is not a straightforward task, because no single accepted micro-economic theory of the decision making by fishermen exists, cf. Kirkley and Strand (1988).

Non-commercial fishermen, which can also in some sense be considered as recreational fishermen, may on the other hand have a behavioural model which is different from the one characterising commercial fishermen. Economic forces do supposedly not drive them in the same degree as in the case for commercial fishermen. Instead fishing is performed as a hobby, where the benefits are of a more immeasurable character, such as the joy of fishing and good fellowship. These factors are most likely also present in commercial fisheries as well, but they are not considered the driving force for their behaviour.

It is also necessary to consider the time perspective when analysing fishermen's behaviour, despite the fact that it complicates things. As mentioned by Bockstael and Opaluch (1983), a deduction can be made between three different time perspectives in fisheries. These are the short run where target species are chosen, the intermediate run where gear type and location in form of fishing area are chosen, and finally there is the long run, where investments and sector entry/exit are determined. The short and intermediate runs coincide to some extent, considering that if one of these is chosen, the other one is partly dependent on this.

The short and intermediate run horizons are primarily applicable when analysing consequences of using management instruments such as quota restrictions, closed areas, closed seasons, limited entry and technical restrictions. In this type of analysis, it is highly relevant to investigate the plausible changes in catches and locations, which the fishermen can be expected to take, if these instruments are implemented. The long run analysis on the other hand primarily relates to the capacity discussion about the optimal size of the fishing fleet and thus investments. In order to limit the following analysis, the focus will only be on the behaviour related to the short and intermediate run decisions[1], and will for simplicity be referred to as short run.

With all of the above in mind, the purpose of this paper is to review some of the most important contributions to the description of commercial fishermen's behaviour in the short run. The behaviour of non-commercial fishermen will not be considered, but many of the points made will be applicable for them as well.

The focus in this paper will be on an economic approach to behavioural modelling, which is as mentioned plausible when only commercial fishermen are considered. However, in order to obtain a more formalistic framework for describing fishermen's behaviour, the review will start with a brief examination of the general theory of human behaviour in section 1. The purpose is to set up the primary components that are necessary to address in the following sections. Sections 2 and 3 will then review some of the tremendous amount of literature within fisheries that describes fishermen's short run behaviour. The focus in section 2 is on the objectives that fishermen are expected to have and how these can be measured, while section 3 reviews the restrictions that fishermen encounter, when conducting their fishing activity. To close the paper, some final comments are made.

1. A general framework of human behaviour

Giving a brief and at the same time thorough description of human behaviour is not an easy task considering the vast amount of literature and theories that are available. The following

[1] Theoretical considerations about investments within fisheries can be found in Clark (1985) and Clark, Clarke and Munro (1979) and some empirical applications are made in Bjørndal and Conrad (1987), Penson, Tettey and Griffin (1988) and Jensen (2000).

section will therefore not go deeply into the different topics, but instead summarise the main outlines of human behaviour as seen from an economic perspective in order to obtain a logical structure for the forthcoming sections.

In his book from 1999, Bruno S. Frey described human behaviour in an economic sphere from the viewpoint of the "New Institutionalist Schools" of thought[2]. The "New Institutionalist Schools" are a collection of schools seeking to explain political, historical, economic and social institutions in terms of neoclassical economic theory. It seeks to expand the neoclassic rationality assumptions of maximisation and no scarcity of information with a broader view, where social rules become important to predict human behaviour. However, the New Institutionalist School does not exclude the neoclassic rationality approach.

Following Frey (1999), the Neoinstitutionalist School describes human behaviour as being "*determined by their wishes (preferences) and the constraints they face*" (Frey 1999, p. 3). This general approach will be used in the following to describe human behaviour.

In order to perform any analysis, it is thus essential to clarify which objectives humans are seeking to accomplish in order to rank his or her preferences[3], and thus decide the behaviour that leads to the best fulfilment of these objectives. The objectives can thus be considered as the driving force behind all actions conducted by humans. Generally, it is in economic theory assumed that humans seek to maximise their utility. This leads to the question of how to measure utility, and many different possibilities have been put forward in the economic literature.

The discussion of how to measure utility will be kept for the next section, but it should be noted that when analysing a group of humans, it is traditionally assumed that utility is measured in the same way. The reason for this assumption is a wish to keep the analysis from becoming too complicated and cumbersome.

When deciding on a specific behaviour in order to obtain their objective, humans are usually restricted by many different factors such as "*income, time, imperfect memory and calculating capacities, and other limited resources, and also by the available opportunities in the economy and elsewhere*" Becker (1993, p. 386). Based on this citation, four groups of restrictions can be derived.

The first group covers what Becker (1993) calls "*income*" and "*other limited resources*". The former can more generally be referred to as the available physical resources that can directly be influenced by the human behaviour. The latter can be perceived as including resources that

[2] Important contributors are Gary S. Becker, Ronald Coase, Armen Alchian, Oliver Williamson and James Buchanan.

[3] Human preferences can be defined as the ranking or ordering over all possible behavioural patterns, no matter whether they are possible or not.

cannot (or only indirectly) be influenced by the human. Regarding the former, these restrictions can be modified. However, this is only to a certain extent, because it is for instance not possible to have a behaviour which imposes a cost in excess of the available money, including borrowing. The former cannot be modified by the human behaviour, but is still a physical restriction limiting his or her behavioural possibilities. Examples could include hours of sun, the number of fish in the oceans etc.

The second group relates to "*time*". Becker (1993) mentions time to be an important restriction considering that there are only 24 hours in each day and that this restriction cannot be changed, as is the case with the physical resources for instance. This of course increases the focus on the best possible utilisation of the time available.

"*Imperfect memory and calculating capacities*" constitute the third group and can be referred to as the mental capacity of the human mind. Within the methodology of economics, these restrictions have primarily been discussed in relation to two rationality concepts. These are unbounded (unlimited) rationality and bounded (limited) rationality, as mentioned by Knudsen (1991). However, other types of rationality such as procedural rationality, intended rationality, subjective rationality and selective rationality have also been suggested, but these will not be described here.

If human behaviour is assumed to be unbounded rational, it implies that the individual seeks to pursue self-interest under perfect information, i.e. has unlimited information about past, present and future events, and unlimited calculation power. These assumptions make the human capable of finding a maximising solution to the decision problem, given the restrictions faced. The neoclassic school of thought is the most well known economic methodology founded on the assumption of unbounded rationality. In this methodology it is assumed that agents being consumers are seeking to maximise their level of utility, while agents being producers are trying to maximise their profits (Quirk 1987). This school of thought, and thus the assumption of unbounded rationality, has gained many supporters, because it makes the mathematical formulations of a society more straightforward.

Even though the new institutionalism is founded on the neoclassic theory, it disagrees with the assumption of unbounded rationality. Chase, Hertwig and Gigerenzer (1998, p. 207) formulate the most severe problem to be "*the unrealistic demands of the mind*". Instead, an assumption of bounded rationality becomes relevant, because it assumes that humans are not equipped with full information and infinite calculation power when making their decisions. Thus, individuals are not capable of finding all possible solutions to their problems, and do therefore not necessarily obtain a maximising solution. A stopping rule is thus needed in order halt the search. One stopping rule could be to consider humans as optimising under constrained information, where the search for a better solution is stopped by taking "*the costs of time, information and computation into account*" (Chase, Hertwig and Gigerenzer 1998, p. 208). Another stopping rule could be that humans have predefined a satisfying solution, and

then halt the search, when this is obtained. None of these solutions necessarily imply realisation of the maximising solution found under unbounded rationality.

Friedman (1953) defended the unrealistic assumption of unbounded rationality by putting forward the famous as-if defence. This defence postulates that even though agents may be bounded rationally, only those who act as-if they were maximising will survive in the long term, thus a form of natural selection, where only the agents finding the maximising solution survives.

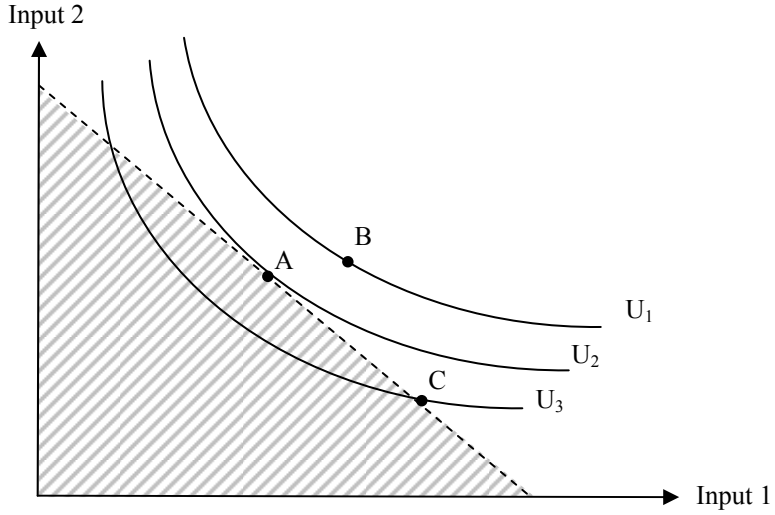
The final fourth group "*the opportunities available in the economy and elsewhere*" can be viewed as the restrictions imposed by the institutions embedded in society and the actions taken by other humans. Regarding the institutions, this refers to all the formal and informal rules and procedures embedded in the society, where the humans behave. The institutions are essential, because they describe the possibilities, but also the restrictions that humans are facing when determining their behaviour. According to Frey (1999), a distinction can be made between three different types of institutions: 1) decision making systems, 2) norms, traditions and other behavioural rules and 3) organisations. All these can have a significant influence on the behaviour conducted by agents in different situations.

Decision making systems refer to the basis upon which decisions are taken in the society analysed, and include topics such as the laws and regulatory framework, how prices are determined and the distribution of authority. Regarding the norms, traditions and other behavioural rules, these are primarily determined historically through religion, upbringing, education, attitudes and motives[4]. Finally, organisations refer to all the different groups present in society. Among these are the state, interest groups and family associations, thus covering actions taken by other humans.

In order to describe human behaviour it is hence necessary to specify the objectives, i.e. preferences and restrictions (physical resources, time, mental resources and institutions). These are all essential, because they define the environment in which the human behaviour and thus choices are being made. To clearly exemplify the set up, an illustrative situation in the two-input case is shown in Figure 1.1.

[4] See McFadden (1999) for a further discussion of attitudes and motives.

Figure 1.1 Utility maximisation



The human seeks to maximise his utility given by U, with $U_1>U_2>U_3$. However, a restriction given by the dotted line restricts the use of input 1 and input 2. In order to maximise utility within the restriction, a point within the grey shaded area must therefore be chosen. It will therefore be optimal to use quantities of input 1 and input 2 as at point A, because this gives rise to the highest possible utility U_2. Point B could give a higher utility U_1, but is not possible due to the included restriction. Point C is on the other hand possible, but will only give a utility of U_3, which is lower than in point A.

With the above framework in mind for describing human behaviour, the following sections will review how utility is measured, and which restrictions can be found in the literature that analyses fishermen's short run behaviour.

2. The objectives of fishermen

As mentioned in the previous section, economic theory generally assumes the overall individual objective to be one of utility maximisation. A commercial fisherman can be put into this framework as being a producer seeking to pursue a behaviour that leads to the maximisation of his utility level. Given the array of uncertainties found in fisheries, it is however commonly assumed that fishermen seek to maximise the expected utility, when making their ex ante decisions about gear and location choice[5].

As also mentioned, utility is not a concept which can be directly measured. It is therefore necessary to find relevant and measurable variables that are considered applicable to indirectly measure the level of utility, i.e. their objective. Despite recognising that utility maximisation is the overriding objective, the literature has traditionally referred to the quantitative measure of utility as being the objective. For example, if it is assumed that

[5] The different uncertainties observed in fisheries will be discussed in the next section.

maximisation of utility is accomplished through profit maximisation, the objective is referred to as profit maximisation. This approach will also be used in the following.

This section will firstly focus on different objectives fishermen can be assumed to have in relation to fisheries. Secondly, a review of empirical studies will be used to identify which objectives fishermen can be assumed to have.

An array of different objectives leading to utility maximisation has been put forward in the literature of economics. The undisputedly most used for firms is profit maximisation, with profit defined as revenues minus costs. The explanation for choosing this could follow along the lines described in Opaluch and Bockstael (1984). Utility is derived from the level of wealth, which is affected by the level of profit. If the profit is positive (negative), the level of wealth increases (decreases) and utility rises (falls). Hence, when fishermen choose a location to fish in, they are assumed to select the one with the highest profit, if unbounded rationality is assumed. Likewise, if bounded rationality is assumed, they choose a location with a satisfying level of profit.

Many examples can be found in the literature, where fishermen are assumed to be profit maximisers. Dating back to the first articles of fisheries economics by Jens Warming in 1911 (Andersen 1983), this assumption has by far been the most utilised objective in the analysis of fishermen's behaviour. A few examples include Squires (1987,1988) analysing the New England otter trawl fishery and Dupont (1990,1991) studying the British Columbia salmon fishery.

Other monetary objectives have also been proposed as a practical method for indirectly obtaining utility maximisation. Baumol (1959) proposed to use revenue maximisation, i.e. fishermen choose to fish in the area where the highest catch value is obtained. Possible explanations for this objective were also put forward in Baumol (1959). One was that firms with low sales lost their visibility on the market, i.e. a marketing set back. Another explanation was personal self-interest from the executives due to a correlation between sales and personal payment. With respect to fisheries, only the latter explanation seems relevant depending on how the remuneration is calculated.

Carlson (1973) proposes that revenue maximisation is a likely behavioural pattern when vessels have chosen an area to fish in. In this situation, fuel cost for instance is approximately known, and maximisation of revenue becomes the only way to obtain the highest profits. Kirkley and Strand (1988) analyse the trawl fishery on Georges Bank, New England, and assumes a single fixed input, thus making the revenue maximisation assumption reasonable. In such a fishery, revenue maximisation will coincide with profit maximisation. Several other articles, in which revenue maximisation is assumed, can be found in Squires and Kirkley (1995).

Cost minimisation has also been considered as a possible objective for fishermen. In situations with very fluctuating or uncontrollable revenues, it can be relevant to minimise the cost level. Fisheries are traditionally characterised by a high degree of stochasticity in catches due to factors such stock and price fluctuations, weather and luck, cf. Gates (1984), which can justify using cost minimisation as the objective. This measure is also relevant in a situation where the output level is specified, in for instance a management system based on total allowable catches.

Compared to profit and revenue maximisation, cost minimisation has not been utilised as frequently in the fisheries literature as a utility maximising objective. Some examples are however available. For instance, Lipton and Strand (1992) assume that fishermen are cost minimisers with a predetermined output level in the Atlantic surf clam industry, and analyse the consequences of changes in stock size and regulations on the industry structure. Bjørndal and Gordon (2001) analyse the Norwegian spring-spawning herring fishery and estimate the economic costs of harvesting herring for three different fleet segments. Gordon, Asche and Bjørndal (2002) estimate optimal quota size, potential rent and optimal fleet size in the output restricted Norwegian cod fishery using the behavioural assumption of cost minimisation.

However, revenue maximisation and cost minimisation are basically identical to profit maximisation, if revenues or costs are assumed fixed in the short run.

Examples of non-monetary objectives applicable as ways of obtaining utility maximisation are not straightforward. Anderson (1980) discusses the term Worker Satisfaction Bonus (WSB), and the importance of including this measure in the utility function. WSB covers an array of elements including "*adventure, risk taking, challenges with the elements, fellowship, and ties to traditional behavior which satisfaction is presumably not available to the same degree in other types of work available to them*" (Anderson 1980, p. 859). Being one's own boss, competition with other fishermen, reputation and opportunity for self-development could be other examples of non-monetary measures, cf. Feeny, Hanna and McEvoy (1996). None of these measures are however directly measurable, or therefore applicable, when trying to model fishermen's choices in the short run. One possible non-monetary measure could be travel time, which is measurable. Due to family reasons, fishermen could prefer fishing grounds close to the homeport, thus seeking to minimise the travel time in order to maximise utility. However, no models have to the knowledge of the author applied this approach in relation to fisheries.

Instead of having only one objective constituting the objective of utility maximisation, one can also include several objectives in the analysis. This is known as multi-objective analysis. This type of analysis necessarily demands determination of the weights attached to each measure. For a given level of utility, a trade-off between the different objectives is thus obtained. Inclusion of several objectives only seems relevant if these to some extent are opposed to each other. Thus, it is not possible to have behaviour where more than one

objective is maximised at the same time. Further insights into the theory of multi-objective analysis can be found in Steuer (1986).

To investigate the most common objectives that fishermen pursue in order to maximise their utility, a distinction can be made between two categories: 1) studies using estimation techniques based on available data of for instance effort and catches and 2) surveys explicitly asking fishermen about their objectives by using questionnaires.

Several methods have been used to study and determine the objectives of fishermen. Hilborn and Ledbetter (1979) use descriptive statistics to analyse the location choice of the British Columbia purse seine fleet fishing for salmon. They conclude that this fleet tends to move between areas in order to maximise the economic gain (profit). They reject that the fishermen have maximisation of catch revenue as their objective. The economic gain is corrected using the relative desirability. In the given framework, this desirability can be considered a restriction in the fisherman's optimisation problem.

Both Dupont (1993) and Eales and Wilen (1986) use econometric methods in their analysis. Dupont (1993) analyses the location choice for the British Columbia salmon fishery on an individual level. Two approaches are used to measure expected utility. In the first, utility depends on profit and its variability, and in the second it depends on profit and wealth, defined as the sum of pre-known wealth and expected profitability of a fishing location. The conclusion is that profit is important for fishermen's location choice, but also that wealth is even more important. Eales and Wilen (1986) examine the pink shrimp fishery, and cannot reject that fishermen are profit maximisers, when making their location choice.

Turning attention to the method of questionnaire surveys, only a few have to the knowledge of the author been performed to reveal fishermen's approaches to maximising utility. These are Hanna (1989), Frost et al. (1993), Hillis et al. (1995) and Robinson and Pascoe (1997)[6]. The first considers fishery in the United States, while the latter three focus on fishermen located in British ports. It has not been possible to obtain a copy of Hanna (1989), and the conclusions from the three other analyses will be briefly summarised in the following.

Frost et al. (1993) interviewed 126 skippers on UK vessels landing their catches primarily in ports around the North Sea. The possible objectives put forward by the fishermen included maximisation of profit, revenue, labour share, quota uptake and other (i.e. good living, survival and highest possible catch).

[6] Hanna and Smith (1993) used questionnaires to investigate 68 Oregon trawler captains' attitudes towards their work (e.g. rewards and risks), resource use (e.g. resource status and effect of fishing) and fishery management (e.g. discards and wrong regulation). However, no direct investigation of objectives and restrictions were performed in this analysis.

Based on their answers, the skippers could initially be divided into skippers seeking to maximise their utility and skippers seeking to obtain a certain amount of utility, i.e. obtaining a satisfying level. The conclusion from the analysis by Frost et al. (1993)[7] was that the primary part (66 per cent) of the skippers were seeking to pursue a maximising behaviour, while 40 per cent focused on profits. Combined, approximately 28 per cent were seeking a behaviour leading to profit maximisation. Interestingly, also a high proportion (22 per cent) of the interviewed had maximisation of revenue as their behavioural goal. However, as mentioned previously, this may be due fishermen considering costs as fixed, and is thus indirectly in line with profit maximisation.

In total, 33 skippers fishing in the Irish Sea were questioned by Hillis et al. (1995). The results were similar to the ones obtained in Frost et al. (1993). Sixty-four per cent of the skippers were trying to maximise their objective, while 39 per cent focused on profits. Overall, 27 per cent tried to obtain profit maximisation. Obtaining maximisation of revenue was the most common answer for the skippers' objective fishing in the Irish Sea.

Robinson and Pascoe (1997) criticised the two analyses performed by Frost et al. (1993) and Hillis et al. (1995), for the lacking precision in the questions asked. However, in their survey covering the UK fishery in the English Channel, they did not directly ask a question regarding the fishermen's objectives. Instead, they asked an array of different motivational question to a total of 64 vessels, and based on these answers they found enough evidence to a conclusion that the vessels behaved in a manner that led to profit maximisation.

Even though the empirical work done to reveal fishermen's objectives is not very extensive, there seems to be reasonable support for the conclusion that the most important objective is maximisation of profits, which is equal to the assumption made in the neoclassical theory of the firm.

3. Restrictions influencing fishermen's behaviour

Besides determining the objective of fishermen, the other important part is to evaluate under which restrictions/constraints this objective is pursued in the short run, when deciding the choice of gear type and the location to fish in. Using the formalistic framework reviewed in section 1, an overall distinction can be made between restrictions related to physical resources, time, mental capacity and institutions. This section will discuss these in detail, with reference to analyses from fisheries whenever possible.

Some of the restrictions can be viewed as individual for each vessel, while others influence all vessels. Furthermore, some restrictions may influence the vessels differently. Take for instance traditions. Some skippers may have long historic family traditions of fishing in a

[7] The questionnaire used in Frost et al. (1993) can be found in Valatin (1991).

specific area, while other skippers are more flexible in this respect. It is necessary to bear in mind when discussing the restrictions that fishermen are limited by.

3.1 Physical resources

As mentioned previously, the physical resources that restrict a fisherman can be divided into those that can be changed and those cannot be changed.

The changeable physical resources primarily refer to the view of the fishing vessel, which can be described in many different ways. When considering the physical resources of a vessel in the short run, it is advantageous to make a deduction between fixed and variable inputs.

The fixed inputs are given in the short run and can thus not be changed[8]. As obvious examples of fixed inputs, the most prominent are the length, tonnage and engine power size. These inputs are important restrictions in the plausible behaviour. For instance, small-sized vessels with low engine power are physically restricted in participating in high-seas fisheries, while large vessels on the contrary often are restricted from conducting coastal fishing. Other important physical inputs fixed in the short run are for instance building materials, age of vessel and electronic equipment such as echo sounders, satellite navigation and radar.

The variable inputs can on the other hand be changed in the short run, although this can be costly for some. Examples of such variable inputs are gear equipment, amount of fuel, crew size and its composition. The gear equipment such as mesh size of nets is important with respect to the species caught. Likewise, the crew size is important in order to obtain and process the catch. However, the composition of the crew may also be important. For instance, a good combination between older and younger crew members could be valuable in order to have experience and strength onboard. The amount of fuel restricts the radius of actions and the possibilities for conducting searches for fish, when arriving at the decided fishing location.

In particular, the fixed physical resources are highly utilised in analysing fishermen's behaviour, because these are relatively easy to measure and therefore obtain. Many articles have therefore used these in specific analyses. Vessel tonnage was for instance included in Kirkley and Strand (1988), Dupont (1991), Squires and Kirkley (1991), Campbell and Nicholl (1994), Alam, Omar and Squires (1996), Jensen (2000) and Bjørndal and Gordon (2001), while Diop and Kazmierczak (1996) and Bjørndal, Koundouri and Pascoe (2003) used engine power; Ward and Sutinen (1994) used vessel length and tonnage; Pradhan and Leung (2004) used length and vessel age; Pascoe and Robinson (1998) used deck area,

[8] In the long run time horizon, these fixed physical characteristics of the vessels can be changed through investments, and the fishermen can thus change their effect as behavioural restrictions.

engine power and gear size; and Campbell (1991) used advanced technology, gross tonnage, year of construction, engine power and fuel tank capacity.

By far the most prominent physical input which restricts the fishermen, but which they cannot influence directly, is the stock situation of the species caught. Because stock is such an important component, it is included in several analyses. For instance, yearly dummies are used in Squires (1987) and Campbell and Nicholl (1994) to account for stock variation, while monthly dummies are included in Campbell (1991). In some articles some kind of stock index is used instead of dummies. Dupont (1991) used a stock index calculated using catch and escapement data, Ward and Sutinen (1994) also used a fishery independent index delivered by the National Marine Fisheries Service (NMFS), Bjørndal, Koundouri and Pascoe (2003) used stock information from the International Council for the Exploration of the Sea (ICES), while Pradhan and Leung (2004) used an index based on catch per unit of effort.

3.2 Time

The daily limitation of 24 hours is for fishermen a naturally given restriction (as it is for other people). For a fisherman, the time at sea can be divided between several activities, cf. Hilborn and Walters (1992) and Hannesson (1993). These are travel time (steaming time), search time, fishing time and handling time. The relative distribution between the four activities may differ from vessel to vessel, depending on the location and type of fishery. For instance, if a vessel fishes at a location far away from the homeport, it has a higher proportion of travel time compared to a vessel fishing close to its homeport, ceteris paribus.

It is seldom that detailed information about the distribution of the different activity measures is available, and the most utilised measure is therefore number of days at sea, cf. Carlson (1973). From an economic point of view, it is important to include all the time at sea in an analysis of fishermen's behaviour, because all activities at sea give rise to revenues and costs. However, for some gear types, the suitable time measure must include more than the number of days at sea. Take for instance vessels using nets and pots. These vessels go out, set the nets or pots, go back home, and then return the following day to collect their catch. In this situation, the number of days at sea will give an inadequate description of the time consumption.

Fishermen can of course seek to utilise the time at sea in the best possible way. This can for instance be done by having a well rested crew ready to work hard, setting the gear in the most favourable time of the day, using steaming time to prepare or de-rig the gear and so forth.

Giving the importance of time, it has therefore been included as a restriction in most of the analyses of fishermen's behaviour. For instance, Kirkley and Strand (1988) used days absent from port, Dupont (1991) used number of fishing days, Campbell and Nicholl (1994) used the number of sets, Diop and Kazmierczak (1996) the number of days spent fishing, Pascoe and

Robinson (1998) used hours fished per day, and Bjørndal, Koundouri and Pascoe (2003) used days at sea.

3.3 Mental capacity and information

Evaluating the mental capacity and calculating the capability of fishermen and agents in general is very difficult. To the knowledge of the author, no analysis has been made about this with regards to fishermen. However, in most articles, fishermen are assumed to have a maximising behaviour. A noteworthy exception is Anderson (2002), where fishermen are assumed to have profit goal behaviour instead of a profit maximising behaviour.

Assuming that fishermen have perfect information about all past, present and future events and their consequences is unrealistic. The number of uncertainties in fisheries are numerous, which restricts such behaviour, and as mentioned in the previous section, these uncertainties result in fishermen maximising their expected utility. Clark, Munro and Charles (1985) distinguish between economic and biological uncertainties, while Gates (1984) gives examples hereof. These examples include uncertainties about stock size and catch rates, prices, weather and quality of inputs, but other examples could also be mentioned including regulatory changes.

Economists acknowledge these facts, and several articles include this in analysing fishermen's behaviour. Andersen (1982) and Dupont (1993) focused on uncertainties with respect to output prices, Andersen and Sutinen (1984), Ward and Sutinen (1994), Mistiaen and Strand (2000) and Baldursson and Magnússon (1997) analysed uncertainties with respect to fish stocks, Eggert and Tveterås (2004) focused on uncertainties with respect to catches in general, while Smith (2002) and Wilen et al. (2002) included weather variables.

It has also been investigated how fishermen seek to collect additional information about fish stocks in order to know where the fish can be found and thus allow them to make better decisions. These include Wilson (1990), Smith and Provencher (2003), Marcoul and Wenninger (2004) and Curtis and McConnell (2004). Allen and McGlade (1986) take the quality of the obtained information into consideration. Curtis and Hicks (2000) include the number of vessels in a given area, assuming that this indicates the quality of the area, where the trade-off is that too many vessels and congestion makes the area less attractive.

3.4 Institutions

An array of institutions influences the behaviour of fishermen. These could be viewed as the foundation upon which fishermen's behaviour is governed, and thus include all the formal and informal rules/relations that are present in society. In order to describe these institutions, a distinction was previously made between 1) decision making systems, 2) norms, traditions and other behavioural rules and 3) organisations. A range of topics relate to these institutions.

However, despite their importance topics, such as how prices are determined in the economy and which political regime is installed, are not addressed in the relevant literature, and will therefore not be covered in the following.

An important restriction in fishermen's behaviour is the regulatory system, which the fishery is subject to. When analysing the regulatory system, a distinction can be made between the general regulation principles and the specific regulation instruments used. The general principles lay the foundation for the type of property-right regime the fishermen are operating in. Feeny, Hanna and McEvoy (1996) refer to the four basic ideal types being open access, private property, communal property and state property. In specific fisheries, variants of these can be found in the form of for instance restricted open access, etc.

The general regulatory principles are often supported by an array of more specific regulations, which are installed to counteract particular unwanted effects and thus obtain a more suitable utilisation of the fish resource. Examples of specific regulation measures can for instance be restrictions on mesh size and landing size, closed areas, quotas and limitations on the number of days at sea.

Reviewing the literature about the influence of regulation on fishermen's behaviour in the short run, reveals that this has especially focused on the topic of fishermen substituting between regulated and non-regulated inputs. Examples hereof are found in Campbell (1991), Dupont (1990,1991), Lipton and Strand (1992), Clay and Revell (1998), Pascoe and Robinson (1998), Del Valle, Astorkiza and Astorkiza (2000). Lipton and Strand (1992) investigate consequences on the industry structure when the regulation on number of hours a vessel is allowed to fish surf clams per season is changed.

Norms, traditions and other behavioural rules include a multifarious set of elements, which are mainly formed over long time periods. Previously, religion, upbringing, education, attitudes and motives were mentioned as being relevant parts. However, despite their importance for fishermen's behaviour, the primary focus in empirical analyses has been on education and risk attitudes.

As with other branches, education and skills are important for fishermen's behaviour, cf. Squires and Kirkley (1999). Despite the general problems of identifying and describing education and skills, some attempts have been made. In Campbell (1991) each skipper is graded by independent fishery officers, while Alam, Omar and Squires (1996) use a dummy to indicate whether the skipper is trained or not. Del Valle, Astorkiza and Astorkiza (2000) use the ratio between the number of small landings and total landings as a measure of skipper skills. Hutton et al. (2004) include the lagged catch value of a given area as a measure of experience.

Investigation of fishermen's attitudes toward risk has been the topic in several articles. Three types of risk attitudes can be identified cf. Friedman and Savage (1948). These are risk-aversion, risk-neutrality and risk-perversion/loving/seeking. In short, risk-neutrality implies that one is indifferent to risk and will neither pay to avoid it nor to take it, thus risk does not affect the decisions. Risk-aversion is where less risk is preferred to more risk, while risk-perversion implies the opposite. Whether fishermen's preferences towards risk have an influence on their behaviour was investigated in Mistiaen and Strand (2000). Fishermen's risk preferences have generally been investigated by including variables indicating the variability in the utility measure. Holland and Sutinen (1999,2000) found indications of risk-loving behaviour, as did Dupont (1993). Larson, Sutton and Terry (1999), Pradhan and Leung (2004) and Eggert and Tveterås (2004) on the other hand observed risk-averse behaviour. Furthermore, Strand (2004) concluded that risk preferences can vary spatially between fishermen.

Traditions are generated through time, where experience and information are carried on from family or the local community. Traditions can be positive, because it gives fishermen a set of rules to conduct their activities within. It may however also be negative, if these for instance restrict fishermen from diverting to other untraditional activities. The importance of traditions with respect to fisheries has been discussed in several articles, cf. Bockstael and Opaluch (1983) and Chakravorty and Nemoto (2001). However, only a few seek to include this in a description of fishermen's behaviour. Holland and Sutinen (1999,2000) include habit variables to reflect whether the current behaviour collides with previous behaviour in the last ten days. Another interesting aspect is the ethnicity of the fishermen. Alam, Omar and Squires (1996) find this to have an influence on fishermen's behaviour. Pradham and Leung (2004) find significant inertia between the current quarter's trip type and the previous quarter's trip type, and relate this to belief, tradition, habit and skill.

The interrelationship between different organisations and the fishermen is difficult to describe and quantify in empirical analysis. The most obvious and quantifiable topics have been discussed above, i.e. management by the state and family traditions. However, other organisations may also influence fishermen's behaviour. An obvious example is environmental organisations seeking to preserve the sea habitats. Other organisations such as oil producers, windmill producers and so forth may also have a perceptible influence on fishermen's behaviour. Unfortunately, the number of articles discussing the relationships is limited. However, parallels can be drawn to the theory of marine reserves/protected areas, because this involves the closure of specific areas for fishing activities[9].

[9] See for instance Hannesson (1998) for further insight into the topic of marine reserves.

Final comments

Investigation into fishermen's behaviour and the factors that drive this behaviour is an important area to perform research within. Improving this knowledge will lead to improved research results, because previously unexplained effects become explainable. This will then hopefully spill-over into better management of the fishery giving rise to improved profitability for fishermen and society in general.

In this paper, a significant number of papers have been reviewed in order to identify the primary factors influencing fishermen's behaviour with respect to choice of gear type and fishing location, i.e. short run choices. A more general framework for approaching fishermen's behaviour has been presented. Based on the New Institutionalist School of thought this has led to a distinction between objectives and restrictions, where the latter can furthermore be subdivided into restrictions related to physical resources, time, mental capacity and information, and finally institutions.

Reviewing the significant amount of literature specifically studying fishermen's behaviour, we find evidence in the literature for assumptions made in the neoclassical theory of the firm. Fishermen primarily seek to maximise their utility through profit maximisation. However, this maximisation is performed under a series of restrictions. In the literature, the focus has primarily been on the physical resources and time. This is probably due to the fact that data for these are relatively easy to measure and thus obtain. The other restrictions are more cumbersome to identify and collect for individual vessels, but it has been possible in some situations, as also noted.

For specific analyses, it is difficult to include every element that influences the fishermen's choices. First of all, measurement problems may simply exclude restrictions, because these are impossible to quantify in a satisfying way. The analysis may also be significantly cumbersome to perform, if all considerations about the restrictions need to be taken into account. Furthermore, some of the restrictions may be of such little importance that the benefits from inclusion do not bear comparison with the difficulties of inclusion.

Identifying all the factors influencing fishermen's behaviour is however still important, regardless of whether they are included in the specific analysis or not. Having identified these, it becomes easier to explain some unexpected results found in the specific analysis, which cannot be evaluated based on the included factors.

Although much research has been performed with respect to fishermen's behaviour, there is still need for more research. Often analysis is concentrated on a simplistic fishery, which makes it difficult to extend the results to more diversified fisheries. Research also needs to focus more on other factors that are given less attention, although acknowledging that this may be rather difficult.

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Using different inputs and outputs to estimate technical efficiency in fisheries: An application to Danish seiners in the North Sea and Skagerrak

by Jesper Levring Andersen

Abstract

The number of articles analysing technical efficiency in fisheries has risen considerably in the last couple of years, and many different measures of inputs and outputs have been applied. At present, however, no consensus has been established about which measures to use in such an analysis. In order to give some insight into which measures to choose, this paper estimates technical efficiency using three different output measures and two different input measures. The estimations are performed assuming that the functional form of the estimated production frontier can be represented by the flexible translog function. Furthermore, inefficiency models are estimated in order to explain why some vessels do not behave as best practice. The dataset used covers the Danish seiner fleet fishing in the North Sea and Skagerrak in the period 1987 to 1999.

The results show that it is not highly important whether output is measured in catch weight or catch revenue with respect to level of technical efficiency and estimation of the inefficiency model, at least for the dataset used. However, using revenue-weighted catch weight as the output measure generally gives other results. Looking at output elasticities, the results are not as decisive. The choice of input measure also has little influence on technical efficiency, but the level of output scale elasticity is affected. Results from the estimated inefficiency models indicate that inefficiency decreases with increases in size, that full-time fishermen are more efficient than other types of fishermen, and that experience with the primary fishing area reduces inefficiency.

Keywords

Technical efficiency, inefficiency model, Danish seiners, input and output measures.

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Introduction

An array of different input and output measures are available for analysing technical efficiency in fisheries. The former is often in form of tonnage, engine power, length, insurance value and/or fishing time, while the latter is in form of catch weight and catch revenue. Despite of the many efficiency analyses that have been performed using these measures, there does not seem to be a general consensus about which type of output measure to use and the specific way to include the input measures.

The outputs produced by fishing vessels can as mentioned be quantified in different ways. Alvarez (2001) distinguished between three in form of weight, revenue or different combinations thereof. Various arguments can be put forward as to which approach should be chosen, however it is unclear whether this choice has any consequences on the output elasticities and the level of technical efficiency. One purpose of this paper is therefore to investigate the effects of using different output measures, when investigating technical efficiency.

Turning attention to the measurement of the inputs used in a fishery, it is often convenient to make a distinction between variable and fixed inputs. An input such as fishing time can be regarded as a variable input, because it can be changed in the short run, i.e. it is a flow. On the other hand, fixed inputs such as tonnage and engine power can be viewed as capacity or stock measures, because they cannot be changed in the short run. Combining the variable and fixed measures into one measure gives an input which can be referred to as a 'service flow', cf. Campbell and Hand (1998). A service flow can thus be defined as the product between the variable and fixed inputs, and i.e. gives the intensity by which the fixed inputs are used in a specific period.

There does not seem to be a clear approach in the literature as to whether the fixed and variable inputs should be included separately in the production function or as a service flow. For instance, Kirkley, Squires and Strand (1995), Sharma and Leung (1999), Eggert (2001), Pascoe, Andersen and de Wilde (2001) all included the fixed and variable inputs separately in the production frontier function, while Campbell and Hand (1998) and Squires et al. (1998) used the service flow approach[1]. Another purpose of this paper is therefore to analyse whether the approach used has any influence on the estimated levels of technical efficiency.

The two purposes mentioned above will be pursued by examining the estimates of technical efficiency and output elasticities derived from the estimated production frontiers. Furthermore, some reasons for any observed technical inefficiency can be extracted from the estimated inefficiency models, and by comparing these, further insight will be gained with respect to the input and output choice.

[1] Smit (1996) also used a service flow approach to analyse productivity developments in fishing effort of a Dutch Cutter fleet.

In order to address these questions a dataset has been compiled, which covers all the Danish seiners fishing in the North Sea and Skagerrak in the period from 1987 to 1999. In total there were 118 Danish seiners registered in the Danish vessel register in 1999, and the main part of these have fished in the two areas included. The Dane Jens Væver invented in 1848 the fishing method, which these vessels use, and it was designed to catch flatfish, especially plaice. However, this fishery has experienced hard times in recent years, primarily due to declines in stocks and heavy regulation.

This paper is structured as follows: Section 1 briefly explains the theory of stochastic production frontiers, while Section 2 describes the dataset used. Section 3 describes the stochastic production model to be estimated and Section 4 presents the estimated production frontiers and some specification tests are performed. The impact on the level of technical efficiency from choosing different input and output measures are analysed in Section 5, while the output elasticities are calculated in Section 6 and compared for the different output measures. Section 7 presents estimates of the inefficiency models, and besides explaining the observed inefficiencies, these are also discussed with respect to the choice of input and output measures. The final section concludes the paper.

1. The theory of technical efficiency

The historical starting point of the theory of efficiency is considered to be the paper from 1957 by M.J. Farrell in which he distinguished between technical and allocative efficiency, using the terms in Coelli, Rao and Battese (1999). Looking at technical efficiency from an output perspective, a firm is considered to be technically efficient if it produces the maximum possible output, given the level of inputs. Allocative efficiency can be separated into input and output allocative efficiency. The former refers to choosing the optimal input mix for given input prices and production technology, while the latter refers to choosing the optimal output mix for given output prices. If all these are fulfilled, then the given firm maximises profits (Pascoe, Andersen and de Wilde 2001).

Due to data limitations only technical efficiency will be analysed. A prerequisite for finding the level of technical efficiency is to find the observed best-practice. Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977) proposed independently of each other how to estimate the following stochastic production frontier (with time included):

$$Y_{j,t} = f(X_{j,t};\beta) + v_{j,t} - u_{j,t} \qquad (1)$$

where $Y_{j,t}$ denotes the output[2] produced by firm j at time t, $X_{j,t}$ is a (1 x k) vector of inputs used by firm j at time t and β is a ((k+1) x 1) vector of parameters to be estimated.

The random errors (noise) for firm j at time t are denoted by $v_{j,t}$, and it accounts for non-controllable factors, e.g. weather and luck, cf. Gates (1984). The random errors are assumed to be independently and identically distributed and to follow a normal distribution with mean zero and variance σ_v^2.

Technical inefficiency for firm j at time t is represented by the term $u_{j,t}$, which is assumed to be non-negative, independently and identically distributed with a variance given by σ_u^2. If $u_{j,t}$ equals zero, then firm j is fully efficient at time t, and therefore produces on the production frontier. However, if $u_{j,t}$ is larger than zero, then firm *j* is inefficient at time *t*.

Different types of distributions can be assumed for the inefficiency term $u_{j,t}$, i.e. half-normal (Jondrow et al. 1982), truncated normal (Aigner, Lovell and Schmidt 1977), exponential (Meeusen and van der Broeck 1977) or gamma distribution (Greene 1990). However, if the purpose of the analysis also is to find possible reasons for any observed inefficiencies, the formulation of an inefficiency model becomes relevant. Battese and Coelli (1995) propose the inefficiency to modelled as:

$$u_{j,t} = \delta z_{j,t} + w_{j,t} \tag{2}$$

where δ is a vector (m x 1) containing unknown parameters of the inefficiency model (including the intercept) and z is a vector of inputs (1 x m) and w is a random error like v.

When an appropriate functional form for f has been chosen, the parameters in the stochastic frontier model can be estimated using Maximum Likelihood Estimation, which is considered the best method, cf. Coelli, Rao and Battese (1999). The estimated f-function thus determines the frontier production, i.e. best practice/maximum output. Using this estimated function, the output of each firm can be compared to the output in the observed best-practice, and a measure of technical efficiency can be calculated.

Technical efficiency is thus a relative measure of firm j's observed output as a proportion of the frontier production, and can be calculated as follows, cf. Coelli, Rao and Battese (1999):

$$TE_{j,t} = E(Y_{j,t} \mid u_{j,t}) / E(Y_{j,t} \mid u_{j,t}=0) \tag{3}$$

[2] It is thus assumed that the production of a firm is either a single output or can somehow be aggregated into one. Methods accounting for several outputs have been developed, cf. Coelli and Perelman (1999, 2000), but they will not be utilised in this paper.

Considering that the stochastic production function is estimated using a parametric method, it is possible to impose a number of different restrictions on the parameters to test the structural form of the production function.

The first test is whether there are any inefficiency effects in the model. If not, the model might as well be estimated using ordinary least squares instead of maximum likelihood. The test is $\gamma = \delta_0 = \ldots = \delta_{(m-1)} = 0$, where γ is given as $\gamma = \sigma_u^2 / (\sigma_u^2 + \sigma_v^2)$. If the hypothesis is accepted, there are no deviations from the production frontier due to inefficiencies, but only due to stochastic errors.

If the above test is rejected, there are inefficiency effects in the model. Whether it is significantly better to include an inefficiency model, instead of assuming that the inefficiency effects are following a normal distribution, can be tested using the following hypothesis $\delta_1 = \ldots = \delta_{(m-1)} = 0$. If accepted, we can assume that the inefficiencies follow a normal distribution with a mean value of δ_0, i.e. the intercept, instead of including the proposed inefficiency model.

It is also possible to test which functional form is the most appropriate for the stochastic frontier production function, for instance whether it is a translog (Christensen, Jorgenson and Lau 1973), generalised Leontief (Diewert 1971), Cobb-Douglas (Cobb and Douglas 1928) or Constant Elasticity of Substitution (Arrow et al. 1961) function. If there are no arguments for choosing a specific functional form, Lau (1986) recommends using either generalised Leontief or translog production functions, because these do not restrict the parameters using a priori assumptions about the output- and substitution elasticities for instance.

Generalised likelihood ratio statistics can be used to either accept or reject the above tests. The value of this is given as $\lambda = -2\times[\ln\{L(H_0)\} \div \ln\{L(H_1)\}]$, and is χ^2-distributed[3]. Likewise, the generalised likelihood ratio statistics can be used to test whether to include variables or groups of variables in the inefficiency model.

This brief theoretical review of the Stochastic Production Frontier approach can be further broadened by reading for instance Kumbahkar and Lovell (2000). A review of the computer programs available to perform estimations of the Stochastic Production Frontier can be found in Herrero and Pascoe (2002).

2. Description of the dataset used

A dataset has been derived from the official data on catches and vessel information collected by the Danish Directorate of Fisheries. The dataset includes monthly catches and number of

[3] The first test regarding whether there are any inefficiency effects in the model is a one-sided LR-test, and follows the distribution given by Kodde and Palm (1986).

days at sea together with vessel characteristics for each of the included Danish seiners fishing in the North Sea or Skagerrak in the period from 1987 to 1999. In total, there are 19,573 observations for 261 different vessels over the thirteen years. Table 2.1 shows how many observations and Danish seiners there are in the dataset for selected years. The average number of observations per vessel per year is also displayed, and a tendency of a decreasing number of observations is observed after a peak in 1991. This decrease can be explained by a general decrease in the number of Danish seiners, combined with decreasing fishing possibilities in the included areas.

Table 2.1 Number of observations and vessels per year

	1987	1989	1991	1993	1995	1997	1999
Number of observations	1,376	2,193	2,057	1,688	1,283	923	805
Number of vessels	146	231	213	191	148	108	98
Average number of obs. per vessel	9.42	9.49	9.66	8.84	8.67	8.55	8.21

In order to ensure robust and reliable results only vessels participating in the fishery for at least 25 months during the 13 years are included in the dataset. Table 2.2 displays how many times the included vessels were present in the dataset for different intervals, e.g. 32 vessels were in the dataset between 25 and 36 times (months). In addition, the total and average number of observations for these intervals is also included in Table 2.2.

Table 2.2 Number of times vessels are represented in the dataset

	----------Interval----------										
	25-36	37-48	49-60	61-72	73-84	85-96	97-108	109-120	121-132	133-144	145-156
Number of observations	957	1,745	2,066	2,035	1,551	2,680	1,738	2,087	2,905	1,662	147
Number of vessels	32	41	37	30	20	30	17	18	23	12	1
Average number of observations	30	43	56	68	78	89	102	116	126	139	147

Three measures of output will be used in the analysis performed in the following sections. The first is total aggregated catch weight, where the catch of the different species s (s=1,…S) is simply aggregated into one single measure without considering their relative importance, i.e.

$$Y_{j,t}^{weight} = \sum_{s=1}^{S} Y_{j,t,s}^{weight} \tag{4}$$

where $Y_{j,t,s}$ measures the catch weight of species s for vessel j in period t.

The second output measure is total aggregated inflated catch revenue[4] denoted as $Y^{inf.\ revenue}$. It is inflated to 1999 values for each species before aggregation using a yearly index I_k (k=1987,…,1999)[5], i.e. the output measure is calculated as:

[4] Catch revenue is in the rest of this paper defined as the total or gross catch value, i.e. no costs are deducted.

$$Y_{j,t}^{inf.\,revenue} = \sum_{s=1}^{S} Y_{j,t,s}^{value} / I_{k,s} \tag{5}$$

where $Y_{j,t,s}$ now measures the catch revenue of species s for vessel j in period t.

The final output measure is weighted catch weight, where the monthly catch weight of each species is weighted using monthly revenue-shares in order to take the importance of each species, (measured in monetary) terms into account, i.e.:

$$Y_{j,t}^{weighted\ weight} = \sum_{s=1}^{S} \frac{Y_{j,t,s}^{revenue} / I_{k,s}}{\sum_{s=1}^{S} \left(Y_{j,t,s}^{revenue} / I_{k,s} \right)} \cdot Y_{j,t,s}^{weight} \tag{6}$$

Descriptive statistics for the three outputs used separately to estimate the level of technical efficiency in the Danish seiner fleet fishing in the North Sea and Skagerrak can be found in Table 2.3. A similar development can be observed for these three measures; an increase in the output revenue until 1989, succeeded by a continued decrease until 1999, with a slight increase in 1997. An increase in the standard deviation is observed in the years 1995 to 1999, which implies that the observations for these years are more differentiated compared to the observations in the other years.

Table 2.3 Descriptive statistics for output measures

		1987	1989	1991	1993	1995	1997	1999
Catch weight (tonnes)	- Total	16,126	30,177	19,333	17,928	17,625	19,374	12,052
	- Average per vessel	110	131	91	94	119	179	123
	- Standard deviation	43	64	38	57	90	348	56
Weighted catch weight (tonnes)	- Total	8,759	16,617	10,111	8,456	8,832	11,890	6,621
	- Average per vessel	60	72	47	44	60	110	68
	- Standard deviation	26	49	24	21	59	311	31
Inflated catch revenue (1,000 DKK)	- Total	217,976	398,886	290,907	253,255	254,116	227,279	178,380
	- Average per vessel	1,493	1,727	1,366	1,326	1,717	2,104	1,820
	- Standard deviation	601	759	593	883	1,286	1,401	927

Notes: The high standard deviation in 1997 (and 1996/1998, not shown here) is due to the presence of several Danish seiners with high catch weights. These have not been considered as outliers.

Various input factors can be expected to influence the output level. A distinction can be made between fishing effort and fish stock (Andersen 1999). The former includes factors the fisherman can control, while the latter is not directly controllable. The fishing effort measure can further be divided into fishing power and fishing time, i.e. fixed and variable inputs in the short run. Fishing power includes input factors that cannot be changed in the short run, for instance tonnage, length, engine power, insurance value and crew size[6]. Descriptive statistics

[5] The index was derived from Danish fishermen's total catch revenue of each species landed in Danish ports.

[6] Crew size can in principle be changed in the short run, although the included measure for crew size is only declared on a yearly basis to the Directorate of Fisheries.

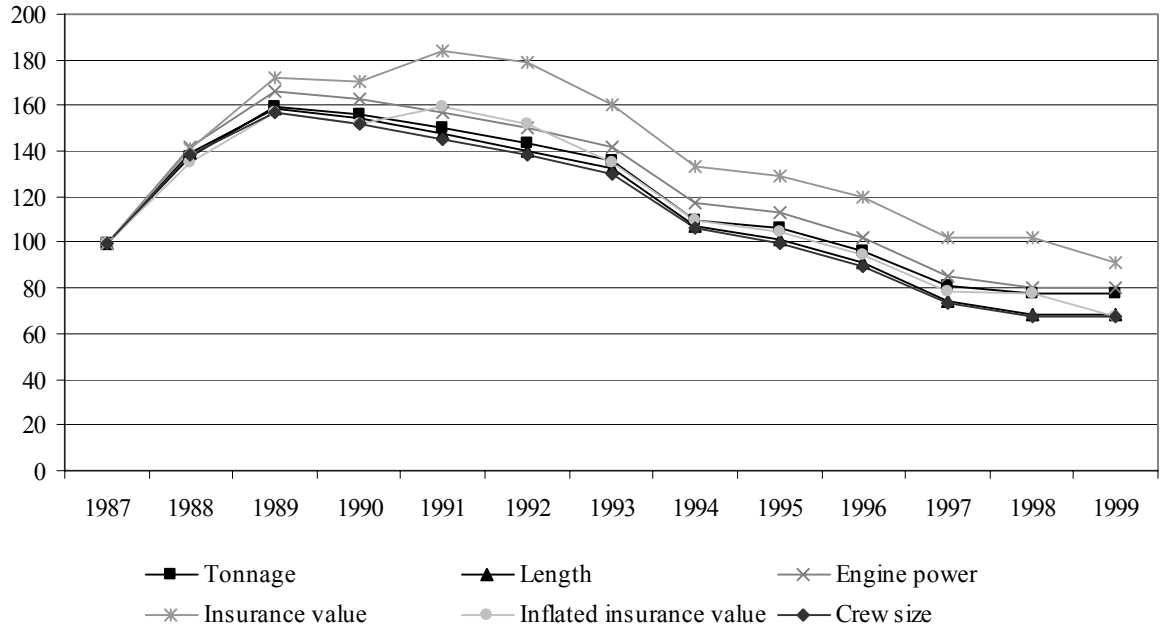
for these factors can be found in Table 2.4, where inflated insurance values are also included[7].

Table 2.4 Descriptive statistics for fishing power measures

		1987	1989	1991	1993	1995	1997	1999
Tonnage	- Total	5,183	8,266	7,796	7,024	5,524	4,181	4,007
(GT/GRT)	- Average per vessel	35.50	35.78	36.60	36.77	37.32	38.71	40.89
	- Standard deviation	9.68	12.85	13.11	13.88	23.33	29.43	30.32
Length	- Total	2,507	3,967	3,694	3,315	2,543	1,856	1,714
(metres)	- Average per vessel	17.17	17.17	17.34	17.35	17.18	17.19	17.49
	- Standard deviation	1.86	2.01	1.96	2.06	2.61	2.87	2.78
Engine power	- Total	20,429	33,983	32,148	28,951	23,135	17,356	16,338
(kW)	- Average per vessel	139.92	147.11	150.93	151.58	156.32	160.71	166.72
	- Standard deviation	39.00	49.41	49.73	51.05	59.24	66.81	67.37
Insurance value	- Total (mill. DKK)	2,054	3,529	3,771	3,290	2,657	2,095	1,865
(1,000 DKK)	- Average per vessel	1,493	1,609	1,833	1,949	2,071	2,270	2,317
	- Standard deviation	705	935	922	1,037	1,379	1,687	1,540
Inflated insurance value	- Total (mill. DKK)	2,772	4,347	4,421	3,732	2,894	2,187	1,865
(1,000 DKK)	- Average per vessel	2,015	1,982	2,149	2,211	2,255	2,369	2,317
	- Standard deviation	952	1,151	1,080	1,176	1,502	1,761	1,540
Crew size	- Total	451	707	655	587	450	330	303
	- Average per vessel	3.09	3.06	3.08	3.07	3.04	3.06	3.09
	- Standard deviation	0.50	0.52	0.52	0.55	0.63	0.67	0.67

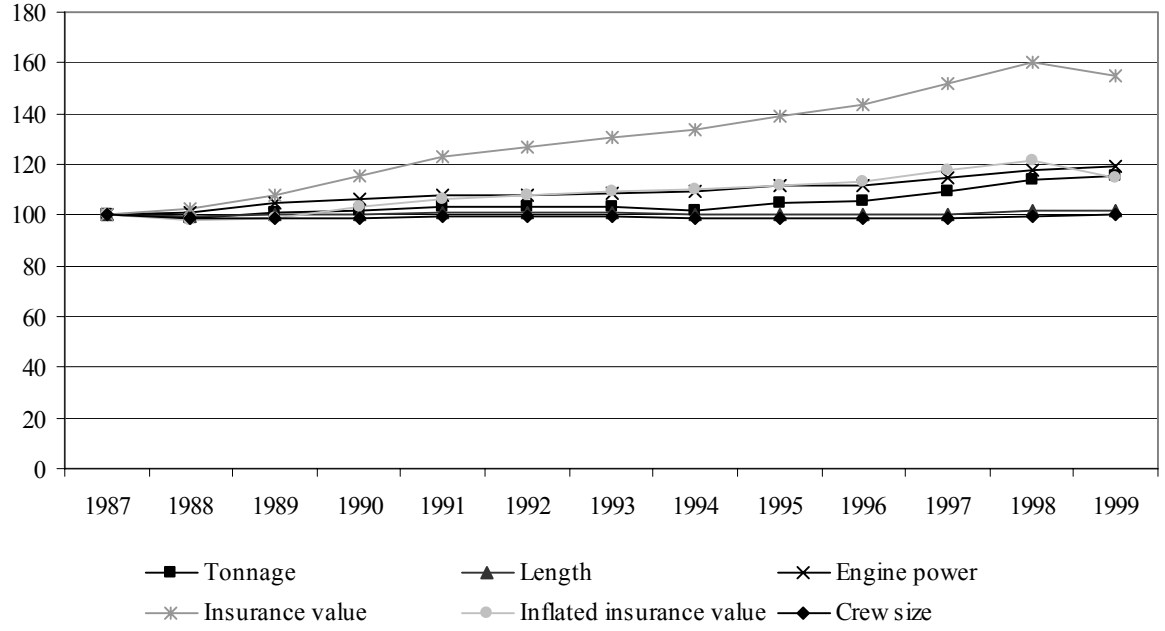
A graphical representation of the development in total and average fishing power measures can be seen in Figure 2.1 and Figure 2.2. A similar decreasing development in total values is observed, and is due to the reduction in number of vessels in the dataset. However, the insurance value increased in 1991, and this can be attributed to general price increases in the Danish economy, since the inflated insurance value follows the same trend as the other measures.

Figure 2.1 Development in total fishing power measures (1987=100)



[7] The standard consumer price index was used to inflate the insurance value with 1999=100.

Figure 2.2 Development in average fishing power measures (1987=100)



As opposed to the development in total fishing power measures, there has been an almost continual increase in the average fishing power measures from 1987 until 1999. The increase is most significant for the insurance value, although this increase can again be attributed to the general price increases in the Danish economy, as described above.

The measure of fishing time used in the analysis is the number of days at sea. This measure thus includes the time used for other purposes than fishing, e.g. travelling time and processing primarily in form of cleaning the fish caught. It could be argued that the time where the fishing gear is in use would be a more appropriate measure to use. However, considering that the analysis seeks to evaluate the technical efficiency related to all activities related to obtaining a catch, the number of days at sea is used as the fishing time measure[8]. From an economic point of view, this is also the best measure to use, because all activities have economics repercussions.

From the descriptive statistics shown in Table 2.5, a significant reduction in the total number of days at sea can be observed, although it seems to have been relatively stable from 1997 to 1999. This development is closely linked with the development in the number of Danish seiners in the dataset, considering that the average number of days at sea per vessel per month is almost constant during the thirteen years.

[8] Comparing with an analysis where gear time is used as a measure of fishing time, could be an interesting topic for further analysis. However, data is currently not available.

Table 2.5 Number of days at sea

	1987	1989	1991	1993	1995	1997	1999
Total	19,698	33,493	31,057	25,249	18,983	12,906	12,224
Average per vessel per month	14.32	15.27	15.10	14.96	14.80	13.98	15.19
Standard deviation per month	6.50	6.70	6.58	6.44	6.50	6.30	6.41

The correlation coefficients between the output and fishing effort measures can be viewed in Table 2.6. A high correlation between weight and weighted weight is observed, while the inflated revenue of the catch is not highly correlated with the other two output measures. Tonnage, engine power, length and insurance value are also highly correlated, while crew size is not as highly correlated with the other fishing power measures. It can be observed from Table 2.6 that tonnage and insurance value are the fishing power measures having the highest correlations with the three output measures. Fishing time measured as the number of days at sea is most correlated with the inflated catch revenue.

Table 2.6 Correlation between output and fishing effort measures

	Catch weight	Weigh-ted catch weight	Inflated catch revenue	Tonnage	Engine power	Length	Insu-rance value	Inflated insu-rance value	Crew size	Days at sea
Catch weight	1.00									
Weighted catch weight	0.94	1.00								
Inflated catch revenue	0.51	0.30	1.00							
Tonnage	0.37	0.27	0.41	1.00						
Engine power	0.22	0.11	0.36	0.68	1.00					
Length	0.26	0.16	0.40	0.80	0.69	1.00				
Insurance value	0.33	0.19	0.47	0.85	0.74	0.73	1.00			
Inflated insurance value	0.32	0.18	0.46	0.84	0.74	0.74	0.99	1.00		
Crew size	0.19	0.10	0.34	0.52	0.48	0.59	0.59	0.60	1.00	
Days at sea	0.35	0.20	0.66	0.21	0.15	0.27	0.18	0.19	0.22	1.00

Stock size is also supposed to be an important determinant of the catch level obtained from fishing, i.e. the more fish in the sea, the more will be caught for a given level of fishing effort, ceteris paribus. As mentioned by Alvarez (2001), the stock cannot be considered a traditional input in a production function, because the individual fisherman cannot directly control it. However, when performing analysis of over time, it would be a mistake to exclude it from the production frontier, if the relationship above is significant.

Different methods have been used to include a fish stock measure in the production function. Kirkley, Squires and Strand (1995, 1998) used an index based measure on relative catch rates obtained from a supposedly bias free method, while Coglan, Pascoe and Harris (1998) and Pascoe and Robinson (1998) used dummy variables to account for stock effects. Pascoe, Andersen and de Wilde (2001) applied stock estimates obtained from the annual stock estimates made by the International Council for the Exploration of the Sea (ICES).

In this paper, the fish stock measure will be based on the annual stock estimates made by ICES, which assesses estimates for an array of fish stocks in the North Sea and Skagerrak, including cod, plaice, sole, sprat, herring, mackerel, etc. Four of the most important species for the Danish seiners (measured in inflated revenue) are cod, plaice, haddock and European hake. Table 2.7 shows that these four species comprise more than 80% of the catches taken by the Danish seiners. A stock measure based on these four species will therefore cover the major part of the catches caught by the Danish seiners fishing in the North Sea and Skagerrak.

Table 2.7 Inflated catch revenue composition for an average Danish seiner fishing in the North Sea and Skagerrak (%)

	1987	1989	1991	1993	1995	1997	1999
Plaice*	46	52	49	46	35	45	47
Cod*	41	34	27	33	46	38	35
Lemon sole	2	3	6	6	4	3	5
Haddock*	4	3	2	3	3	4	2
Common dab	2	2	2	2	3	2	2
European hake*	1	2	4	3	2	1	1
Witch flounder	1	2	1	1	1	2	3
Catfish	2	1	3	1	1	0	1
Anglerfish	0	0	2	2	1	1	1
Turbot	0	0	1	1	1	1	1
Total	99	99	96	97	96	97	98
Total of biomass species	92	91	82	84	85	87	86

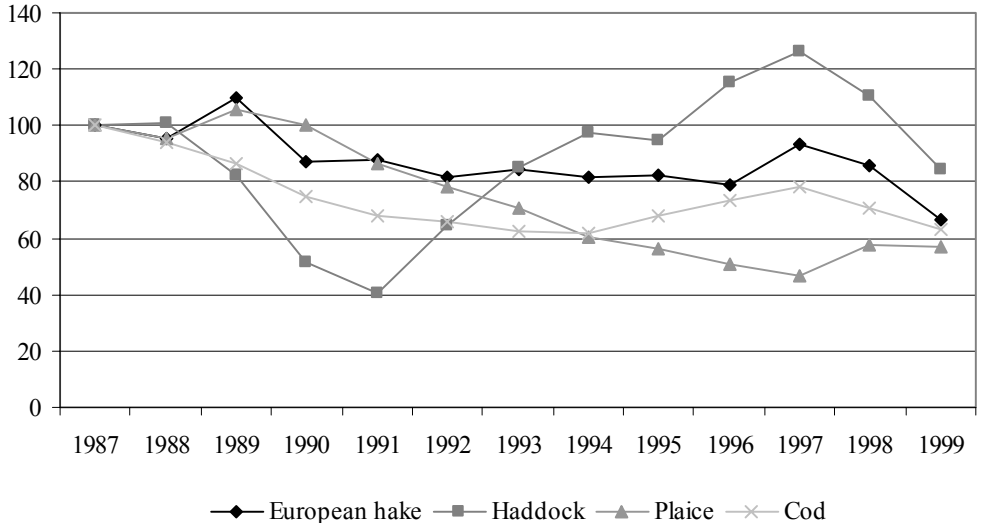
Notes: * indicates species with biologically assessed biomass.

Technically, the stock measure for each Danish seiner was calculated on a monthly basis using the relative inflated revenue shares and indexed stock estimates for the different areas[9]. It was necessary to index the stock estimates in order to account for differences in their magnitude. For example, if a Danish seiner catches 60% cod and 40% plaice in January 1995, and the stock index for cod is 68 and 56 for plaice, then the stock measure for this vessel will be 63 (calculated as $0.60 \cdot 68 + 0.40 \cdot 56 = 63$).

Figure 2.3 shows the development in the included stock indices. The stock indices of the four species decreased overall from 1987 to 1999, most significantly for cod and plaice, which are the two most important species for the Danish seiners. There are some fluctuations for each of the different species, especially for haddock, which after a decrease from 1987 to 1991, increased until 1997, but then decreased to a lower level in 1999 compared to 1987.

[9] A deduction is made between southern (4C), central (4B) and northern (4A) North Sea and Skagerrak (3AN).

Figure 2.3 Development in stock indices (1987=100)



3. Specification of the stochastic production frontier model

When specifying the stochastic production frontier to be estimated, an assumption about the functional form of the production function is necessary. There are no initial reasons for choosing one functional form instead of another, and hence a translog function is chosen for the purpose of this paper. The translog function has several advantages, e.g. it is a flexible function and imposes only few prior restrictions on the parameters, cf. Lau (1986) and Morey (1986)[10]. The estimated function is thus given as:

$$\begin{aligned} \ln Y_{j,t} = {} & \beta_0 + \beta_{FP} \ln FP_{j,t} + \beta_{FT} \ln FT_{j,t} + \beta_S \ln S_{j,t} + \beta_T T_{j,t} + \\ & \beta_{FPFP} (\ln FP_{j,t})^2 + \beta_{FTFT} (\ln FT_{j,t})^2 + \beta_{SS} (\ln S_{j,t})^2 + \beta_{TT} (T_{j,t})^2 + \\ & \beta_{FPFT} (\ln FP_{j,t} \cdot \ln FT_{j,t}) + \beta_{FPS} (\ln FP_{j,t} \cdot \ln S_{j,t}) + \beta_{FPT} (\ln FP_{j,t} \cdot T_{j,t}) + \\ & \beta_{FTS} (\ln FT_{j,t} \cdot \ln S_{j,t}) + \beta_{FTT} (\ln FT_{j,t} \cdot T_{j,t}) + \beta_{ST} (\ln S_{j,t} \cdot T_{j,t}) + \\ & v_{j,t} - u_{j,t} \end{aligned} \tag{7}$$

where FP is the fishing power measured in tonnage[11], FT is fishing time measured as the number of days at sea, S is the stock index calculated as explained in Section 2 and T is the monthly index of time. j refers to the j'th vessel (j=1,...,261) and t refers for the t'th month (t=1,…,156) from January 1987 to December 1999.

The time index $T_{j,t}$ can be included in the production frontier in several ways. However, it has been chosen to use the approach proposed by Coelli, Rao and Battese (1999) and applied in

[10] A thorough investigation of the translog production function is found in Boisvert (1982).

[11] Tonnage is chosen as the measure of fishing power due to the high correlation with the output measures and the other fishing power measures in general, cf. the conclusions derived from the dataset description.

relation to fisheries by Campbell and Hand (1998). The time index measures movements in the frontier and could at least partly be considered to measure technological progress[12].

The time index is included in the same way as the other variables in the production function, i.e. with squared- and cross-terms. It can be discussed how to interpret the cross product between the stock and time indices, although in order to follow the intentions of the translog functional form as a second order approximation to some unknown production function, it has been decided to include the terms. Another argument is that the two terms, T and T^2, may also include some of the variation in the stock index, as long as the stock index is included in the production function.

One of the objectives in this paper is to analyse the consequences of including fishing effort as a separate or composite measure in the production function. The second function to be estimated is therefore:

$$\begin{aligned} \ln Y_{j,t} = & \beta_0 + \beta_{FE} \ln FE_{j,t} + \beta_S \ln S_{j,t} + \beta_T T_{j,t} + \\ & \beta_{FEFE} (\ln FE_{j,t})^2 + \beta_{SS} (\ln S_{j,t})^2 + \beta_{TT} (T_{j,t})^2 + \\ & \beta_{FES} (\ln FE_{j,t} \cdot \ln S_{j,t}) + \beta_{FET} (\ln FE_{j,t} \cdot T_{j,t}) + \beta_{ST} (\ln S_{j,t} \cdot T_{j,t}) + \\ & v_{j,t} - u_{j,t} \end{aligned} \tag{8}$$

where FE denotes the fishing effort given as FP times FT. The variables are defined as in equation (7).

In equation (7) and (8), Y is measured as the monthly output given as either inflated catch revenue[13], weighted catch weight or catch weight, i.e. $Y^{\text{inf. revenue}}$, $Y^{\text{weighted weight}}$ and Y^{weight}, cf. the previous section.

A total of six production functions will thus be estimated. The acronyms used for each of these models in the following sections are displayed in Table 3.1.

Table 3.1 Acronyms used for the estimated models

Input measure / Output measure	Inflated revenue (IV)	Weighted weight (WW)	Weight (W)
Fishing power and fishing time included as separate variables	Model IV.a	Model WW.a	Model W.a
Product of fishing power and fishing time	Model IV.b	Model WW.b	Model W.b

[12] Technological progress could be included in other ways, see for instance Heathfield and Wibe (1987). Some estimations have been made with technological progress included via the intercept term as $\delta_0 = \delta_0 e^{mt}$ and via the fishing power and fishing time measures as $FP_t^{TECH} = e^{nt} \cdot FP_t$ and $FT_t^{TECH} = e^{nt} \cdot FT_t$, respectively. However, the estimated efficiency levels were highly correlated and not significantly different from each other.

[13] Sharma and Leung (1999) mentioned some limitations of using catch revenue as the output measure. For instance, there is the unclear deduction between technical and allocative efficiency.

As mentioned in Section 1, the inefficiency term can be modelled by assuming some kind of distribution of this term or including an inefficiency model. Here the latter is chosen in order to explain some of the possible reasons for any observed inefficiencies. A number of factors are available to explain the observed inefficiencies. The utilised inefficiency model therefore consists of both quantitative and dummy variables. It is for all the estimations specified as:

$$u_{j,t} = \delta_0 + \delta_1 \ln INS_{j,t} + \delta_2 \ln VIN_{j,t} + \delta_3 DsN_{j,t} + \delta_4 DsT_{j,t} + \delta_5 PF_{j,t} + \delta_6 HS_{j,t} + \delta_7 UF_{j,t} + \delta_8 PFA4B_{j,t} + \delta_9 PFA4C_{j,t} + \delta_{10} PFA3AN_{j,t} + \delta_{11} EXPA_{j,t} + \delta_{12} EXPG_{j,t} + \delta_{13} FEB_{j,t} + \delta_{14} MAR_{j,t} + \delta_{15} APR_{j,t} + \delta_{16} MAY_{j,t} + \delta_{17} JUN_{j,t} + \delta_{18} JUL_{j,t} + \delta_{19} AUG_{j,t} + \delta_{20} SEP_{j,t} + \delta_{21} OCT_{j,t} + \delta_{22} NOV_{j,t} + \delta_{23} DEC_{j,t} + w_{j,t} \quad (9)$$

The first variable is inflated insurance value (INS), which is included in order to test whether the vessel size has any influence on the level of efficiency. Pascoe, Andersen and de Wilde (2001) concluded that the size has an influence on the technical efficiency level of the Dutch beam trawlers, while Vestergaard et al. (2003) have the same conclusion for Danish industrial vessels. Both analyses found that larger vessels have a higher efficiency than smaller vessels.

The construction year of the Danish seiner (VIN) is included to test whether older Danish seiners are more inefficient than newer ones. However, this may not be the case considering that maintenance and investments may eliminate or at least reduce any differences. Campbell and Hand (1998) included dummy variables to model the effects of construction year on the level of technical efficiency, although their conclusion on the effect related to the construction year is unclear. The average age of the included Danish seiners increased from 31 years in 1987 to 37 years in 1999 with a standard deviation of around 12. The newest Danish seiner was from 1994, while the oldest was from 1913.

In the Danish vessel register, each Danish seiner is classified as either an ordinary Danish seiner, a Danish seiner with the ability to also use nets (DsN), or a Danish seiner with the ability to also act as a stern trawler (DsT). Dummy variables are included in the inefficiency model to analyse whether the two multi-gear vessels have any efficiency advantages compared to an ordinary Danish seiner. The expectation would be that this is the case, considering it will be easier for a multi-gear Danish seiner to adjust to any changes in the catch possibilities.

The skippers on the vessels can also have a different commercial status. A distinction is made between three types, i.e. commercial (full-time) fishermen, part-time fishermen (PF) or hired skipper (HS), where a firm primarily hires the latter. There is also a fourth type, which covers unknowns (UF), although the main part of these is most likely part time fishermen. Dummy variables are used to analyse whether the commercial status of the fisherman has any influence on the level of technical efficiency. It is expected that full-time fishermen have the greatest incentive to be efficient, considering that part-time fishermen do not have fishing as

their primary occupation Further, hired skippers are not solely getting the benefits from being efficient due to the payment schemes used in fisheries.

A primary fishing area is derived for each observation, using the method proposed by Campbell and Hand (1998). The primary fishing area is thus assigned to be the area, where the largest relative part of the catch revenue is caught. Four distinct areas are defined, i.e. northern, central (PFA4B) and southern (PFA4C) part of the North Sea and Skagerrak (PFA3AN). The variables thus account for different area conditions, such as seabed and height of waves.

Two variables are included in order to reflect each Danish seiner's (fisherman's) experience of fishing in the included areas (EXPA) and with their primary gear (EXPG). The former measures, on a yearly level, the share of days at sea in the North Sea and Skagerrak compared with the total days at sea. The latter is on a monthly basis, and measures the share of days at sea, where the primary gear (i.e. Danish seine) is used instead of other gear types such as trawl, net, line, etc.

Finally, eleven monthly dummy variables are included in order to reflect any seasonality in the technical inefficiency (FEB,…,DEC). It can be discussed whether these dummies should have been included in the production function instead, in order to account for monthly differences in the production technology. Coelli, Perelman and Romano (1999) investigate the issue of including environmental factors. Based on empirical estimations they find that the obtained rankings are similar for the methods, but that the levels differ to some extent. Furthermore, they recommend including the environmental factors in the inefficiency model, as done here with the monthly dummies, because the estimated frontier then reflect the outer boundaries of the production possibility set.

Unfortunately, it is not possible to include any dummy variables reflecting regulatory changes in the inefficiency model. Although such changes have taken place during the analysed period, it is not possible to identify the most important ones at the required level of detail.

To avoid the dummy trap when estimating the inefficiency model, one dummy variable is excluded in every set of dummy variables, cf. Hardy (1993). The reference situation is thus an ordinary Danish seiner with a commercial full-time fisherman as skipper, fishing in the northern part of the North Sea in January.

4. Estimations of the frontier production function

As mentioned in the previous section, six frontier production functions are estimated in total, cf. Table 3.1. This is done by using FRONTIER 4.1 (Coelli 1996). The results from these estimations and some specification tests are presented in this section.

Table 4.1 shows the results from estimating the production frontier for Model IV.a, Model WW.a and Model W.a, while Table 4.2 shows the results obtained for Model IV.b, Model WW.b and Model W.b.

Most of the variables included in the production frontier turn out to be significant in both models, but unfortunately the estimated coefficients are in general difficult to interpret, cf. Campbell and Hand (1998) and Eggert (2001). Instead it is recommended to calculate elasticities, which will therefore be done in Section 6.

Table 4.1 Estimation of the frontier production function in Models IV.a, WW.a and W.a

		------ Model IV.a ------		----- Model WW.a -----		----- Model W.a -----	
	Parameter	Coefficient	Standard deviation	Coefficient	Standard deviation	Coefficient	Standard deviation
	β_0	11.41	0.57***	16.17	0.75***	14.51	0.56***
Ln (tonnage)	β_{FP}	-0.59	0.17***	-2.80	0.22***	-2.38	0.17***
Ln (days at sea)	β_{FT}	1.28	0.10***	0.48	0.13***	0.99	0.10***
Ln (stock)	β_S	-0.69	0.15***	-3.77	0.21***	-2.04	0.14***
Time	β_T	-0.02	0.00***	0.01	0.00***	-0.01	0.00***
Ln (tonnage)^2	β_{FPFP}	0.09	0.01***	0.14	0.02***	0.16	0.01***
Ln (days at sea)^2	β_{FTFT}	-0.01	0.01**	-0.02	0.01***	-0.01	0.01
Ln (stock)^2	β_{SS}	0.13	0.01***	0.43	0.02***	0.17	0.01***
Time^2	β_{TT}	0.00	0.00***	0.00	0.00***	0.00	0.00***
Ln (tonnage) × Ln (days at sea)	β_{FPFT}	0.04	0.02**	0.04	0.02*	0.05	0.02***
Ln (tonnage) × Ln (stock)	β_{FPS}	0.02	0.03	0.45	0.04***	0.32	0.03***
Ln (tonnage) × time	β_{FPT}	0.00	0.00***	0.00	0.00***	0.00	0.00***
Ln (days at sea) × Ln (stock)	β_{FTS}	-0.11	0.02***	0.07	0.02***	-0.05	0.02**
Ln (days at sea) × time	β_{FTT}	0.00	0.00***	0.00	0.00***	0.00	0.00***
Ln (stock) × time	β_{ST}	0.00	0.00***	-0.01	0.00***	0.00	0.00
Sigma-squared	σ^2	0.52	0.02***	1.29	0.09***	0.55	0.02***
Gamma	γ	0.77	0.01***	0.78	0.01***	0.76	0.01***

Notes: *** significant at the 1% level, ** significant at the 5% level, * significant at the 10% level.

Table 4.2 Estimation of the frontier production function in Models IV.b,WW.b and W.b

		------ Model IV.b ------		---- Model WW.b ----		------ Model W.b ------	
	Parameter	Coefficient	Standard deviation	Coefficient	Standard deviation	Coefficient	Standard deviation
	β_0	5.24	0.45***	8.04	0.57***	6.32	0.46***
Ln (tonnage×days at sea)	β_{FE}	1.77	0.08***	0.54	0.10***	1.06	0.08***
Ln (stock)	β_S	-0.28	0.13**	-2.84	0.17***	-1.28	0.13***
Time	β_T	-0.02	0.00***	0.01	0.00***	-0.01	0.00***
Ln (tonnage×days at sea)^2	β_{FEFE}	-0.05	0.00***	-0.04	0.00***	-0.04	0.00***
Ln (stock)^2	β_{SS}	0.12	0.01***	0.41	0.02***	0.16	0.01***
Time^2	β_{TT}	0.00	0.00***	0.00	0.00***	0.00	0.00***
Ln (tonnage×days at sea) × Ln (stock)	β_{FES}	-0.11	0.01***	0.15	0.02***	0.04	0.02**
Ln (tonnage×days at sea) × time	β_{FET}	0.00	0.00	0.00	0.00***	0.00	0.00
Ln (stock) × time	β_{ST}	0.00	0.00***	0.00	0.00***	0.00	0.00***
Sigma-squared	σ^2	5.24	0.45***	8.04	0.57***	6.32	0.46***
Gamma	γ	1.77	0.08***	0.54	0.10***	1.06	0.08***

Notes: *** significant at the 1% level, ** significant at the 5% level, * significant at the 10% level.

Instead, the estimated frontier production functions will be tested in order to check whether these are well specified and whether it is appropriate to include an inefficiency model at all. This will be done by using the different tests mentioned in Section 1. The test results are given in Table 4.3.

Table 4.3 Testing the specification of the frontier production function

No inefficiency[1)]	Ln[L(H_0)]	Ln[L(H_1)]	LR	Critical χ^2	Number of restrictions	Decision
Model IV.a	-17,334	-14,432	5,804	37.066*	25	Reject
Model IV.b	-19,056	-15,437	7,237	37.066*	25	Reject
Model WW.a	-21,517	-20,021	2,991	37.066*	25	Reject
Model WW.b	-22,772	-20,660	4,223	37.066*	25	Reject
Model W.a	-17,637	-14,732	5,809	37.066*	25	Reject
Model W.b	-19,349	-15,729	7,239	37.066*	25	Reject

Cobb-Douglas production function[2)]	Ln[L(H_0)]	Ln[L(H_1)]	LR	Critical χ^2	Number of restrictions	Decision
Model IV.a	-14,864	-14,432	864	16.92	9	Reject
Model IV.b	-15,833	-15,437	791	12.59	6	Reject
Model WW.a	-20,863	-20,021	1,684	16.92	9	Reject
Model WW.b	-21,380	-20,660	1,440	12.59	6	Reject
Model W.a	-15,369	-14,732	1,273	16.92	9	Reject
Model W.b	-16,188	-15,729	918	12.59	6	Reject

No time effects[3)]	Ln[L(H_0)]	Ln[L(H_1)]	LR	Critical χ^2	Number of restrictions	Decision
Model IV.a	-14,962	-14,432	1,061	11.07	5	Reject
Model IV.b	-15,977	-15,437	1,080	9.49	4	Reject
Model WW.a	-20,883	-20,021	1,723	11.07	5	Reject
Model WW.b	-21,513	-20,660	1,705	9.49	4	Reject
Model W.a	-15,255	-14,732	1,045	11.07	5	Reject
Model W.b	-16,253	-15,729	1,048	9.49	4	Reject

Notes: * Critical values obtained from Kodde and Palm (1986).

1) The null hypothesis is: H_0:$\gamma = \delta_0 = \ldots = \delta_{23} = 0$.

2) The null hypotheses are: H_0:$\beta_{FPFP}=\beta_{FTFT}=\beta_{SS}=\beta_{TT}=\beta_{FPFT}=\beta_{FPS}=\beta_{FTS}=\beta_{FTT}=\beta_{ST}=0$ or H_0:$\beta_{FEFE}=\beta_{SS}=\beta_{TT}=\beta_{FES}=\beta_{FET}=\beta_{ST}=0$, depending on the model.

3) The null hypothesis is: H_0:$\beta_T=\beta_{TT}=\beta_{FPT}=\beta_{FTT}=\beta_{ST}=0$ or H_0:$\beta_T=\beta_{TT}=\beta_{FET}=\beta_{ST}=0$, depending on the model.

The first test focuses on whether there are any inefficiency effects in the model. It follows from Table 4.3 that the hypothesis of no inefficiency effects is rejected at the 5% level in all the models, and Maximum Likelihood shall therefore be used to estimate this model in order to get efficient estimates[14]. Whether the functional form of the production function can be reduced to a Cobb-Douglas form is also tested, and this test is also rejected at a high level of significance for all the models. Finally, the hypothesis of not including time effects in the model is also rejected.

[14] An estimator is considered efficient if the unbiased estimator has a smaller variance than any other unbiased estimators for a given sample, cf. Pindyck and Rubinfeld (1991).

Having thus tested and found that the model is well specified, the next step is to consider consequences of choosing different output and input measures.

5. Impact on the level of technical efficiency

The technical efficiency measure estimated in the Stochastic Production Frontier models used here is output-oriented, i.e. it measures the output of a firm relative to the output produced by firms which are fully efficient, given that the employed inputs remain unchanged.

The average efficiency scores are presented in Table 5.1 for each of the models analysed. The average efficiency, in the model with inflated revenue used as output measure is estimated to be 62-63% depending on the input measure used. A Danish seiner fishing in the North Sea and Skagerrak therefore on average over the thirteen years only caught 62-63% of the value caught by a fully efficient Danish seiner. The estimated efficiency levels with output measured as either weighted weight or weight can be interpreted likewise.

Table 5.1 Average efficiency scores from 1987 to 1999

	Model IV.a	Model IV.b	Model WW.a	Model WW.b	Model W.a	Model W.b
Average efficiency	0.62	0.63	0.66	0.64	0.64	0.64
Standard deviation	0.20	0.22	0.18	0.20	0.20	0.22
Maximum efficiency	0.95	0.94	0.94	0.93	0.96	0.95
Minimum efficiency	0.01	0.02	0.00	0.00	0.01	0.02

The relative distribution of the efficiency scores, cf. Table 5.2, shows that the models estimated with weighted weight have a tendency to have a relatively lower number of efficiency scores in the interval 0.9-1.0 compared to the other models. Instead, these models have a higher percentage of scores in the intervals from 0.6-0.7 and 0.7-0.8.

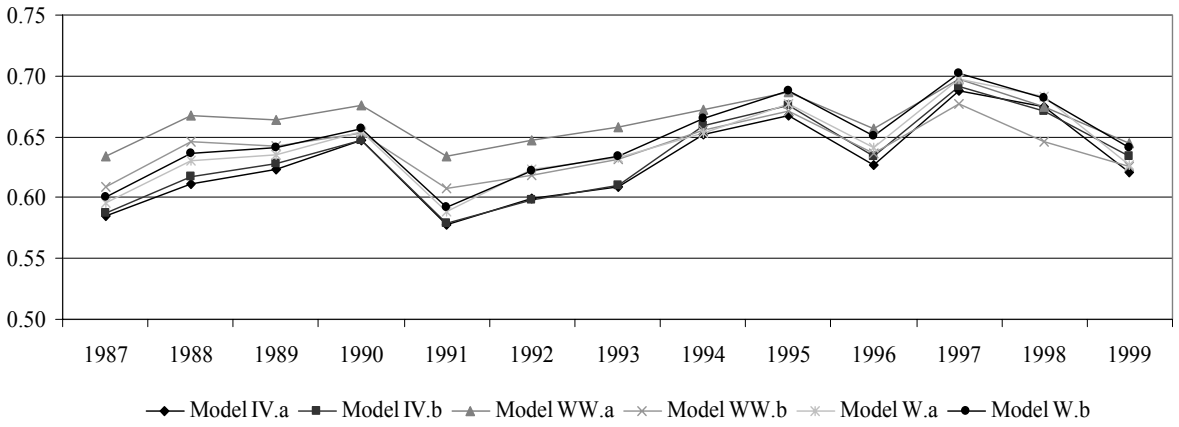
Table 5.2 Relative distributions of efficiency scores

		Model IV.a	Model IV.b	Model WW.a	Model WW.b	Model W.a	Model W.b
Efficiency score	0.0-0.1	0.68	0.95	0.52	0.93	0.58	0.84
	0.1-0.2	2.84	3.56	2.00	2.91	2.74	3.41
	0.2-0.3	5.84	6.22	3.46	4.71	5.26	5.82
	0.3-0.4	7.83	7.82	5.25	6.08	7.40	7.04
	0.4-0.5	9.65	8.81	7.08	8.06	9.04	8.44
	0.5-0.6	11.84	10.44	10.92	10.97	11.13	9.76
	0.6-0.7	15.75	13.66	17.20	16.50	15.24	12.63
	0.7-0.8	22.77	21.82	28.62	27.07	22.20	21.18
	0.8-0.9	21.43	25.25	24.64	22.47	25.05	29.22
	0.9-1.0	1.38	1.48	0.32	0.28	1.34	1.66

The development in the average efficiency scores from 1987 to 1999 is presented in Figure 5.1. There has been a tendency for scores to increase from 1987 to 1999, but there are, however, significant drops in 1991, 1996, 1998 and 1999. This means that the overall

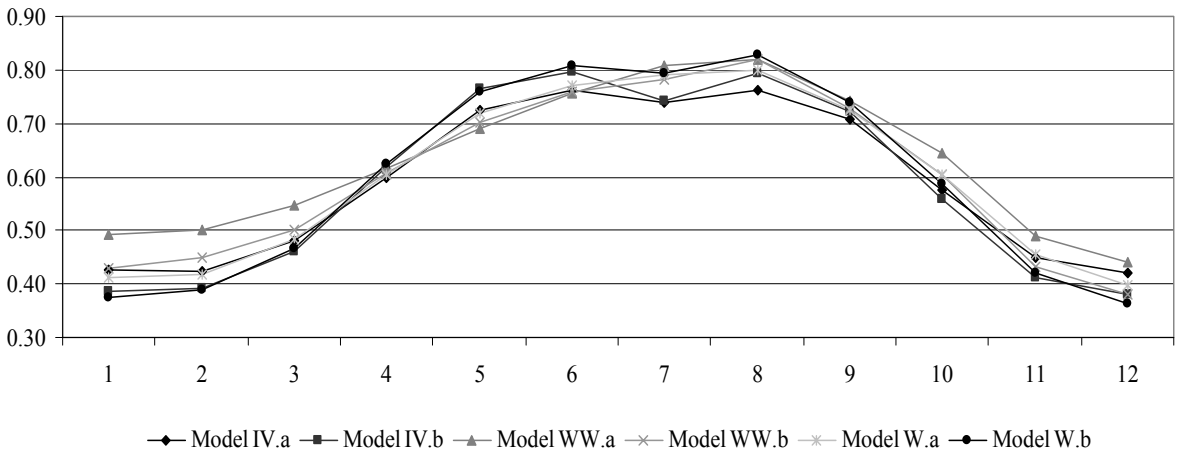
increase has only been minor. The development in the average yearly efficiency for each of the models followed almost the same pattern, and this is confirmed by looking at the correlation between the average yearly efficiency scores, cf. Table 5.3.

Figure 5.1 Development in yearly efficiency scores



Looking at the average monthly efficiency levels, an obvious trend can be observed, cf. Figure 5.2. Starting with an average efficiency of 42% in January, it increases until reaching a maximum of approximately 80% in August. From August, the average monthly efficiency starts to decline, ending up in December with an efficiency of 40%. Again, a similar development can be observed for each of the models estimated, and it corresponds with the estimated parameters for the monthly dummy variables in the inefficiency models, cf. Section 7. This development is most likely influenced by the magnitude of cod and plaice in the catches of the Danish seiners, which are high during the summer months.

Figure 5.2 Development in monthly efficiency scores



Despite that the previous figures seem to indicate that the choice of output and input measures are unimportant, the picture changes when looking at the correlation coefficients, cf. Table 5.3 to Table 5.5.

The focus is first on the correlations between the different output measures. These are observed to be higher for the models with output measured as revenue and weight, while these are lower when comparing with the weighted weight output measure. The efficiency levels estimated using revenue and weight seem to be more alike than when compared to the weighted weight efficiency.

Table 5.3 Correlations between the estimated efficiencies

	Model IV.a	Model IV.b	Model WW.a	Model WW.b	Model W.a	Model W.b
Model IV.a	1.00					
Model IV.b	0.94	1.00				
Model WW.a	0.82	0.81	1.00			
Model WW.b	0.79	0.86	0.96	1.00		
Model W.a	0.96	0.92	0.88	0.84	1.00	
Model W.b	0.90	0.97	0.86	0.91	0.94	1.00

The correlation between the average yearly efficiencies estimated using tonnage and days at sea separately, compared to the service flow measure, is in all models estimated to be high, disregarding which output measure is used, cf. Table 5.3.

The general conclusion is thus that the choice of input measure does not seem to result in significantly different estimations of technical efficiency. However, the technical efficiencies seem to be influenced by the choice of output measure, despite that approximately the same levels are estimated. The variation primarily seems to be for revenue and weight on one side and weighted weight on the other side.

If analysis is performed on more aggregated levels of technical efficiency, higher correlations between the different measures are observed, cf. Table 5.4 and Table 5.5, but the ones related to revenue and weight still correlate higher compared to weighted weight.

Table 5.4 Correlations between the average yearly efficiencies

	Model IV.a	Model IV.b	Model WW.a	Model WW.b	Model W.a	Model W.b
Model IV.a	1.00					
Model IV.b	0.99	1.00				
Model WW.a	0.92	0.91	1.00			
Model WW.b	0.91	0.92	0.99	1.00		
Model W.a	0.98	0.97	0.94	0.92	1.00	
Model W.b	0.99	0.99	0.93	0.93	0.99	1.00

Table 5.5 Correlations between the average monthly efficiencies

	Model IV.a	Model IV.b	Model WW.a	Model WW.b	Model W.a	Model W.b
Model IV.a	1.00					
Model IV.b	1.00	1.00				
Model WW.a	0.97	0.96	1.00			
Model WW.b	0.99	0.98	1.00	1.00		
Model W.a	1.00	0.99	0.99	0.99	1.00	
Model W.b	1.00	1.00	0.98	0.99	1.00	1.00

6. Impact on the output elasticities

Based on the previous section, it seems necessary to further investigate the output measures used. This will be done by calculating the output elasticities, which thus furthermore facilitates a more thorough discussion of the coefficients found for the frontier production functions.

The output elasticities are found by taking the derivative of each input with respect to the output. If for instance the input measure is tonnage, the output elasticity is, when inputs are included separately, found as follows[15]:

$$\frac{\partial \ln Y}{\partial \ln FP} = \beta_{FP} + 2 \cdot \beta_{FPFP} \cdot \ln FP + \beta_{FPFT} \cdot \ln FT + \beta_{FPS} \cdot \ln S + \beta_{FPT} \cdot \ln T \qquad (10)$$

The average output elasticities evaluated in mean values over the thirteen years from 1987 to 1999 for the six models are presented in Table 6.1.

Table 6.1 Average yearly output elasticities

	Model IV.a	Model WW.a	Model W.a	Model IV.b	Model WW.b	Model W.b
Tonnage	0.27	0.26	0.29			
Days at sea	0.94	0.90	0.96			
Tonnage×days at sea				0.72	0.68	0.74
Stock	0.37	1.26	0.40	0.40	1.28	0.44
Time	0.0012	0.0045	0.0010	0.0014	0.0046	0.0012
Scale elasticity*	1.21	1.16	1.25	0.72	0.68	0.74

Notes: * The scale elasticity is only calculated for the factors which the fishermen can influence.

In the models with tonnage and days at sea included as separate variables in the production frontier, the output elasticities are estimated to be relatively close to each other. On average, a 10% increase in tonnage will give rise to an increase in catch, measured in either revenue or weight, of approximately 2.7%. Similarly, a decrease in the number of days at sea of 10%

[15] The output derivative with respect to time is for the average values calculated as follows:

$$\frac{\partial \ln Y}{\partial T} = \beta_T + 2 \cdot \beta_{TT} \cdot T + \beta_{FPT} \cdot \ln FP + \beta_{FTT} \cdot \ln FT + \beta_{ST} \cdot \ln S$$

Since the time measure is not transformed by taking the logarithm, i.e. the derivative gives the relative effect on output of an absolute change in time.

will result in a 9.3% decrease in catch on average. When including tonnage and days at sea as a composite measure, a decrease of 10% in the composite measure will result in an average decrease of 7.1% in the catch level.

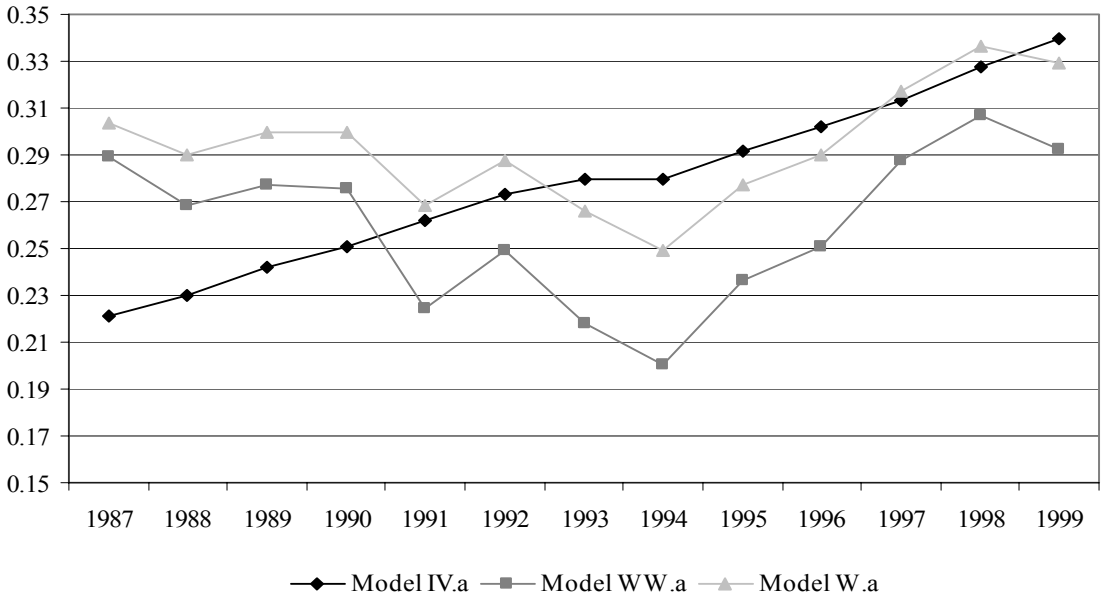
Calculating the scale elasticity for the factors which the fisherman can influence, gives a figure above one in the approach where these factors are included separately. This implies increasing returns to scale, and this may be an explanation for the increase in size of the average Danish seiner in the dataset, cf. Table 2.4. However, using the service flow approach gives scale elasticity below one, indicating decreasing returns to scale.

Turning attention to the output measures, it is observed that the weighted weight systematically gives lower output elasticities for tonnage, days at sea and service flow measures. The opposite is observed for the stock related output elasticities. In this case, the output elasticity is estimated to be three times higher, when using the weighted weight output measure, regardless of how input is measured.

The output elasticity calculated with respect to the index of time shows the same pattern as observed with the stock. Similar figures for the catch revenue and catch weight are found, while using the weighted catch weight again results in much higher output elasticities.

Figure 6.1 to Figure 6.3 shows the development in output elasticities for the different output and input measures used, when evaluated as mean values for each year[16]. For tonnage, the development over the years is almost identical for weight and weighted weight, while value gives a more smooth development, cf. Figure 6.1.

Figure 6.1 Development in output elasticities with respect to tonnage



[16] The development for the output elasticity related to the stock is not included for Model IV.b, Model WW.b and Model W.b, because these are similar to those observed in Model IV.a, Model WW.a and Model W.a.

The number of days at sea also shows a similar development with a tendency to converge in the latter years. This can be seen in Figure 6.2.

Figure 6.2 Development in output elasticities with respect to days at sea

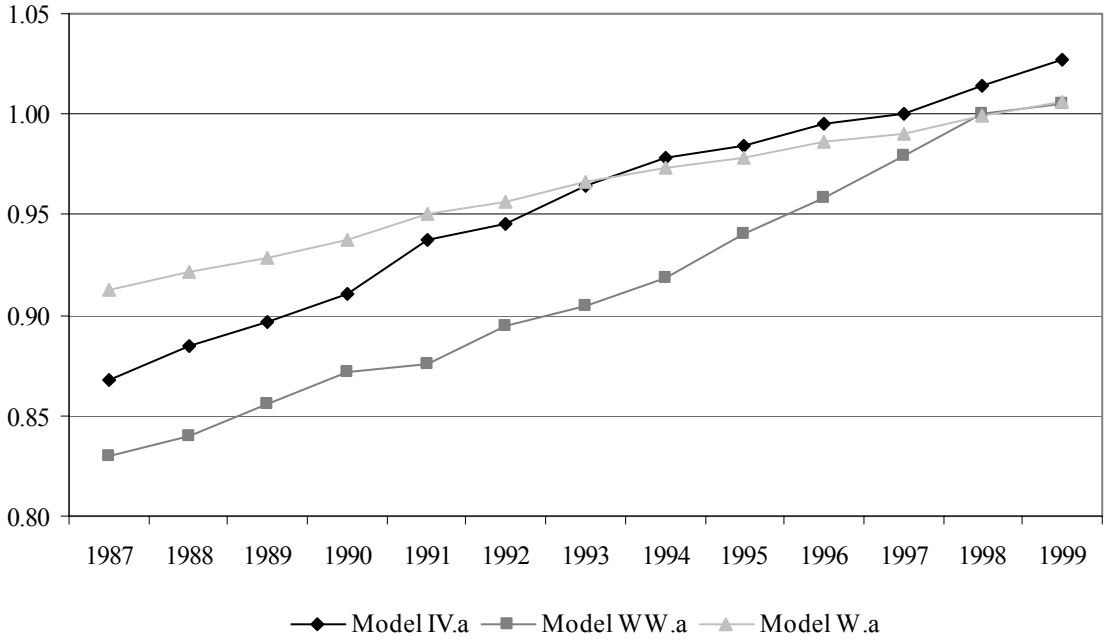
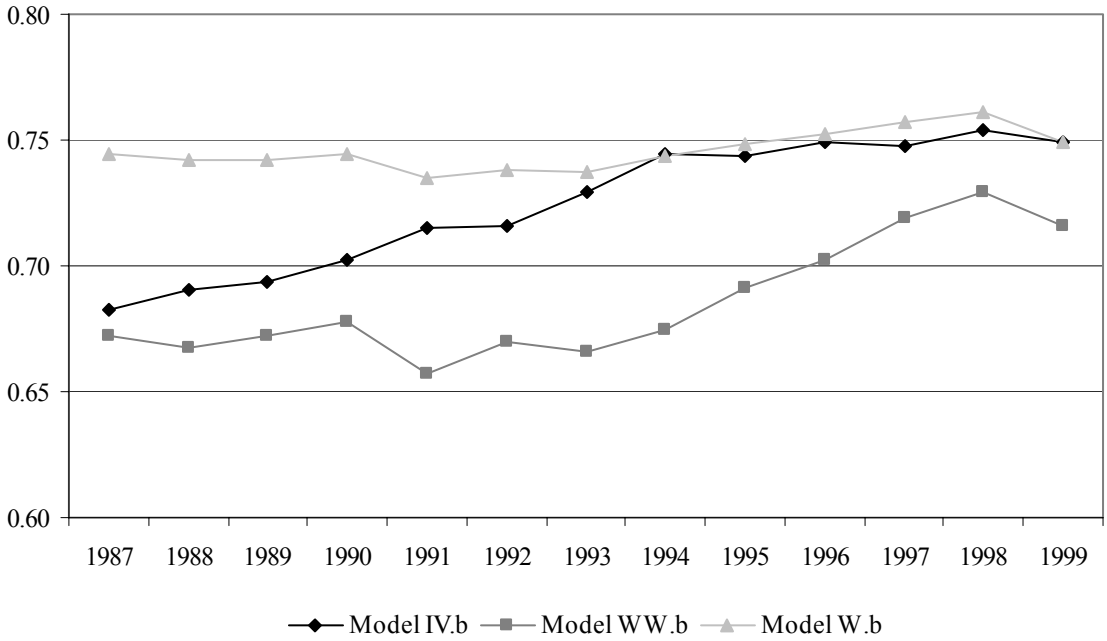


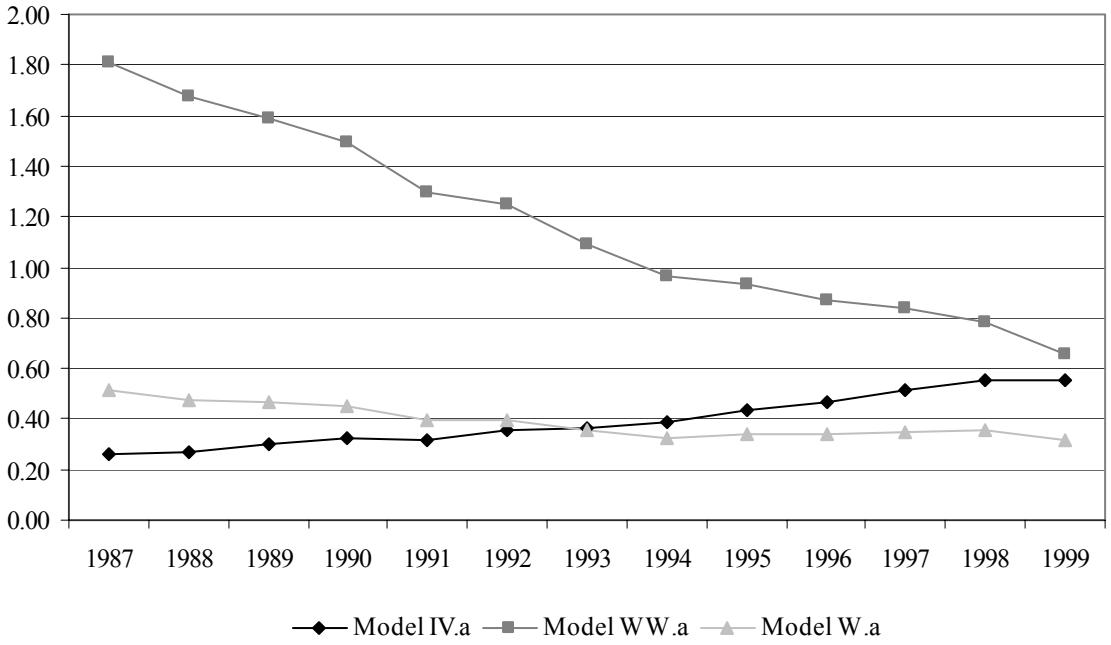
Figure 6.3 shows the development in output elasticities, when using the service flow approach. The elasticities for the different models have a tendency to converge, and is most profound for the models using inflated revenue and weight.

Figure 6.3 Development in output elasticities with respect tonnage times days at sea



For the output elasticity of the stock, the development is scattered, cf. Figure 6.4. Using revenue and weight, the development is contrary to each other. Using the service flow approach gives a different development for each output measure. Regarding the stock, the output elasticity measured with respect to weight decreases from 1987 to 1999, but increases when revenue is used. However, using the weighted catch weight gives different results, considering that it is at a very high level in 1987, but then converges significantly towards the others.

Figure 6.4 Development in output elasticities with respect stock



Investigation of the output elasticities thus reveals a scattered pattern, where the different output measures seem to give various estimates. Based on the average over the thirteen years, the weight and revenue output measures seem to give approximately equal results. However, this conclusion is to some extent undermined when looking at the yearly output elasticities. It is noticeable though that the stock and time elasticities with the weighted weight output measure are significantly different to the other two output measures. A conclusion could therefore be that the output elasticities are generally more alike when the output measures are revenue and weight, while weighted weight in some cases can give other elasticities.

7. Estimations of the inefficiency model

When estimating the frontier production functions, inefficiency models are also estimated. These models can be used to evaluate which factors influence fishermen's level of technical efficiency and thus indirectly influence their behaviour. The results for the six estimated models are presented in Table 7.1 and Table 7.2.

Table 7.1 Estimations of the technical inefficiency model in Models IV.a,WW.a and W.a

	Para-meter	----- Model IV.a ------ Coef-ficient	Standard deviation	----- Model WW.a --- Coef-ficient	Standard deviation	----- Model W.a ------ Coef-ficient	Standard deviation
	δ_0	17.15	13.14	15.65	31.38	22.62	14.14
Inflated insurance value	δ_1	-0.74	0.03***	-0.37	0.06***	-0.64	0.03***
Construction year	δ_2	-0.68	1.77	-1.11	4.21	-1.55	1.90
Danish seines/netter	δ_3	-0.38	0.07***	-0.81	0.15***	-0.24	0.06***
Danish seiner/stern trawler	δ_4	-0.13	0.08*	-0.10	0.10	0.10	0.07
Part time fisherman	δ_5	0.28	0.09***	0.99	0.17***	0.25	0.10**
Hired skipper	δ_6	0.51	0.14***	0.67	0.26**	0.43	0.15***
Unknown commercial status	δ_7	0.22	0.02***	0.34	0.04***	0.23	0.02***
Primary fishing area 4B	δ_8	0.24	0.09***	-0.91	0.11***	0.06	0.08
Primary fishing area 4C	δ_9	0.22	0.29	0.06	0.52	0.27	0.32
Primary fishing area 3AN	δ_{10}	-0.06	0.09	-0.60	0.12***	-0.19	0.08**
Time in NS and Skagerrak	δ_{11}	-0.68	0.06***	-0.97	0.11***	-0.74	0.06***
Time with primary gear	δ_{12}	0.15	0.04***	0.02	0.06	-0.03	0.04
February	δ_{13}	-0.02	0.04	-0.06	0.07	-0.04	0.04
March	δ_{14}	-0.28	0.04***	-0.47	0.08***	-0.32	0.04***
April	δ_{15}	-0.77	0.05***	-1.09	0.12***	-0.83	0.05***
May	δ_{16}	-1.45	0.07***	-1.87	0.19***	-1.46	0.07***
June	δ_{17}	-1.76	0.09***	-2.86	0.31***	-1.90	0.10***
July	δ_{18}	-1.55	0.08***	-3.98	0.47***	-2.05	0.11***
August	δ_{19}	-1.74	0.09***	-4.38	0.54***	-2.14	0.11***
September	δ_{20}	-1.32	0.07***	-2.59	0.26***	-1.48	0.07***
October	δ_{21}	-0.65	0.05***	-1.28	0.12***	-0.81	0.05***
November	δ_{22}	-0.13	0.04***	-0.10	0.07	-0.19	0.04***
December	δ_{23}	0.03	0.05	0.21	0.08***	0.04	0.05

Notes: *** significant at the 1% level, ** significant at the 5% level, * significant at the 10% level.

Table 7.2 Estimations of the technical inefficiency model in Models IV.b,WW.b and W.b

	Para-meter	------ Model IV.b ------ Coef-ficient	Standard deviation	---- Model WW.b ---- Coef-ficient	Standard deviation	------ Model W.b ------ Coef-ficient	Standard deviation
	δ_0	103.09	15.62***	138.81	27.80***	117.01	16.43***
Inflated insurance value	δ_1	-0.26	0.03***	0.32	0.05***	-0.13	0.03***
Construction year	δ_2	-12.88	2.09***	-18.60	3.73***	-14.91	2.20***
Danish seines/netter	δ_3	-1.07	0.11***	-1.43	0.19***	-0.84	0.09***
Danish seiner/stern trawler	δ_4	-0.33	0.11***	-0.23	0.13*	-0.10	0.10
Part time fisherman	δ_5	0.26	0.12**	0.85	0.16***	0.25	0.13*
Hired skipper	δ_6	0.46	0.18***	0.10	0.22	0.10	0.19
Unknown commercial status	δ_7	0.22	0.03***	0.27	0.04***	0.23	0.03***
Primary fishing area 4B	δ_8	0.22	0.10**	-0.79	0.11***	0.03	0.09
Primary fishing area 4C	δ_9	0.18	0.42	-0.06	0.46	0.18	0.39
Primary fishing area 3AN	δ_{10}	-0.21	0.10**	-0.66	0.12***	-0.35	0.09***
Time in NS and Skagerrak	δ_{11}	-0.95	0.07***	-1.12	0.10***	-0.99	0.07***
Time with primary gear	δ_{12}	0.12	0.04***	0.04	0.06	-0.02	0.04
February	δ_{13}	-0.10	0.05**	-0.15	0.07	-0.12	0.05***
March	δ_{14}	-0.42	0.05***	-0.56	0.07***	-0.46	0.05***
April	δ_{15}	-1.11	0.06***	-1.35	0.11***	-1.17	0.06***
May	δ_{16}	-2.16	0.11***	-2.27	0.18***	-2.14	0.11***
June	δ_{17}	-2.55	0.14***	-3.17	0.29***	-2.74	0.15***
July	δ_{18}	-1.92	0.10***	-3.58	0.33***	-2.53	0.14***
August	δ_{19}	-2.48	0.13***	-4.54	0.48***	-3.05	0.17***
September	δ_{20}	-1.74	0.08***	-2.61	0.19***	-1.92	0.09***
October	δ_{21}	-0.80	0.06***	-1.25	0.10***	-0.96	0.06***
November	δ_{22}	-0.13	0.05***	-0.10	0.07	-0.20	0.05***
December	δ_{23}	0.12	0.05**	0.30	0.08***	0.14	0.05***

Notes: *** significant at the 1% level, ** significant at the 5% level, * significant at the 10% level.

Before interpreting the estimated coefficients, it is generally observed that the models using revenue and weight as output measure estimate coefficients are more alike compared to the weighted weight coefficients. However, the estimated coefficients generally seem to have the same signs. The derived conclusions in the following will therefore be covering all models.

All the estimated inefficiency models have inflated insurance value to be significant, and are negative with only one exception (Model WW.a). This implies that the higher the inflated insurance value, the higher the level of technical efficiency, i.e. the larger a Danish seiner is, the more efficient it will be.

There is no general agreement on whether the construction year of the Danish seiner has any influence on the level of technical efficiency. Only in the models using the service flow approach does the construction year turn out to be significant. In this case, it is observed that new Danish seiners are more efficient than older ones.

A Danish seiner with the capability of using nets is estimated to be significantly more efficient in all the models compared to the ordinary Danish seiners. The Danish seiners with stern capabilities are also, when the coefficient is significant, estimated to have a higher level of technical efficiency compared to ordinary Danish seiners. This corresponds to the former argumentation that vessels capable of using several gear types are more flexible in their fisheries and thus more efficient.

The commercial status also influences the level of efficiency for the Danish seiners. The estimated coefficients show that Danish seiners with skippers as commercial fishermen are more efficient than those Danish seiners where the skippers have another commercial status. Vessels that are skippered by hired skippers have the lowest level of technical efficiency. This result is interesting, especially if it is seen in a principal-agent framework, where the owner of the vessel cannot observe the effort of the skipper, cf. Tirole (1988).

In some of the estimated inefficiency models, the primary fishing area turns out to be significant, while in others it does not. However, in five of the six models, the dummy variable for Skagerrak as the primary fishing area is significant, and all the estimated coefficients point to the conclusion that Danish seiners primarily fishing in Skagerrak are more efficient than Danish seiners fishing in the northern part of the North Sea. This could be related to the distance to the specific fishing location in the different fishing areas, although this has not been possible to verify.

As an indicator of experience related to the fishing area and the fishing gear, two variables have been included. Using the number of days at sea in the North Sea and Skagerrak relative to the total number of days at sea helps to reflect the former. This turned out to be significant in all models by having a negative coefficient. This implies a positive relationship between the total time a Danish seiner spent in the North Sea and Skagerrak with the level of

efficiency of the vessel. However, the variable reflecting the number of days at sea using the primary gear, relative to the total number of days at sea in the included areas, is only significant when output is measured as inflated revenue. In this case, the coefficients are positive, implying that the efficiency level decreases when the primary gear is used more. This result seems contradictive to what would be expected. However, it is noteworthy to observe that the variable is only significant when output is measured as inflated catch revenue.

The included monthly dummy variables are supposed to reflect changes in the technical efficiency due to monthly variations. Almost all these variables were significant in the six estimated models. The level of efficiency rose to a higher level during the summer months, i.e. June to August, while the winter months, December to February, have almost the same low levels of technical efficiency.

Conclusion

The importance of how output is measured and how inputs are included have been analysed using the stochastic production frontier approach for a dataset comprised of Danish seiners fishing in the North Sea and Skagerrak in the period from 1987 to 1999. Six models were estimated using a translog functional form as an approximation for the true functional form of the production function. In the estimations, inefficiency models were also included in order to find some explanations for the observed inefficiency.

Three measures of output were used, i.e. catch weight, inflated catch revenue and revenue weighted catch weight. These were separately estimated against a production function where the factors controllable by the fisherman, i.e. measures of fishing power and fishing time, were included separately or as a service flow calculated as tonnage multiplied by number of days at sea. The production function also included an index of stock and a time measure.

The first comparisons were related to the estimated levels of technical efficiency, and how these differed between the estimated models. One conclusion from these comparisons was that the choice of method to include inputs did not influence the estimated levels of technical efficiency significantly. The choice of output measure did on the other hand seem to be important. The estimated levels of technical efficiency were generally at the same levels, and so was the development over the thirteen years. However, the distribution of the efficiency levels and the correlation coefficients revealed that using revenue and weight as output measures produced more comparable results than the ones obtained using weighted weight.

The next step was therefore to perform some further comparisons between the different output measures. This was done by calculating the output elasticities, which at the same time facilitated the interpretation of the estimated parameters in the translog frontier production function. The conclusions derived from this analysis were ambiguous. The thirteen year

averages were approximately equal when measuring output with revenue and weight, while the weighted weight measure gave different elasticities, especially with respect to stock and time. Looking at the development over the thirteen years we saw that the elasticities differ depending on the different measures used. This is especially the case for the elasticities with respect to time and stock. The general conclusion was however that the output elasticities seem to be more alike when the output measures are revenue and weight, while weighted weight in some cases gives other elasticities.

Turning attention to the inefficiency models, it was observed that for the significant coefficients, the models using revenue and weight as output measure gave more similar estimates. As expected the coefficients differed with respect to the input measure used.

To finally conclude on the choice of output and input measure, it can for the analysed fishery be concluded that: 1) the choice between including input separately or as a service flow does not seem to influence the level of technical efficiency, although (as expected) the level of scale size and coefficients in the inefficiency models are affected; 2) the choice between output measures as revenue, weight or weighted weight are more difficult, but the analysis generally shows that using revenue and weight gave approximately equal levels of technical efficiency and coefficients in the inefficiency models, while the pattern is more diversified with respect to the output elasticities. Thus, the utilised input inclusion approach must be decided considering the actual analysed fishery, while further investigations are required to choice between revenue or weight instead of weighted weight as the output measure.

A range of observations can also be derived from the estimated inefficiency models with respect to the factors influencing fishermen's level of technical efficiency. It can for instance be observed that a larger Danish seiner is more efficient than a small one. Full-time fishermen are more efficient than part-time fishermen, while hired skippers are most inefficient. The fishing area chosen also seems to have an influence on the level of technical efficiency. For instance, vessels fishing in Skagerrak tend to have higher efficiency compared to those fishing in the North Sea. The more frequently a fisherman fish in the North Sea and Skagerrak during a given year also seem to affect their efficiency level positively. However, the time allocated to their primary gear seems to negatively influence the level of efficiency. Finally, the summer months are the most efficient months to fish in, while December, January and February are the least efficient.

Several topics for further investigation and discussion can be suggested following this analysis. For instance, the inclusion of a time trend in the translog functional form is not straightforward. Different methods can be used and it would be interesting to investigate the importance of this more closely. The inclusion of a stock measure in the production frontier model in order to account for stock developments is also troublesome. Danish fisheries are generally a multi-species fisheries and one must therefore consider several different stocks,

the relative importance which depends on the vessels analysed, and the target species. The relevance of misreporting may also be analysed, cf. Pascoe, Herrero and Mardle (2001).

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The Inclusion of Stocks in Multi-species Fisheries: The Case of Danish Seiners

by Jesper Levring Andersen

Abstract

Efficiency analysis in fisheries has become an area of increased research. However, setting up models to perform such analyses is complicated and several important modelling issues, including choice of inputs and outputs, level of aggregation and inclusion of stock indices, have only briefly been addressed in the literature. The latter issue is addressed in this paper, using data on Danish seiners and Data Envelopment Analysis (DEA) to estimate efficiency. Production in fisheries is obviously dependent on the fish stocks and comparing vessel efficiency, therefore, needs to account for stock developments. Three methods to include fish stocks are analyzed. It is shown that estimations based on the Catch Per Unit Effort (CPUE) stock measure differ from the estimations based on independent stock measures, and is independent of the choice of time horizon and choice of input/output measures.

Keywords

Data Envelopment Analysis, fish stock, multi-species fisheries, technical efficiency.

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Introduction

Traditionally, estimated production functions only include controllable (discretionary) input factors; i.e., factors that the producers can influence directly through their behaviour (Alvarez 2001). For some sectors in the economy, however, it is necessary to include non-controllable factors as well. In particular, this is the case where there are considerable variations in the conditions experienced by the producers across time, space, and production unit. The fishing industry is one such sector.

The early seminal articles within fisheries economics already recognize the importance of considering fish stocks (Gordon (1954), Schaefer (1957), and Clark (1973a, 1973b)). Fishermen's catches are highly dependent on the availability of fish in the respective fishing areas. If the stocks are low, a given effort will result in a lower catch in contrast to a situation with high fish stocks. Excluding fish stocks from production and efficiency analysis will, therefore, provide misleading results.

Different methods to include fish stocks in production functions have been suggested. However, there is no consensus about which method to use. This is due to several reasons. One is the type of fishery analyzed; e.g., single- or multi-species fishery. Another is describing the state of the fish stock; e.g., is independent stock measures available or not?

It is important to investigate whether different methods of stock inclusion give different results, because the analysis can have a significant influence on management recommendations. For example, if a "wrong" instead of a "right" method for stock inclusion is used, the choice of regulation may be inappropriate and give rise to social losses. Webster, Kennedy and Johnson (1998, p. 3) recommend with reference to Valdmanis (1992) and Nunamaker (1985) to "*run a number of different models from each dataset and evaluate the sensitivity of the results to changes in model specification.*"

The purpose of this paper is to analyze methods which include fish stock measures when estimating technical efficiency. The three methods investigated are: 1) inclusion of a stock index for each primary species based on Catch Per Unit Effort (CPUE), 2) inclusion of one stock index obtained from independent stock assessments for each of the primary species, and 3) inclusion of one composite stock index for each observation based on the independent stock measures and the relative importance of the primary species.

The analysis is based on data for Danish seiners between 18 and 24 meters for the years 1995 to 1999. The results of using different measures will be tested for consistency, and whether the conclusions depend on the time horizon being short or long run will be analyzed. The three consistency tests presented in Bauer et al. (1998) are adopted. These tests investigate the following questions: 1) Are similar means and standard deviations observed? 2) Do the vessels obtain the same ranking? and 3) Are the same vessels classified as "best" and "worst"?

The paper is organized as follows: The first section discusses different methods for including stocks in fisheries production analysis. The following section briefly introduces the utilized estimation method. Based upon the two previous sections, three methods for stock inclusion are identified and each method is presented in the third section, which also includes a general formulation of the programming problem to be estimated. The data used in the analysis are described in the fourth section, and the results are presented in the fifth section. The paper closes with a conclusion and a discussion of topics for future research.

1. Inclusion of Fish Stocks in Production Analysis

When a fishery is characterized as operating under changing or unequal resource conditions, it is necessary to consider this when performing production analysis (Morrison 2000). In such situations, the lack of including stock measures in the analysis will assign any resource effects to inefficiency and give a wrong impression of the level of technical efficiency. The consequence can, for instance, be that management decisions are made on an incorrect basis, leading to the regulation of a specific fishery that is not optimal.

Reasons for considering variations in resource conditions can be due to changes over time, between fishing areas, and/or between vessels. Changing resource conditions over time and/or fishing areas may be relevant in both single-species and multi-species fisheries. In these situations, inclusion of fish stock measures are important to ensure that vessels fishing in periods or areas with low fish stocks are not disfavoured when compared to vessels fishing in another period or area with higher fish stocks.

It is generally not necessary to consider changing resource conditions between vessels if the analysis is performed on cross-sectional data for a single-species fishery, because the resource conditions are equal for all vessels. An example is Bjørndal (1989), who estimates production functions for the North Sea herring fishery. However, if the analyzed fishery is characterized by multi-species with vessels targeting different species, it is important to account for different resource conditions between the vessels[1]. In this situation, the species caught may have a different relative importance for each vessel. If the technical efficiency scores between the included vessels are to be compared, it is necessary to account for this by including some measure of fish stock in the estimations. This applies whether cross-sectional or panel data for a multi-species fishery are used.

During the last decades, several methods have been used to include fish stock measures in production analysis. The optimal situation would be to have an independent stock measure for each vessel for every period and area. However, such measures are almost impossible to

[1] If vessels target only one species in a multi-species fishery with bycatch of other less important species, the analysis can be treated as a single-species fishery, depending on the specific fishery. However, if comparison across time or areas is required, it is still necessary to include a stock index for the target species.

obtain at reasonable costs. Other methods have been used in the literature, and these will briefly be presented and discussed. An important aspect in choosing a method is the accessibility of possible independent stock measures[2]. If such estimates are available in form of biological assessments of fish stocks, these can often be applied.

Consider first a fishery without the availability of independent fish stock measures. Technical efficiency analysis of such fisheries is possible despite this lack of information. Several methods have been suggested in the literature to account for this.

One method is to use dummy variables as a method to consider stock fluctuations. For instance, Pascoe and Robinson (1998) and Coglan, Pascoe, and Mardle (1998) analyzed the multi-species fishery in the English Channel using dummy variables for years, months, and métiers (area) to account for any stock effects. Campbell and Hand (1998) also use this approach to analyze the Solomon Islands pole-and-line fishery. A dataset covering two years is used to analyze the New England otter trawl fleet by Squires (1987), and stock changes are accounted for by including one dummy variable in the analysis. Kompas and Nhu (2002) do not apply available independent stock measures, and argue that weather dummies can account for important stock variations in the Australian northern prawn fishery. However, the inclusion of dummies to account for stock effects is not without problems, because it can result in a significant loss of degrees of freedom[3]. This depends on the number of fishing areas, time periods, and fishing vessels.

There are also examples of analyses where CPUE is used as a measure of fish availability. Comitini and Huang (1967) use "catch per skate" as a measure of stock density in the North Pacific halibut fishery. Eggert (2001) analyses the Swedish trawl fishery for Norway lobster and uses the overall average landings value as a proxy of stock availability. Analyzing demersal trawlers in the English Channel, Pascoe and Coglan (2002) use average catch value per hour fished. However, the use of CPUE as a measure of stock abundance is not straightforward. It depends on other inputs used in the production, as mentioned by Sharma and Leung (1998). The measure can also reflect a change in vessel composition of the specific place and point in time.

Richards and Schnute (1986) test whether there is any correlation between CPUE and availability of fish. They find that this measure is not preferable when based on data from commercial fishery statistics, at least not when analyzing the inshore rockfish fishery in the Strait of Georgia in British Columbia. Based on data from the International Council for the Exploration of the Sea (ICES), Harley, Myers and Dunn (2001) compare CPUE with

[2] Stock measures can be considered independent if they are calculated without being directly related to the analysed fishery.

[3] The loss of freedom is especially important when SPF is used. DEA can be performed with dummy variables by dividing data into groups using categorical DMUs, cf. Cooper, Seiford and Tone (2000). This approach, however, demands an ability to compare every area and period in order to make a hierarchy.

independent stock abundance data. They find that there does not seem to be proportionality between stock and CPUE for three groups of fish, i.e. cod, flatfish, and gadiformes. Hilborn and Walters (1992) discuss why different aspects of fishermen's behaviour will cause CPUE not to be proportional to abundance. As mentioned by Pascoe and Herrero (2004), a problem of using the CPUE approach is that an implicit assumption is made about constant returns to scale between fish stock and effort.

If independent stock measures are available, the fish stock can be considered as natural capital in line with man-made capital in classic production theory. Several types of stock estimates have been applied in the literature, and some collect these for the specific analysis. Others seek to estimate these and some use stock information obtained from organizations delivering biological assessments. ICES and the Inter-American Tropical Tuna Commission (IATTC) are examples of such organizations.

Kirkley, Squires and Strand (1995, 1998) analyze the single-species sea scallop fishery in the Mid-Atlantic. As a measure of abundance, supposedly bias-free samples are obtained using the last tow of approximately 50 vessels. This method is based on individually collected data. Pascoe and Herrero (2004) estimate abundance indicators for the Spanish octopus fishery in the South Atlantic region and use them to modify the dependent variable.

Several articles use independent stock estimates published by biological institutions. Hannesson (1983) uses ICES biomass assessments to estimate production functions in the Norwegian Lofoten fishery. Eide et al. (1998) use the same approach when analyzing the Norwegian bottom trawlers fishing for northeast Arctic cod, using total yearly biomass. An independent measure of tuna stock abundance is also used by Cabrera-Muro (2002) in an analysis of the Mexican tuna fishery from 1992 to 1995. Grafton, Squires, and Fox (2000) look at the British Colombia halibut fishery. They obtain yearly data on the weight of the total available halibut stock from an independent biological survey.

Pascoe, Andersen and de Wilde (2001) estimate technical efficiency for Dutch beam trawlers. They include a composite Fisher quantity index based on biomass for sole and plaice and the related overall prices for these species. Data on biomass was obtained from the Netherlands Institute for Fisheries Research. The prices were used as weights, when aggregating the two stocks into one.

Several methods have been applied in order to account for stock effects in production analysis. The choice of method is dependent upon the type of fishery to be analyzed, the type of analysis to be performed, and the availability of independent stock measures.

Only one of the reviewed articles applies Data Envelopment Analysis (DEA) to estimate technical efficiency (Pascoe and Coglan 2002), while the rest primarily uses the Stochastic Production Frontier approach. However, Pascoe and Coglan (2002) did not have independent

stock measures, and instead used year, month, and métier as categorical variables to estimate technical efficiency separately for each category. Hence, this excludes the possibility of comparison between vessels in different years, months, and métiers.

2. The Theory of Data Envelopment Analysis

Measuring the level of efficiency for different Decision Making Units (DMUs) has received increasing attention among scientists, managers, and regulators[4]. The questions asked include: Why do some DMUs have higher efficiency levels than others? How can DMUs with low levels of efficiency improve? And how does regulation influence the observed efficiency levels?

Efficiency is not one single concept. From an economist's point of view, the primary objective is to obtain economic efficiency, which refers to a situation where the DMUs are maximizing their profits. However, economic efficiency can be decomposed into allocative and technical efficiency, respectively. Allocative efficiency measures whether the input mix used by the DMUs minimizes cost, given the input prices.

The interpretation of the technical efficiency measure depends on the orientation used. In an output orientation, the objective is to maximize the output level given the observed input level. Here, technical efficiency is a measure of the relative change (increase) in output that can be obtained keeping the inputs unchanged. The input orientation, on the contrary, aims to minimize the use of inputs for a given output level. Hence, technical efficiency measures the possible decrease in input use while keeping the output level constant. In the following, the Farrell (1957) efficiency measure of maximal radial expansion (contraction) in outputs (inputs) that are feasible for the DMU is used[5]. Technical efficiency can furthermore be subdivided into other efficiency measures, cf. Webster, Kennedy and Johnson (1998).

Estimation of technical efficiency hinges on the estimation of production frontiers that compare observed production with maximal production. Traditionally, production functions have been estimated as average production functions. However, the classic notation of a production function is as a frontier giving the maximal possible output for a given input (Quirk 1987). The awareness of this discrepancy has increased, and today there are several methods for estimating production frontiers. These methods are gathered under the term distance functions, which measure the distance between actual production and the best-practice production. The two most prominent methods are the parametric Stochastic Production Frontier (SPF) method and the non-parametric DEA method.

[4] The term Decision Making Unit is used instead of firm, because DEA is also well suited to analyse other types of units, such as government services and non-profit organisations, cf. Steering Committee for the Review of Commonwealth/State Service Provision (1997).

[5] Other non-radial measures of technical efficiency are also available as discussed by Färe and Lovell (1978) and Russell (1985).

Both methods have their advantages and disadvantages. SPF is advantageous when data are highly influenced by idiosyncratic randomness. In the SPF method, it is also possible, through statistical tests, to evaluate the results obtained. However, SPF assumes specific functional forms for the production function[6], and furthermore the handling of several outputs is not straightforward[7]. DEA avoids the two disadvantages of SPF. However, DEA does not deal with stochasticity[8] and all deviations from the production frontier are considered to be due to pure inefficiencies and not noise. Several articles compare the results obtained by using SPF and DEA, respectively. Among these are Lee and Holland (2000) and Coglan, Pascoe and Mardle (1998), but their comparisons do not produce any solid conclusion about which method to use.

In this paper, DEA has been chosen as the method to perform the estimations of technical efficiency. It can be argued that when analyzing a fishery, it is necessary to consider stochasticity. However, Coglan, Pascoe and Mardle (1998) point out that if monthly or longer time period data are used, the trip-related stochasticity is reduced and the necessity for dealing with stochasticity is not as important. Because the forthcoming analysis is based on individual monthly data, DEA without stochasticity is considered a valid method.

The following review of the DEA theory is intended to give the reader the basic knowledge needed to understand the method[9]. The review will be input-oriented due to the fact that the vessels being analyzed are restricted by catch limitations in form of quotas. Combined with the biological circumstances, it seems irrelevant to use an output-oriented approach, where the fishermen are assumed to maximize their output given the current input use.

DEA is a technique using mathematical programming methods[10] to find the frontier that envelops the data observed and thus reflect the best-practice. The relative efficiency of each observation is then measured relative to this frontier, as observations on the frontier are considered fully efficient. The technique has been used to analyze the structures of many different industries. Besides fisheries, examples include hospitals (Dervaux, Kerstens and Leleu 2000), schools (Arnold et al. 1996), banks (Sherman and Gold 1985), and farms (Battese 1991)[11].

DEA can be conducted with a short-run or long-run time horizon. In the long run, all inputs that the DMU can directly influence are considered variable or discretionary, and thus

[6] Webster, Kennedy, and Johnson (1998) consider this to be an advantage because it enables one to perform solid tests of the results.

[7] Coelli and Perelman (1996, 1999, 2000) use parametric distance functions to analyse a multi-output situation for European railways.

[8] DEA has been modified to consider stochasticity. See Grosskopf (1996) for a survey of the different methods.

[9] Readers with special interest in DEA are encouraged to read Charnes et al. (1994) and Cooper, Seiford and Tone (2000). Coelli, Rao and Battese (1999) also discuss SPF and productivity measurement.

[10] The parametric SPF method uses econometric theory to estimate the frontier.

[11] An extensive reference list can be found on www.deazone.com.

changeable at a minimum cost. In the short run, some inputs may be fixed or non-discretionary, and a distinction between variable and fixed inputs is necessary. However, under both time horizons, some important inputs can be directly uncontrollable for the DMU. An example is fish stocks. Although these inputs cannot be changed by the DMUs, they are still important when estimating the level of technical efficiency and inclusion is, therefore, relevant (Golany and Roll 1993).

The input-oriented DEA with only discretionary inputs seeks to identify the radial reduction in all inputs that will make the DMU technically efficient. However, with non-discretionary inputs in the production structure, these cannot be altered, and the efficiency measure only indicates the necessary radial reductions in the discretionary inputs, leaving the non-discretionary inputs unchanged. Following Charnes, Cooper, and Rhodes (1978) and Banker and Morey (1986)[12], the problem for DMU *o* of the J DMUs can, assuming variable returns to scale, formally be written as:

$$\text{Min}_{\theta,\lambda} \quad \theta_o \tag{1}$$

$$\text{subject to} \quad -y_{ok} + \sum_{j=1}^{J} \lambda_{oj} \cdot y_{jk} \geq 0 \qquad k = 1,\ldots,K \tag{2}$$

$$\theta_o \cdot x_{ol}^{D} - \sum_{j=1}^{J} \lambda_{oj} \cdot x_{jl}^{D} \geq 0 \qquad l = 1,\ldots,L \tag{3}$$

$$x_{oi}^{ND} - \sum_{j=1}^{J} \lambda_{oj} \cdot x_{ji}^{ND} \geq 0 \qquad i = 1,\ldots,I \tag{4}$$

$$\lambda_{oj} \geq 0, \ \sum_{j=1}^{J} \lambda_{oj} = 1 \qquad j = 1,\ldots,J, \tag{5}$$

where *j* is the number of DMUs or observations (j = 1,…,J), *k* is the number of outputs y (k = 1,…,K), *l* is the number of discretionary inputs x^D (l = 1,…,L), and *i* is the number of non-discretionary inputs x^{ND} (i = 1,…,I). The radial reduction in the discretionary inputs necessary to make DMU *j* fully efficient is measured by the scalar θ, which is constrained to be equal or below one in an input-oriented approach[13]. It can be seen that no reductions are imposed in the non-discretionary input observed for DMU *j*. *λ* is a vector of *j* intensity variables identifying the extent observation *j* is used to construct the piecewise linear frontier approximation that envelops the data. Constant returns to scale is assumed if no restriction is imposed on the sum of λ.

[12] Golany and Roll (1993) modify the DEA problem with respect to two aspects. One is to allow for the simultaneous presence of non-discretionary inputs and outputs. Another is the presence of only partially discretionary input and outputs.

[13] This measure is exactly equal to the inverse of the input distance function, which is constrained to be equal to or above one. See Coelli, Rao and Battese (1999) for further insights.

Restrictions (2) to (4) secure that the DMU is within the production possibility set for the industry, while reducing the discretionary inputs x^D. The production possibility set for the industry is based on the assumption that it is impossible to produce more than any of the observed outputs, or linear combinations of these (ensured by restriction (2)), using less than any of the observed inputs or linear combinations of these (ensured by restrictions (3) and (4)).

3. Three Methods for Stock Inclusion

An array of approaches for including fish stocks into production analysis was reviewed in the first section. To my knowledge, no comparative studies analyzing the consequences of choosing a specific approach to biomass inclusion has been performed. It is thus difficult to prefer one approach to another. As mentioned in the introduction, the primary purpose of this paper is to perform such a comparison. It is also the intention to provide insight into the practical importance of these methods in order to recommend the use of a common method.

In this section, the stock inclusion methods to be analyzed will be identified and discussed. Furthermore, the programming problem related to each of these methods will be formulated using the DEA theory presented in the previous section. Three methods have been chosen. In one method, the stock index is derived from the catch data, while the two other methods are based on independent fish stock measures, and the methods are as follows:

1. CPUE stock indices
2. Separate stock indices
3. A composite stock measure

Method 1, *CPUE stock indices*, includes one stock index for each of the primary species. The stock index for each species is calculated on a monthly basis by dividing the catch/landings with the number of days at sea conducted by the relevant vessel, and is the same for all vessels participating in a given month. It follows along the lines of Comitini and Huang (1967), Eggert (2001), Pascoe and Coglan (2002).

The formula for calculating the fish stock measure in Method 1, $\hat{s}$, is:

$$\hat{s}_{km} = \sum_{j=1}^{J} \frac{y_{jkm}}{x^D_{jm}} \geq 0 \qquad j = 1,\ldots,J, \qquad (6)$$

where the notation is as used previously, but with *m* indicating the time period (m=1,…,M), i.e. month. Observe that the discretionary input in this formula is the number of days at sea.

Method 2, *separate stock indices*, simply includes one stock index, $\bar{s}$, for each of the primary species, as also done by Eide et al. (1998) and Hannesson (1983). In Method 2, the stock indices are on a yearly basis, because the available biological fish stock measures are only calculated yearly.

Method 3, *a composite stock measure*, considers the relative importance when including fish stocks in the technical efficiency analysis in line with Pascoe, Andersen and de Wilde (2001). None of the two previous methods consider the relative importance of each primary species. For instance, even though all vessels catch the primary species, these may make up different relative amounts of the catch for different reasons. Method 3 accounts for this by calculating a monthly individual composite stock index, $\tilde{s}$, by using the following formula:

$$\tilde{s}_{jm} = \sum_{k=1}^{K} \bar{s}_k \cdot \frac{y_{jkm}}{\sum_{k=1}^{K} y_{jkm}} \geq 0 \qquad j = 1,\ldots,J, \tag{7}$$

where $\bar{s}$ is the independent stock index for each of the primary species used in Method 2.

With the presented stock indices in mind, it is possible to point to some advantages and disadvantages of each method. Method 1 does not require the availability of independent fish stock measures, which may be the case in many fisheries. However, as discussed previously, some analyses have shown that the correlation between stock and CPUE is problematic. Method 2 is, on the other hand, based on independent measures, but does not consider the relative importance of the primary species for each vessel. Method 3 remedies this by calculating a stock index using the independent stock indices and the available catch data. However, a stock index based on the output measures could give rise to some theoretical considerations about consistency, as was also the case for Method 1.

With the above methods in mind, the following programming problem must be solved in order to calculate the level of technical efficiency for vessel *o* in month *m*:

$$\text{Min}_{\theta,\lambda} \quad \theta_{om} \tag{8}$$

subject to

$$-y_{okm} + \sum_{j=1}^{J} \lambda_{jm} \cdot y_{jkm} \geq 0 \qquad k = 1,\ldots,K \tag{9}$$

$$\theta_{om} \cdot x_{olm}^{D} - \sum_{j=1}^{J} \lambda_{jm} \cdot x_{jlm}^{D} \geq 0 \qquad l = 1,\ldots,L \tag{10}$$

$$x_{oim}^{ND} - \sum_{j=1}^{J} \lambda_{jm} \cdot x_{jim}^{ND} \geq 0 \qquad i = 1,\ldots,I \tag{11}$$

$$s_{okm}^{ND} - \sum_{j=1}^{J} \lambda_{jm} \cdot s_{okm}^{ND} \geq 0 \qquad m = 1,\ldots,M \tag{12}$$

$$\sum_{j=1}^{J} \lambda_{jm} = 1,\ \lambda_{jm} \geq 0 \qquad j = 1,\ldots,J. \tag{13}$$

Observe that the dimensions of the non-discretionary stock index differ between the methods, cf. $\hat{s}_{km}$, $\bar{s}_k$ and $\tilde{s}_{jm}$. Also observe that in Methods 1 and 3, the stock index is on a monthly basis, while Method 2 uses a yearly index, and that the number of stocks differ from the number of outputs in Methods 1 and 2, i.e. only stocks for species in K'$\subseteq$K are included.

In the programming problem, it has been assumed that variable returns to scale apply, cf. restriction 13. In this paper, both short-run and long-run analysis are performed. Grosskopf and Valdmanis (1987) argue that contrary to long-run analysis, short-run analysis does not presuppose constant returns to scale. Instead, they suggest the use of variable returns to scale in the short run. Because the objectives of this paper are not to evaluate the consequences of different scale assumptions, variable returns to scale is assumed for both time horizons.

4. Description of the Data

Having defined the methods to be analyzed and the programming problem to be solved, the utilized dataset will be described. The dataset was extracted from the databases hosted by the Danish Directorate of Fisheries. The dataset covers the Danish seiners between 18 and 24 meters fishing in the period from 1995 to 1999 in the North Sea, Skagerrak, Kattegat, and/or Baltic Sea. However, only those vessels that were registered in the Danish Vessel Register by the end of 1999 were included.

By the end of 1999, 43 Danish seiners were active compared to 36 in 1995. These Danish seiners had a varied behavioural fishing pattern with respect to the choice of location, considering that they fished in all four of the primary Danish fishing waters mentioned above. The number of observations available for each separate area is shown in Table 1. Considering that there are too few observations available in Kattegat and the Baltic Sea, these areas are excluded in the analysis.

Table 1 Number of observations available for the Danish seiners

	1995	1996	1997	1998	1999	Total
The North Sea	243	246	268	276	267	1,300
Skagerrak	126	125	133	134	118	636
Kattegat	16	16	6	10	7	55
The Baltic Sea	35	42	59	65	88	289

The fishing effort of vessels can be decomposed into two separate measures in the form of fishing power and fishing time (Segura 1973). The former measures the amount of capital and labour used, while the latter measures the amount of time it is active. Andersen (1999) discusses this topic in more detail.

Several physical measures are available for the Danish seiners. Based on the coefficient of variation, which is a relative measure calculated as the standard deviation divided by the average value, length and engine power have the lowest relative dispersion, and these are used in the following analysis. Their characteristics are presented in Table 2.

Table 2 Descriptive statistics for fishing power measures, average 1995-1999

	Average value	Standard deviation	Minimum	Maximum
Length (meters)	19.19	0.91	18.00	22.00
Engine power (horsepower)	196.91	69.17	121.36	444.24

High correlation coefficients are observed between the two measures of fishing power. However, as mentioned by Nunamaker (1985), this should not form the basis for omitting variables in the analysis. This is opposed to parametric analysis, where the inclusion of highly correlated variables could significantly change the efficiency estimates.

Besides fishing power measures of the Danish seiners, it is also important to get an impression of their fishing time. This can be measured as the time in which the gear is active or as the length of a fishing trip. Here the latter is used, because it includes all the time where an economic activity is conducted. Table 3 shows the number of days at sea per month in each of the analyzed fishing areas.

Table 3 Descriptive statistics for fishing time measure, average 1995-1999

	Average number of days at sea	Standard deviation	Minimum	Maximum
The North Sea	14.57	6.92	1.00	31.00
Skagerrak	12.58	7.26	1.00	31.00

The Danish seiners use a technology invented by the Dane Jens Væver in 1848. The technology generates a relatively 'clean' fishery with little by catch and high quality fish. The two primary species are cod and plaice, measured in terms of catch weight and revenue. Table 4 shows the catch weight composition for the two areas.

Table 4 Average catch composition for different fishing areas, weight (%)

		1995	1996	1997	1998	1999
The North Sea	Plaice	30	38	53	42	55
	Cod	53	46	36	47	31
	Other species	18	16	11	11	14
Skagerrak	Cod	41	38	42	45	37
	Plaice	35	33	31	27	36
	Other species	24	29	27	28	27

From Table 4, a trend towards a higher catch proportion of plaice can be observed. This development is to a high degree in line with the developments in cod and plaice stock indices[14]. Table 5 shows a decrease in cod stocks compared to an unchanged/minor increase in plaice stocks. The availability of fish and the following management initiatives, i.e. gear and catch restrictions, may be the primary reason for the reduced importance of cod in the catch composition for the Danish seiners.

Table 5 Development in stock indices for different fishing areas, 1995-1999 (1995=100)

	---------- Cod ----------	---------- Plaice ----------	
	The North Sea and Skagerrak	The North Sea	Skagerrak
1995	100	100	100
1996	108	90	100
1997	115	82	107
1998	104	101	108
1999	92	101	103

Source: The International Council for the Exploration of the Sea (ICES)

Turning attention to catches measured in weight and deflated revenue, Table 6, the most important fishing area for the Danish seiners is the North Sea. Here, approximately 65% of the catches are caught. Skagerrak is the second most important area with approximately 30%. In these two areas, total catches are at their highest in 1997, while average catches peaked in 1998.

Table 6 Yearly catches for different fishing areas (tonnes and 1,000 DKK)

		1995	1996	1997	1998	1999
The North Sea	Total catch weight	3,852	3,422	4,731	4,444	4,277
	Total catch deflated revenue	56,787	50,771	70,934	67,869	64,839
	Average catch weight	133	114	135	135	116
	Average catch revenue	1,958	1,692	2,027	2,057	1,752
Skagerrak	Total catch weight	1,681	1,633	2,364	2,167	1,611
	Total catch revenue	24,254	24,116	35,988	31,830	25,912
	Average catch weight	62	74	95	108	64
	Average catch revenue	898	1,096	1,440	1,591	1,036
Total	Total catch weight	5,533	5,056	7,095	6,611	5,888
	Total catch revenue	81,041	74,887	106,922	99,699	90,750
	Average catch weight	154	140	177	165	140
	Average catch revenue	2,251	2,080	2,673	2,492	2,161

[14] The stock assessments made by ICES are besides commercial landings data, primarily based on survey data from research vessels and discard samplings.

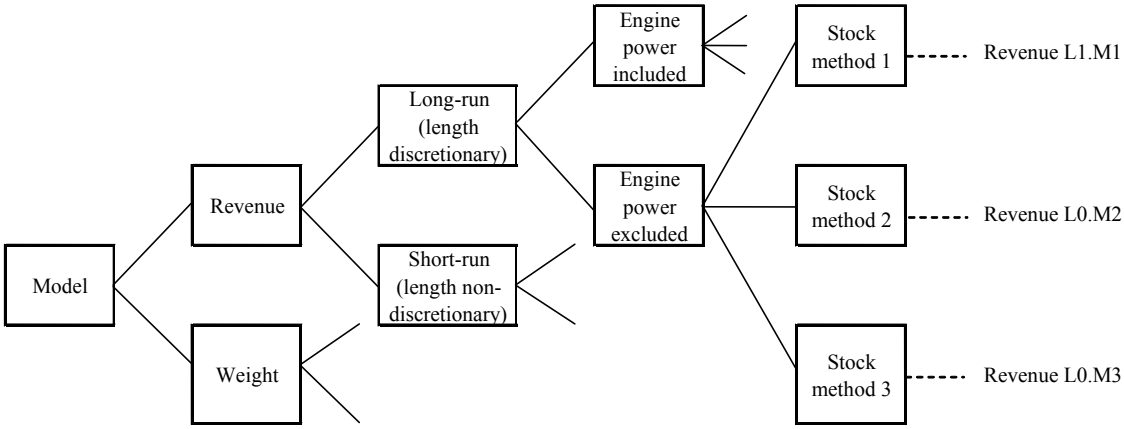
Data are generally considered reliable. However, the output measures (weight) are based on landings and not actual catch. This implies that discards are not included, thus underestimating the actual production. For the specific fishery, the discards are estimated to be around 15% and 13% in the North Sea and Skagerrak, respectively (Krog 2003), but no information on specific vessels is obtainable, and the output figures are therefore not corrected to take this into account. Technical efficiency can thus be underestimated for some vessels.

5. Analysis of the Danish Seiners

5.1 Estimated Models

Several models are estimated in order to pursue the objectives of this paper and to test the robustness of the results. This sub-section will briefly describe these models. In total, 48 models are estimated, 24 models for each of the two fishing areas used by the Danish seiners between 18 and 24 meters. With reference to the taxonomy in Figure 1, the three-step procedure for understanding the taxonomy of the estimated models will be explained.

Figure 1 Taxonomy of the Estimated Models



Firstly, a choice has to be made about the way to measure outputs. Two choices are available in the dataset: catches in weight or deflated revenue. The use of revenue as an output measure is discussed. Traditional production theory uses the physical units to measure outputs. However, practical analysis often tends to use monetary units instead. This is despite the fact that "*the specified frontier is not truly a production function*" (Sharma and Leung 1998, p. 273). There can be different motives for choosing revenue instead of weight. For example, if production is characterized by being multi-product, prices can be used to aggregate these outputs into one or several groups of output. Price variation is often considered a problem when using revenue, and hence the use of deflated catch revenues is recommended.

The former section showed that the Danish seiners fishing in the North Sea and Skagerrak primarily fish for cod and plaice. Hence, the number of outputs included in the mathematical programming problems are cod, plaice and other species.

Secondly, the fishing effort measures have to be defined. These measures are dependent on the time horizon, because this determines whether measures are changeable. In the short run, all included fishing power measures are non-discretionary, while they are discretionary in the long run. The measure of fishing time is, on the other hand, discretionary in both the short and long runs.

In practice, two fishing power measures are used, i.e. length and engine power. Length is included in all of the estimated models as being either non-discretionary or discretionary, depending on the time horizon. Engine power is, on the other hand, only included in some of the models and has, if it is included, the same attribute as length, i.e. non-discretionary in the short run and discretionary in the long run. The measure of fishing time in form of the number of days at sea is included in all of the estimated models and assumed discretionary.

Finally, the method for including fish stocks in the models is chosen. As explained previously, the different methods are used to investigate the inclusion of fish stocks in efficiency analysis of the Danish seiners. However, irrespective of the method and time horizon, the fish stock measure is always considered to be non-discretionary.

Considering the large number of models to be estimated, acronyms have been given to each model for convenience. Each acronym is formulated from the basic rule *Model te.m*, and consists of three parts. *Model* can be replaced with either revenue or weight, depending on the choice of output measure. *t* specifies the time horizon chosen and can be either S for short run or L for long run; thus, $t \in \{S,L\}$. *e* denotes whether engine power is included or not. If included, *e* equals 1, otherwise it equals 0; thus, $e \in \{0,1\}$. Finally, *m* represents the stock method used. It can have a value of M1, M2, or M3, cf. the methods presented in the second section; thus, $m \in \{M1,M2,M3\}$.

In Figure 1, an example of an associated acronym is given. *Revenue L1.M1* is the acronym for a long-run model with revenue as output measure; engine power included and stock Method 1 used to account for stock conditions. In Appendix 1, an overview of all variables in the estimated models is available, including the acronyms used.

5.2 Choice of Method for Fish Stock Inclusion

With the taxonomy in mind, programming problems have been estimated using the General Algebraic Modeling System (GAMS) (Brooke et al. 1998), assuming variable returns to scale and strong disposability. Given that data are on a monthly basis, a total of 1,300 and 636

programming problems were solved for the North Sea and Skagerrak, respectively, in all 48 models.

Based upon these estimations of technical efficiency using DEA, the three methods for including fish stocks will now be compared. To compare the estimations and evaluate the level of consistency between these, Bauer et al. (1998) mention several conditions that need to be fulfilled. Three of these are related to investigating whether the methods give the same results (Pardina, Rossi and Ruzzier 1999), and will, therefore, be used in the following. They are:

1. Similar means and standard deviations should be observed.
2. The DMUs should obtain the same rank.
3. The same DMUs should be classified as "best" and "worst".

The fulfilment of these conditions is considered for the analyzed data in relation to the objectives of this paper. The comparisons are made between the monthly score for each observation; not between the scores of each month, and the methods used for testing these relationships will follow along the lines found in Pardina, Rossi and Ruzzier (1999).

The first condition is considered using the means and standard deviations obtained from the estimations. The second condition is approached by using three tests, cf. below, and the third condition is considered using the upper and lower quartiles, i.e. the 75% quartile and 25% quartile.

The tests used to investigate the second condition are the: 1) Spearman rank correlation test, 2) Friedman test, and 3) Wilcoxon test. The first evaluates the strength of association between two variables, or in this case, the estimated models. The second and third tests whether the distribution in each of the estimated models can be considered to be similar. The Friedman test is used when comparing more than two groups of data, and the Wilcoxon test is used, when comparing two groups of data. The three tests are all non-parametric, implying that they do not *a priori* require any knowledge of the distribution of the obtained scores. The advantage is that an assumption of normally distributed scores is not necessary, and the tests are so-called "distribution free." Further insight into the theoretical foundation of the three tests can be found in Sigel and Castellan (1998) and Conover (1999)[15].

The average efficiencies and standard deviations for the estimated models are presented in Table 7 for the North Sea and Skagerrak, respectively.

[15] All tests were performed by using an add-in for Microsoft Excel called Analyse-it. The programme can be downloaded from www.analyse-it.com.

Table 7 Average technical efficiencies for Danish seiners

		---- Model S0.m ----		---- Model S1.m ----		---- Model L0.m ----		---- Model L1.m ----	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
North Sea	Weight te.M1	0.47	0.24	0.53	0.27	0.95	0.04	0.96	0.04
	Revenue te.M1	0.49	0.24	0.56	0.27	0.95	0.04	0.95	0.04
	Weight te.M2	0.46	0.24	0.53	0.26	0.95	0.04	0.96	0.04
	Revenue te.M2	0.47	0.25	0.53	0.27	0.95	0.04	0.95	0.04
	Weight te.M3	0.41	0.23	0.46	0.25	0.95	0.04	0.95	0.05
	Revenue te.M3	0.41	0.23	0.47	0.26	0.95	0.04	0.95	0.04
Skagerrak	Weight te.M1	0.57	0.27	0.61	0.28	0.96	0.04	0.96	0.04
	Revenue te.M1	0.55	0.26	0.59	0.26	0.96	0.04	0.96	0.04
	Weight te.M2	0.53	0.25	0.57	0.26	0.95	0.04	0.95	0.04
	Revenue te.M2	0.53	0.24	0.56	0.26	0.95	0.04	0.95	0.04
	Weight te.M3	0.47	0.25	0.50	0.25	0.95	0.04	0.95	0.04
	Revenue te.M3	0.47	0.23	0.50	0.26	0.95	0.04	0.95	0.04

Notes: Model $\in$ {Revenue,Weight}, t $\in$ {S,L}, e $\in$ {0,1}, m $\in$ {M1,M2,M3}.

As expected, the level of technical efficiency increases with increasing flexibility in the choice of non-discretionary input variables. In the least flexible model, i.e. Model S0.m, technical efficiency varies between 0.41 and 0.49 in the North Sea and between 0.47 and 0.57 in Skagerrak. In the most flexible model, i.e. Model L1.m, technical efficiency is around 0.95 in both areas. However, the two long-run models do not reflect this difference. This indicates that vessel length generally restricts the possibilities for adaptation[16].

Comparing the short-run and long-run models, a high similarity is observed in the average means between Model te.M1 and Model te.M2, and they generally seem to estimate higher values of technical efficiency compared to Model te.M3. The standard deviations, on the other hand, are rather similar in the three methods. This does not seem to be influenced by the choice of fishing area or output measure.

High and significant correlations are observed between the different inclusions of fish stocks within each of the three models, Table 8, again irrespective of which fishing area is analyzed. However, there seems to be a tendency for higher correlations between Model te.M2 and Model te.M3. Generally, the estimated technical efficiencies in the three models seem to vary in similar ways, no matter which fish stock measure is applied.

[16] The dataset includes an implicit assumption which influences the estimations. Looking at the North Sea, the maximum length is 22 meters, while the minimum is 18 meters. This implies that θ cannot be lower than 0.82, and this conclusion is not altered when including engine power. In the short run, the number of days at sea imposes the restriction, and here θ cannot be lower than 0.03. The larger difference in the average technical efficiencies in the short-run models is due to the increased ability to distinguish the DMUs from each other.

Table 8 Spearman rank correlations between technical efficiency estimations1)

		Weight te.M1	Weight te.M2	Weight te.M3	Revenue te.M1	Revenue te.M2	Revenue te.M3
North Sea	Model S0.M1	1.00			1.00		
	Model S0.M2	0.85	1.00		0.83	1.00	
	Model S0.M3	0.90	0.92	1.00	0.87	0.93	1.00
	Model S1.M1	1.00			1.00		
	Model S1.M2	0.82	1.00		0.80	1.00	
	Model S1.M3	0.87	0.89	1.00	0.83	0.89	1.00
	Model L0.M1	1.00			1.00		
	Model L0.M2	0.90	1.00		0.91	1.00	
	Model L0.M3	0.91	0.95	1.00	0.90	0.96	1.00
	Model L1.M1	1.00			1.00		
	Model L1.M2	0.87	1.00		0.79	1.00	
	Model L1.M3	0.89	0.93	1.00	0.80	0.94	1.00
Skagerrak	Model S0.M1	1.00			1.00		
	Model S0.M2	0.71	1.00		0.72	1.00	
	Model S0.M3	0.70	0.89	1.00	0.70	0.89	1.00
	Model S1.M1	1.00			1.00		
	Model S1.M2	0.71	1.00		0.71	1.00	
	Model S1.M3	0.72	0.89	1.00	0.72	0.89	1.00
	Model L0.M1	1.00			1.00		
	Model L0.M2	0.77	1.00		0.80	1.00	
	Model L0.M3	0.73	0.94	1.00	0.82	0.94	1.00
	Model L1.M1	1.00			1.00		
	Model L1.M2	0.77	1.00		0.79	1.00	
	Model L1.M3	0.76	0.94	1.00	0.81	0.94	1.00

Notes: Model $\in$ {Revenue,Weight}, t $\in$ {S,L}, e $\in$ {0,1}, m $\in$ {M1,M2,M3}.

1) All the correlations were tested to be significantly different from zero at the 1% level.

Tests for statistical significant differences in the distributions between the methods are then undertaken. Firstly, the Friedman test is applied. However, the null hypothesis is rejected in all models. Therefore, despite the high correlations between the efficiency estimates in the three models, these models do not seem to have identical distributions. The highest Spearman correlations are observed between Model te.M2 and Model te.M3. In order to test whether the distributions observed in Model te.M2 and Model te.M3 are identical, a Wilcoxon test is applied. The hypothesis of equal distribution is, however, rejected for these two models.

The last condition for consistency is to identify whether the same DMUs are categorized as the "best" and "worst" between the three different methods. Using the upper and lower quartiles, this hypothesis can be accepted if the percentage of DMUs that are simultaneously present in the quartiles is high. The percentages in the two quartiles are given in Table 9.

Table 9 Percentage of DMUs simultaneously present in upper or lower quartile

		-Model S0.m-		-Model S1.m-		-Model L0.m-		-Model L1.m-	
		Q75	Q25	Q75	Q25	Q75	Q25	Q75	Q25
North Sea	Weight te.M1/te.M2/te.M3	55.77	64.92	54.03	61.93	59.57	85.79	51.46	75.54
	Weight te.M1/te.M2	59.69	70.21	57.43	71.12	60.54	86.81	59.24	85.16
	Weight te.M1/te.M3	65.97	71.12	63.92	67.54	61.41	87.36	54.50	78.77
	Weight te.M2/te.M3	77.40	86.05	78.65	80.79	95.09	97.25	79.76	86.19
	Revenue te.M1/te.M2/te.M3	57.56	55.67	48.86	52.17	69.57	87.29	44.55	70.16
	Revenue te.M1/te.M2	64.77	63.27	53.62	60.80	73.99	89.94	47.62	70.53
	Revenue te.M1/te.M3	63.92	60.80	56.65	60.00	70.33	87.85	47.62	71.43
	Revenue te.M2/te.M3	79.66	82.86	77.65	77.78	91.93	96.69	85.96	97.56
Skagerrak	Weight te.M1/te.M2/te.M3	37.19	45.09	50.61	51.75	35.96	59.72	37.83	57.89
	Weight te.M1/te.M2	47.91	57.84	45.21	53.11	39.65	61.76	44.39	59.90
	Weight te.M1/te.M3	41.96	55.56	39.47	54.59	39.62	63.81	42.86	62.80
	Weight te.M2/te.M3	67.37	64.95	64.77	58.42	83.23	91.06	77.91	89.83
	Revenue te.M1/te.M2/te.M3	39.09	45.91	37.92	54.50	58.08	77.61	44.34	59.81
	Revenue te.M1/te.M2	49.30	58.42	50.00	57.64	48.60	64.95	49.76	62.25
	Revenue te.M1/te.M3	47.22	56.10	42.60	55.34	49.30	65.50	48.54	63.46
	Revenue te.M2/te.M3	62.24	66.67	66.49	60.80	71.89	89.14	80.00	91.28

Notes: Model $\in$ {Revenue,Weight}, t $\in$ {S,L}, e $\in$ {0,1}, m $\in$ {M1,M2,M3}.

The percentage of DMUs simultaneously present in the upper and lower quartile varies considerably; when comparing the different models. The highest percentages are found when comparing Model te.M2 and Model te.M3. This is most evident in the long-run models, where the percentage in some situations is above 90%. The lowest percentages are generally observed when comparing all three models, while comparing Model te.M1 with Model te.M2 and Model te.M1 with Model te.M3 gives approximately the same percentages. There seems to be a general tendency towards lower percentages of DMUs simultaneously present in the respective quartiles in Skagerrak compared to the North Sea, but the trends are the same as above.

A mixed conclusion can be drawn about consistency based on the above investigation of the three conditions. Comparing the three methods with respect to "similar means and standard deviations," they all seem to perform well. However, with respect to "the DMUs should obtain the same ranks," Methods 2 and 3 seem to perform well with respect to high and significant correlations between the models, but perform poorly with respect to obtaining identical distributions. Finally, Methods 2 and 3 perform well with respect to the condition that "the same DMUs should be classified as best and worse." Method 1 only seems to perform well in obtaining "similar means and standard deviations," when being compared to the two other methods. Regarding the two other consistency conditions, Method 1 generally performs poorly.

Based on the three conditions for consistency, it can thus be concluded that Methods 2 and 3 obtain approximately the same technical efficiency levels for the DMUs. Method 1 obtains the same average scores as Methods 2 and 3, but are not identical when comparing the

individual DMUs. This conclusion is valid irrespective of the choice of time horizon, input measures, and output measures. This indicates that the conclusions are robust and not dependent on model specification.

Concern of whether the stock indices are binding restrictions in the estimations may arise and can result in the influence of these not appearing in the results. This can be investigated by performing additional estimations for some of the models. In these estimations, the previously non-discretionary inputs were assumed discretionary, while the previously discretionary inputs were reduced to the efficient level and assumed non-discretionary. Hereby, it becomes possible to estimate an efficiency level with respect to the stock indices, i.e. a slack value. The results show that the efficiency levels are high and very often equal to one, thus indicating that the stock indices are binding restrictions in the performed estimations.

Conclusion

Estimation of technical efficiency has increased significantly since M.J. Farrell's thoughts on efficiency in 1957. In order to perform a reliable analysis, many aspects have to be addressed. However, in fisheries one of the most important aspects is the inclusion of fish stocks in order to account for fish stock developments.

Several methods have been used in the fisheries literature, but with no discussion as to which method is preferable. This paper has, therefore, addressed this problem. In total, three methods have been considered. Method 1 used CPUE data from the included vessels to derive a stock index, which, on a monthly level, was the same for all the analyzed vessels. The two other methods were based on independent biological fish stock assessments. Method 2 simply included, on a yearly basis, a fish stock for each of the primary species without distinguishing between vessels. Method 3 considered a composite fish stock measure for each individual vessel based on the relative importance of the primary species for a vessel and the independent stock measures.

Several techniques have been suggested as ways of performing estimations of technical efficiency. In this paper, the DEA was used. This technique uses mathematical programming to estimate the frontier of the analyzed dataset. Afterwards, the production of each decision-making unit is compared with this frontier to find the level of technical efficiency. Danish seiners between 18 and 24 meters were used to analyze this issue. Both short- and long-run models were included with different output and input measures. This was done in order to test the robustness of the obtained results. However, fish stocks were assumed non-discretionary in all of the estimations.

In order to compare the estimations, the approach considered in Bauer et al. (1998) was used. This approach is based on three consistency conditions, namely the: 1) efficiency levels and

standard deviations, 2) obtained rankings and 3) simultaneous identification of the same "best" and "worst" vessels.

Based on the chosen approach, it can be concluded that when comparing Methods 2 and 3, conditions 1 and 3 were satisfied, while condition 2 was partly satisfied. Thus, these methods were considered to obtain approximately similar results. Method 1, on the other hand, only performed well with condition 1, when being compared to Methods 2 and 3. These conclusions were robust to changes in choice of time horizon and output and input measures. It is important to note whether the included fish stock measure is based on independent stock assessment data or not. However, when using indices based on independent stock measures, it does not seem to matter how these are included.

The comparison of different approaches to include fish stocks in the analysis of technical efficiency is considered a necessary first step to determine the best way to do this. A logical next step would be to test which stock inclusion method actually gives the correct answers. This can be analyzed using three other consistency conditions mentioned by Bauer et al. (1998), which as mentioned by Rossi and Ruzzier (1999), focus on whether the answers are correct, not whether they are the same. The three conditions are as follows: 1) measures should be consistent with other performance measures, 2) the efficiency measure for a DMU should be stable over time, and 3) the results should agree with prior expectation. On the current basis, it has not been possible to investigate these conditions more thoroughly.

Several other topics could also be investigated in future research. The conclusions in this paper have been based on the analysis of Danish seiners, which only have two important species. A next step would be to investigate whether the conclusions change for fisheries with more than two important species. For example, including a large number of separate fish stocks may make the vessels more distinct from each other. This implies a higher technical efficiency score, because a larger fraction of the vessels is used to envelope the dataset.

Another further step could be to investigate whether the application of statistical tests changes the derived conclusions. The literature on using statistical tests in relation to DEA is evolving. Kittelsen (1999, p. 3) points to the fact that more simulations are necessary to "*draw clear conclusions about the usefulness of the suggested approximate hypothesis tests*." However, Banker (1993, 1996) and Simar and Wilson (1995, 2002) have investigated this topic.

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Appendix 1 Estimated models and their acronyms

Model[1)]	Outputs	Discretionary Inputs	Non-discretionary Inputs
Model S0.M1	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) CPUE dependent cod stock index 3) CPUE dependent plaice stock index
Model S0.M2	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) Independent cod stock index 3) Independent plaice stock index
Model S0.M3	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) One stock index based on the relative importance of cod and plaice
Model S1.M1	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) Engine power 3) CPUE dependent cod stock index 4) CPUE dependent plaice stock index
Model S1.M2	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) Engine power 3) Independent cod stock index 4) Independent plaice stock index
Model S1.M3	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea	1) Length 2) Engine power 3) One stock index based on the relative importance of cod and plaice
Model L0.M1	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length	1) CPUE dependent cod stock index 2) CPUE dependent plaice stock index
Model L0.M2	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length	1) Independent cod stock index 2) Independent plaice stock index
Model L0.M3	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length	1) One stock index based on the relative importance of cod and plaice
Model L1.M1	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length 3) Engine power	1) CPUE dependent cod stock index 2) CPUE dependent plaice stock index
Model L1.M2	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length 3) Engine power	1) Independent cod stock index 2) Independent plaice stock index
Model L1.M3	1) Catch of cod 2) Catch of plaice 3) Catch of other species	1) Number of days at sea 2) Length 3) Engine power	1) One stock index based on the relative importance of cod and plaice

Notes: [1)] If catch weight is used to measure output, the model name is "Weight S0.M1," etc. When deflated catch revenue is used, the model name is "Revenue S0.M1," and so forth.

Rational Inefficiency in Fisheries

by Jesper Levring Andersen and Peter Bogetoft

Abstract

Efficiency evaluations of Decision Making Units (DMUs) are usually done ex post and not ex ante. This may be a too harsh approach, especially if the DMUs are operating under significant uncertainty. Fishermen are often considered to operate in such an environment. The output arising from using given inputs is seldom known with certainty, because external factors such as availability of fish, equipment performance and weather may have a significant influence. Thus, when fishermen decide the inputs to bring on a trip, they try to be in the best possible position to handle the expected uncertainty. This may result in bringing excess inputs that are not used or strictly needed. This situation will usually be interpreted as inefficiency in ex post analyses despite of the fact that it may have been rational to bring them in the first place. One can denote such inefficiency as rational inefficiency.

In this paper, we investigate the allocation of inefficiency on the different input factors and we use this to infer which factors are most useful to insure against the ex ante risk. More specifically, we use the method from Bogetoft and Hougaard (2003) to find the allocation of slack that is consistent with rational behaviour. Based on data from 308 Danish vessels, we show that fishermen tend to allow for the highest flexibility in crew payments, followed by fuel costs. Sales costs and ice/provision costs seem to be the least flexible. Based upon specific utility functional forms, we find support for these conclusions.

Keywords

Rational inefficiency, fishermen, behaviour, allocative efficiency, uncertainty

JEL-classification

C14, Q22

Introduction

In traditional production analysis Decision Making Units (DMUs) are evaluated based on the ex post observation of input use. If however compared to best practice ex post, outputs are too low or inputs too high, and is thus usually interpreted as inefficiency. However, judging the performance of a DMU in this way may be too harsh a method, especially if the DMUs are operating in environments with significant uncertainty. In such settings, rational DMUs have ex ante incentives to allocate too many inputs to the production to insure against the uncertainty. This is done in order to have the necessary flexibility to cope with uncertain conditions ex post in the best possible way.

Fishermen are an example of DMUs operating in an uncertain environment. Several external factors such as availability of fish, equipment performance and weather (Gates 1984) influence their production of output (fish). When fishermen ex ante decide to go fishing, they want to equip their vessel in a way which secures the best possible flexibility to deal with the uncertainties. These inputs may afterwards have been superfluous if conditions are more favourable than expected. Thus, in ex post efficiency analyses, these vessels will be found to be inefficient, while the vessels that optimistically hoped for favourable conditions and therefore equipped their vessel with less inputs are estimated to be efficient.

Of course the more efficient vessels may have a better ability to predict the encountered conditions, but if we ignore the uncertainty aspect, we may mix up efficiency with risk attitudes and luck.

Based on the above considerations, it becomes interesting to analyse which inputs fishermen choose to keep in excess amounts, when they try to cope with uncertainty. Do they for instance bring extra crew in order to handle large catches? Or extra fuel to increase their range of operation? This will be investigated further in this paper.

The method used to investigate these aspects was introduced in Bogetoft and Hougaard (2003). Instead of considering inefficiency as waste, they regard it as a rational choice of the DMU, thus giving rise to the concept of rational inefficiency. Using the notion of allocative efficiency, the cost minimising mix of input can be determined. Comparing this level to the actual level of input use, the amount of slack and its allocation between different production factors can be determined. These slack values can be seen as buffers against uncertainty, and indicate which inputs are most often included in excess amounts.

The outline of this paper is as follows. In Section 1 we provide an introduction to the Bogetoft and Hougaard (2003) approach, and we develop an extension of their approach that stresses the uncertainty aspects. In Section 2 we introduce a Data Envelopment Analysis (DEA) model of the fishery problem and we briefly review how to calculate technical, allocative and cost efficiency in this framework. In Section 3 we present the empirical

analysis of the excess use of resources and its interpretation as rational inefficiency. The last section provides some final remarks.

1. Rational inefficiency

As mentioned in the introduction, Bogetoft and Hougaard (2003) discussed the background and theoretically derived the framework for calculating rational inefficiency. The conceptual idea is that observed inefficiencies in production units (DMUs) are not wasted, but instead used to produce outputs that are not included in the analysis. These outputs may secure loyal employees, facilitate rent seeking behaviour, and maybe most importantly with respect to fisheries, enabling the DMU to cope with uncertainty. There may thus be several reasons for not eliminating inefficiencies, and in turn this should be able to give us insights into the effects of for instance management changes.

Take initially a general situation, where a DMU uses $x \in \Re_+^p$ inputs to produce $y \in \Re_+^q$ outputs. The input requirement set L in the input space can then be defined as:

$$L = L(y) = \left\{ x \in \Re_+^p \middle| x \text{ can produce } y \right\} \tag{1}$$

In the following, we assume L to be non-empty, closed, convex and characterised by free disposability (i.e. $L + x \subseteq L \subseteq \Re_+^p$). One way to think of L is as the inputs of labour, fuel etc., needed on a vessel to catch the allocated production quota y.

The next step is to define an efficient subset of L, which contains the technically efficient production plans. We define this as:

$$F(L) = \left\{ x' \in L \middle| \forall x'' \in R^p : \left[x'' \leq x', x'' \neq x' \right] \Rightarrow x'' \notin L \right\} \tag{2}$$

Based on the above, we can now define the slack which measures the excess usage of inputs, cf. Fried, Schmidt and Yaisawarng (1999)[1]. Assume that the DMU has used an inefficient input combination $x \in L \backslash F(L)$. This means that the DMU could have chosen to use production procedures corresponding to an underlying production plan z that weakly dominates x, i.e. $z \in L$ and $z \leq x$. The excess usage of inputs of the underlying z is used as the anchor and can be calculated as the difference between x and z, i.e. the slack is given as:

$$s = x - z \in \Re_+^p \tag{3}$$

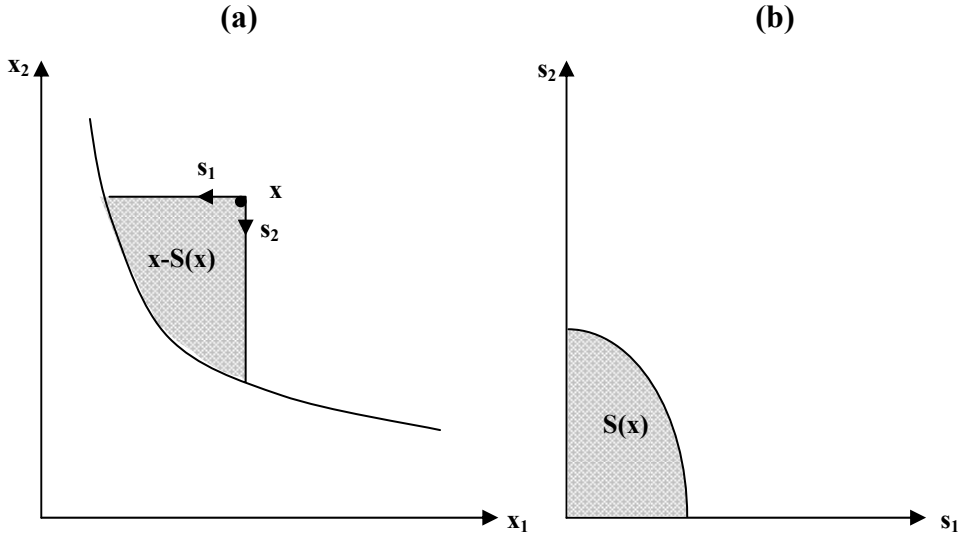
[1] A deduction can be made between the radial slack, which by definition is the same proportion for all inputs, and the non-radial slack, which is not the same proportion for all inputs.

To calculate the excess use of resources this way, we must have more information about the underlying production plan z used by the DMU. Without such information, the slack s must be included in the slack possibility set S(x) with the observed x defined as:

$$S(x) = \{s | s = (x - z), z \in L, z \leq x\} \tag{4}$$

A graphical illustration of the slack possibility set is found in Figure 1.

Figure 1 The slack possibility set given actual inputs



There are at least three possible interpretations of the slack, i.e.:

s^W : real waste due to sub-optimal production procedures
s^R : a rent in form of on-the-job consumption
s^B : a buffer against uncertainty, an insurance premium

From an agency perspective, these three interpretations reflect the idea that agents may lack abilities, may be lazy or may be risk averse. The former type of slack represents waste in a more traditional sense, while the two other slack types are not irrational as such, but instead rational decisions by the DMUs. We will in the following briefly review the theoretical aspects of viewing slack as on-the-job consumption and then we will turn to an analysis of slacks as a buffer against uncertainty. We will not consider the issue of slack as waste, but instead refer to Cooper, Seiford and Tone (2000) for further information on this more traditional interpretation.

1.1 Rational inefficiency as a buffer for rent

Bogetoft and Hougaard (2003) stressed the rent interpretation and investigated firm's decisions between off-the-job profit π, i.e. profits to owners, and on-the-job profit/slack $s^R \in \Re^p_+$, i.e. excess use of inputs. They assumed that the DMUs utility depends on both of these, and that the underlying utility function has the form:

$$U = U(\pi, s^R) \tag{5}$$

which is assumed to be increasing in both arguments.

Assuming preferential independence between π and s^R, the level of profit does not affect the trade-off between the different slack types, and the utility function can therefore be written as:

$$U = U(\pi, s^R) = V(\pi, g(s^R)) \tag{6}$$

with $g(\circ): \Re^p_+ \rightarrow \Re$ being an increasing function aggregating the value of the different types of slack.

Assume next that the DMUs are operating in a price based regime with given input prices. Having a certain budget, the aim of the individual DMU is then to solve the following problem:

$$\max_{\pi, s, x} U(\pi, s^R) \tag{7}$$

$$\text{s.t.} \quad \pi \leq b - w \cdot x \tag{7.a}$$

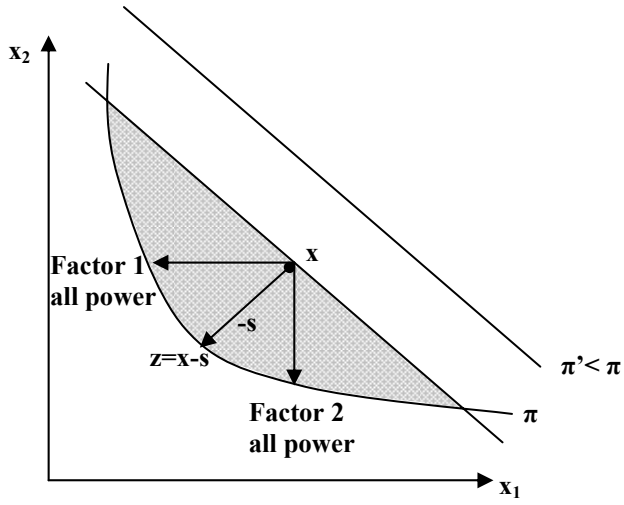
$$x - s^{\mathbf{R}} \in L \tag{7.b}$$

$$s^R \geq 0, x \geq 0 \tag{7.c}$$

where x is the vector of actual input consumption, b is the budget allocated and w is the input factor price.

The DMU's decision problem in the price based regime can be graphically illustrated as in Figure 2. Decreasing the profit level π=b–w·x, i.e. moving the isoprofit line towards north-east, the DMUs slack possibilities (as reflected by the shaded area) increase. For any given profit level, the choice of x and s reflects the relative weights associated with the different slacks.

Figure 2 Price based planning

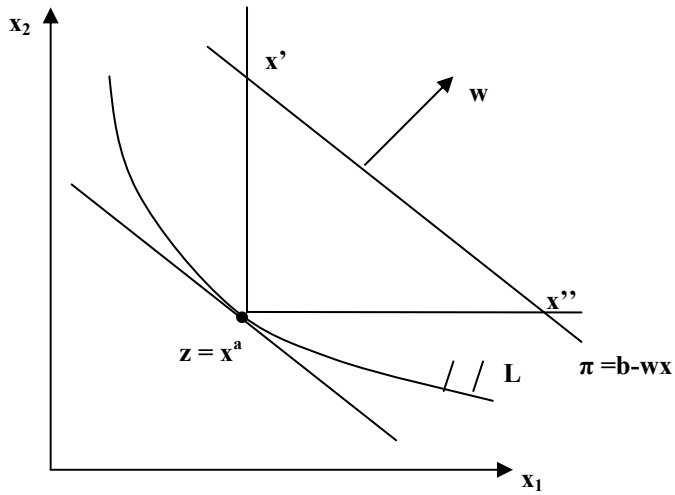


In a price based regime, the optimal underlying production plan z is an allocatively efficient input combination, thus implying that $z=x-s \in X^a$ as shown by Bogetoft and Hougaard (2003)[2]. The intuition behind this result is illustrated in Figure 3. If the DMU is assumed to be rational, it will seek to generate the outputs in the cheapest possible way by using $z = x^a \in X^a$. The remaining budget, $b-w\cdot x^a$, can then be used for either profit or slack. This decision problem can be formulated as follows:

$$\max_{s^R \in \Re^p_+} U(b - w\cdot x^a - w\cdot s^R, s^R) \tag{8}$$

Having chosen an optimal underlying production plan, the remaining decision for a DMU is to select the optimal allocation between profit and slack.

Figure 3 Choice of underlying production in a price based regime



[2] How to calculate the allocative efficient input combination is presented in the next section.

Based on the DMU's actual input use, one can by assuming a specific functional form for the slack preference function g(◦), estimate the trade-off between different slacks. Bogetoft and Hougaard (2003) analyse three specific preference functions. These are:

1) a Nash bargaining model: $g(s) = s_1^{\alpha_1} \cdot s_2^{\alpha_2} \cdot \ldots \cdot s_p^{\alpha_p}$
2) a weighted fairness model: $g(s) = \min \{\alpha_1 s_1, \alpha_2 s_2, \ldots, \alpha_p s_p\}$
3) a fair gains model: $g(s) = \min \{s_1 - \alpha_1, s_2 - \alpha_2, \ldots, s_p - \alpha_p\}$

Based on these specific functional forms, the relative importance or relative bargaining power of each input factor i=1,…,p can be calculated as follows:

1) $\alpha_i = \dfrac{w_i s_i}{\sum_{j=1}^{p} w_j s_j}$

2) $\alpha_i = \dfrac{1}{s_i (\sum_{j=1}^{p} s_j^{-1})}$

3) $\alpha_i = s_i + \dfrac{(1 - \sum_{i=1}^{p} s_i)}{p}$

The interpretation of these weights is that they indicate which inputs factors or which group of employees have most bargaining power and are hereby able to attract the highest proportion of on-the-job slack. Large values of α in 1) and 3) and low values in 2) is a sign of high bargaining power.

The decision problem for the DMU is thus a two-step procedure, where the allocation between off-the-job profits and on-the-job slack is made in the first step, while the allocation of on-the-job slack is considered in the second step. In the first step, the allocation can for instance be decided by negotiations between owners and employees, while the second step slack allocation is decided through bargaining between the different groups of employees or other production factors.

1.2 Rational inefficiency as a buffer for uncertainty

For several types of production, it is relevant to interpret the observed slack as a buffer against uncertainty instead of some on-the-job resources used by the employees. An obvious example is the fishery. When fishermen decide ex ante what to bring on their forthcoming fishing trip, they allow for a buffer in order to have flexibility for handling unforeseen events, such as less favourable stock conditions for instance. Organisational theorists have long recognised this type of slack, cf. Galbraith (1974) and Staber and Sydow (2002) and hence

this is not a new idea. However, no formal investigations of this type of decision making have been undertaken within fisheries to the knowledge of the authors[3].

To formalise, we can introduce uncertainty by including possible states of nature given by the set $\omega \in \Omega$. The setting considered now is therefore one where a DMU ex ante decides to use $x \in \Re_+^p$ inputs to produce $y \in \Re_+^q$ outputs in the state of nature $\omega \in \Omega$. The technology of a DMU can be defined by the following input requirement set:

$$L = L(y;\omega) = \left\{ x \in \Re_+^p \middle| x \text{ can produce y in state of nature } \omega \right\} \tag{9}$$

The presence of uncertainty can be thought of by considering the output y as given, say by the quota, and the state of nature as affecting the inputs required. If state ω^1 is more favourable than state ω^2, then the input requirement set is larger in state ω^1, i.e. $L(y;\omega^1) \supseteq L(y;\omega^2)$.

Due to the ex ante decisions by the DMU about producing y outputs using x input resources, it may turn out ex post that not all of these are strictly needed, i.e. $x \in L(y;\omega) \setminus F(L(y;\omega))$ in the actual state of nature ω. Assume that the DMU picked $x = L(y;\omega^2)$, because he wanted to be able to catch his quota in conditions at least as favourable as ω^2. Now, if ω^1 is realised, this gives the following slack:

$$s^B \in x - L(y;\omega^1) \tag{10}$$

which is the excess usage of inputs, when the DMU ex ante assumed to be in state ω^2, but instead ended up in a more favourable state ω^1.

The interpretation and possible values of the slack depends on the ability of the DMU to adjust production procedures after the state of nature has been revealed. Two possibilities may arise, one where the production procedures cannot be modified and one where they can be adjusted.

Assume firstly that the planned production procedures cannot be modified in the view of new information regarding the state of nature ω. In this case the excess usage of inputs can be thought of as an insurance premium that DMUs pay to be able to produce y in less favourable states.

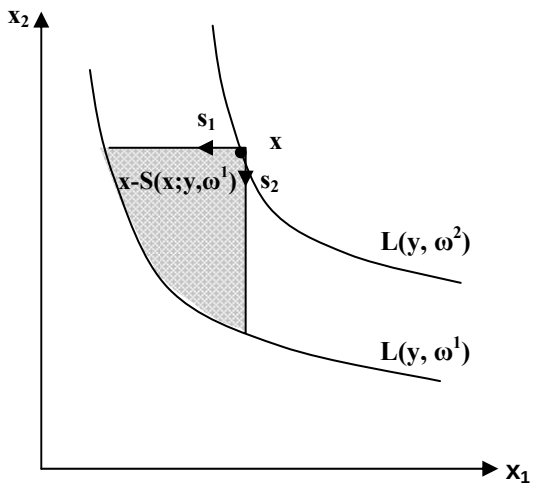
Assume secondly that the inputs x decided ex ante can be adjusted thus making the actual input usage equal to z, when the state of nature is known. This second possibility is more in

[3] Chambers and Quiggin (2000) analyse state-contingent production choices under uncertainty proposing to use dual methods for estimations.

line with the spirit of the original rational inefficiency notion, because a bargaining situation arises about how to allocate these input factor savings. In fisheries, unused fuel can for instance be saved for the next trip and the savings can be paid out to the crew.

The situation is illustrated in Figure 4 for a situation with two states of nature ω^1 and ω^2, where ω^1 is assumed to be more favourable than ω^2. The DMU decides ex ante to use x inputs in order to facilitate the production of y outputs, if the "worst" state of nature ω^2 is realised. However, the state of nature instead becomes more favourable than expected and less inputs are therefore actually needed. If the input use cannot be adjusted, the DMU still uses x to produce y, but if it can be adjusted, the production plan is chosen within the shaded area in Figure 4. The actual placement herein is determined by the bargaining between the input factors.

Figure 4 Slack as a buffer for uncertainty



1.3 Further developments

To further develop the idea of rational inefficiency as a buffer against uncertainty, we need more specific models to analyse the impact of state of nature on the technology. We will discuss two hypotheses here.

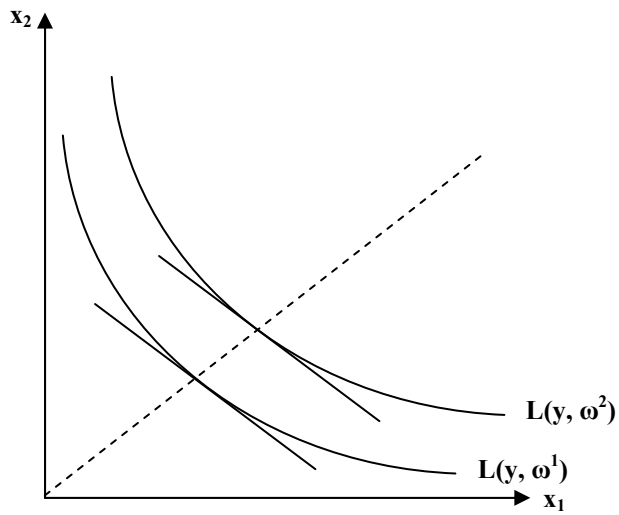
One hypothesis is that the effect of uncertainty has a multiplicative or homothetic impact as given in the following form:

$$L(y;\omega) = H(\omega) \cdot \overline{L}(y) \tag{11}$$

where H(◦) maps the set of possible states Ω into positive real numbers $\Re_+$ and $\overline{L}$ is a given base isoquant. In fisheries, the interpretation can be that the days at sea needed to obtain a given catch is uncertain, and the necessary variable inputs therefore must be expanded in a proportional fashion, if conditions are non-favourable.

The marginal rates of substitution between the inputs in this technology are the same along a ray from the origin. This implies that the allocatively efficient input combinations in the different states of nature are also on a given ray, determined by the relative input prices. The situation is graphically illustrated in Figure 5. We can in this set-up interpret H(ω) as being the relative complexity of producing in state ω.

Figure 5 Homothetic input requirement sets



With such a technology, a DMU will always choose an allocative efficient input combination. The level of the input combination depends on his risk attitude[4]. A high level of technical inefficiency indicates a high level of risk aversion, while the opposite is the case for a low level of technical inefficiency. From this we can derive testable hypotheses. All DMUs shall locate approximately on the allocatively efficient ray. If this does not happen, the combined hypothesis of 1) rational inefficiency as a buffer against uncertainty and 2) homothetic impact of uncertainty must be rejected.

An alternative hypothesis is that the effect of uncertainty has an additive structure instead of the previous multiplicative structure. A possibility is that:

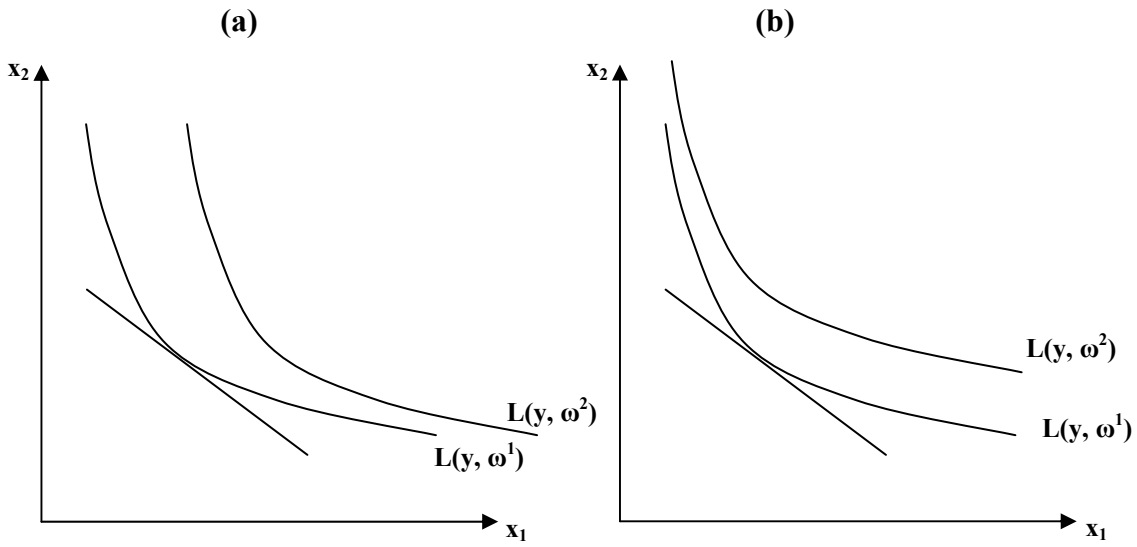
$$L(y;\omega) = h(\omega)\cdot\bar{x} + L(y) \tag{12}$$

where h(◦) plots the set of possible states Ω into positive real numbers $\Re_+$ and $\bar{x}$ is the input base translation of the base isoquant.

[4] Several investigations have found fishermen to be risk averse, cf. for instance Larson, Sutton and Terry (1999), Pradham and Leung (2004) and Eggert and Tveterås (2004). However, some find that fishermen have a risk loving behaviour, cf. Holland and Sutinen (1999, 2000) and Dupont (1993).

A graphical illustration of this set-up is presented in the two graphs in Figure 6. In Figure 6.a, input x_1 is the primary buffer against uncertainty, while x_2 has this characteristic in Figure 6.b. In informal terms, this can be thought of as the factor which can best mitigate uncertainty and thus is the most flexible production factor.

Figure 6 Additive input requirement sets



Under the assumption that the uncertainty effect has an additive structure, the rational DMU will still have incentives to choose an input combination x, such that $x-h\cdot\overline{x}$ is allocatively efficient. The slack level is in this situation calculated as $s=x-x^a(y)$ with the latter term being the allocative efficient production plan. The size of h then reflects the risk aversion of the DMU, i.e. the larger the h, the higher risk aversion.

Again, this leads to a testable hypothesis. From the slack values, an estimation of the input base translation can be derived by using the following formula:

$$\overline{x} = \frac{s_k^i}{\sum_{j=1}^{p} s_j^i}, k = 1,...p \tag{13}$$

If these vectors vary extensively between the DMUs, the technological and behavioural assumptions must be rejected, i.e. the impact of uncertainty is not a translation of isoquants, or the DMUs are not rationally inefficient, or both. However, if they do not deviate much, we can accept the hypothesis and the flexibility of the different resources can be evaluated using the $\overline{x}$ vector.

2. Calculation of slack values

In order to address the question of which input factors contribute most to the rational inefficiency, it is necessary to calculate the slack values for each input. The slack values can be estimated by comparing the present input use with the optimal input use. It is thus necessary to obtain estimations of the optimal input use.

As mentioned in the previous section, Bogetoft and Hougaard (2003) derived that a rational DMU will seek to produce the outputs in an allocative efficient way, where costs are minimised. A measure of the slack value is thus obtained as the difference between the allocative efficient input use and the observed input use. The purpose of this section is to present methods to derive these.

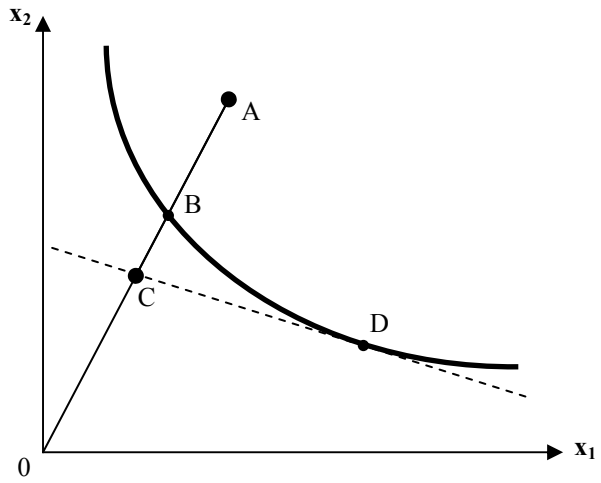
For the ease of exposition, we start by presenting the different efficiency concepts. Because these concepts are dependent on the assumptions made about agent's behavioural objectives (Coelli, Rao and Battese 1999), simply assume that the objective of the DMU is cost minimisation[5]. With this assumption, economic efficiency, also referred to as cost efficiency, measures the ability to produce a given output level at minimum cost for given input prices.

Continuing with the objective of cost minimisation, the availability of input price information facilitates a further deduction of economic efficiency into technical and allocative efficiency, cf. Farrell (1957). Technical efficiency in an input-orientated approach measures the possible decrease in input use with a constant output level, while allocative efficiency measures the possible decrease in cost that can be obtained, if the right input mix is used given input prices.

Before presenting a mathematical method to calculate technical, allocative and cost efficiency, it is instructive to give a graphical illustration of these, cf. Figure 7, where the best-practice frontier is given by the bold line. Technical efficiency is then measured by comparing the observed input use at point A with the use at the best-practice point B, thus measured as |0B|/|0A|. Including the dotted isocost line indicating the input price ratio, allocative efficiency is then measured as |0C|/|0B|, and cost efficiency is finally measured as |0C|/|0A|. Thus, while point A indicates the observed input usage, point D gives the allocative efficient input usage.

[5] Other objectives could be revenue or profit maximisation.

Figure 7 Technical, allocative and cost efficiency



Source: Cooper, Seiford and Tone (2000)

With this verbal and graphical introduction of the efficiency concepts, the next step is to present how to mathematically calculate the levels of technical, allocative and economic efficiency in an empirical application. To do so, we propose to use Data Envelopment Analysis, cf. Charnes, Cooper and Rhodes (1978,1979)[6].

Assume that the DMU has both discretionary and non-discretionary inputs in the production and that this production is characterised by variable returns to scale. In this set up, the input-orientated level of technical efficiency TE for DMU v′ can be found by solving the following linear programming problem, cf. Banker, Charnes and Cooper (1984) and Banker and Morey (1986):

$$\underset{(TE^{v'},\lambda^{v'v})}{\text{Minimise}}\ TE^{v'} \tag{14}$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot y_m^{obs\ v} \cdot d^{v'v} \geq y_m^{obs\ v'} \qquad M = 1,\ldots,M \tag{14.a}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot x_n^{obs\ v} \cdot d^{v'v} \leq TE^{v'} \cdot x_n^{obs\ v'} \qquad n = 1,\ldots,\tilde{N} \tag{14.b}$$

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

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

[6] To obtain a more general overview of the method given here, readers are referred to for instance Charnes, Cooper, Lewin and Seiford (1994), Coelli, Rao and Battese (1999) and Cooper, Seiford and Tone (2000).

where y_m denotes output m, x_n represents input n of which Ñ are discretionary and N-Ñ-1 are non-discretionary. The intensity variable λ measures the weight by which the activity of each DMU should be included when determining the input minimising frontier for DMU v′. If the observed value of a variable is used, this is indicated by the superscript obs.

In the above problem, a variable d is furthermore included. This variable is a technical comparison vector indicating which other DMUs in the dataset that DMU v′ can be compared with (see Andersen and Bogetoft (2004) for further elaboration).

Having found the minimising level of input use, the obvious next step is to find the cost minimising level of input use, if input prices are available. This is done by solving the following individual linear programming problem:

$$\underset{(x_n^{v'},\lambda^{v'v})}{\text{Minimise}} \sum_{n=1}^{\tilde{N}} w_n^{obs\,v'} \cdot x_n^{v'} \tag{15}$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot y_m^{obs\,v} \cdot d^{v'v} \geq y_m^{obs\,v'} \qquad M = 1,\ldots,M \tag{15.a}$$

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

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

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

where $w^{obs\,v'}$ denotes the observed input prices for each vessel v′.

Compared to the technical efficiency problem, the input use is here allowed to change in different proportions as seen by the inclusion of the endogenous variable x_n for each vessel v′. The optimal values of the inputs depict the allocatively efficient input combination. This is the combination that a rational inefficient DMU uses as the underlying production plan.

Based on the minimum input use found in the above problem, the level of cost efficiency can be calculated as follows:

$$CE^{v'} = \frac{w_n^{obs\,v'} \cdot x_n^{v'}}{w_n^{obs\,v'} \cdot x_n^{obs\,v'}} \tag{16}$$

Finally, the level of allocative efficiency can be calculated as:

$$AE^{v'} = CE^{v'} / TE^{v'} \tag{17}$$

These different efficiency measures will in the following be calculated by using the General Algebraic Modelling System, GAMS (Brooke, Kendrick, Meeraus and Raman 1998)[7].

3. Rational inefficiency and Danish Fisheries

To illustrate at least some of the above ideas, a dataset has been compiled based upon the annual account statistics for a representative part of the Danish commercial fishery collected by the Food and Resource Economics Institute. In 2002, information was collected from 331 fishing firms. However, specialised mussel and horse shrimp fisheries are excluded from the present dataset giving a total of 308 observations. Within this data set, several vessel types are represented, ranging from netters and Danish seiners to purse seiners and different types of trawlers.

The information in the dataset for each vessel is extensive, including catch weight; catch value, several types of costs, investments, asset values and so forth. For practical purposes, we have chosen to include nine outputs, four variable costs and two fixed costs. The nine outputs measured in tonnes of catch weight are as follows: 1) cod, 2) other codfish, 3) plaice, 4) other flatfish, 5) herring, 6) mackerel, 7) lobster and shrimp, 8) other consumption species and 9) industrial species. The variable costs measured in Danish kroner are: 1) fuel and lubricants, 2) ice and provisions, 3) sales and 4) crew. The two fixed costs are: 1) maintenance and 2) insurance and other services.

Table 1 gives an overview of the average values of catch weights, values and costs for the different gear types represented in the dataset.

Table 1 Average catch weight (tonnes), catch value and costs in 2002 (1,000 DKK)

	Catch weight	Catch value	Fuel	Ice and provisions	Sales	Crew	Mainte-nance	Insurance etc.
Beam trawl	1,310	21,909	5,050	133	2,421	6,599	2,306	1,173
Danish seine	572	7,940	377	134	922	3,953	1,026	635
Net/line	324	5,759	284	85	590	3,590	613	492
Multi-purpose	801	8,284	793	91	665	4,011	963	603
Purse seine	8,583	25,465	1,792	151	586	7,586	3,780	2,079
Trap	253	4.048	118	70	370	2,577	466	357
Trawl	6,815	13,499	1,476	338	1,198	4,788	1,500	847
Average, all	4,259	11,207	1,089	231	972	4,453	1,285	767

Source: Food and Resource Economics Institute

[7] Several computer programs have been developed to calculate these efficiency measures. Examples are for instance OnFront (Färe and Grosskopf 2000) and DEAP (Coelli 1996). One can also model these programs in Excel or statistical programs such as SAS or SHAZAM. The applied GAMS programs are available upon request from the authors.

Based upon this dataset, the input-orientated technical, allocative and cost efficiency can be calculated using the approach presented above. The technical comparison vector secures that only vessels using the same gear type are compared. Descriptive statistics for these efficiency measures are found in Table 2.

Table 2 Average efficiency scores

	Technical efficiency score	Allocative efficiency score	Cost efficiency score
Beam trawl	1.00	1.00	1.00
Danish seine	0.98	0.99	0.97
Multi-purpose	1.00	0.98	0.98
Net/line	0.93	0.90	0.84
Purse seine	1.00	0.99	0.99
Trap	1.00	1.00	1.00
Trawl	0.89	0.89	0.80
Average, all	0.92	0.91	0.85

For several fleet segments we observe that although they are technically efficient they are not allocative efficient, and thus not cost efficient. The trawlers are the worst performers, because they have the lowest scores. This indicates that significant input and cost reductions can be realised, if the correct input use is implemented.

The initial input use for each vessel can be subtracted from the allocative efficient input use. In this way, a measure of slack for each input is obtained. Given the theory discussed in Section 1, this slack can be seen as a measure of flexibility for the vessels, giving them the ability to deal with the uncertain environment they operate in. Table 3 gives the descriptive statistics for the slack values.

Table 3 Descriptive statistics of slack values

	Fuel		Ice and provisions		Sales		Crew	
	Average	Coefficient of variation	Average	Coefficient of variation	Average	Coefficient of variation	Average	Coefficient of variation
Beam trawl	0	0.00	0	0.00	0	0.00	0	0.00
Danish seine	9,778	4.49	14,589	3.29	20,379	3.90	139,274	3.08
Multi-purpose	2,460	4.24	-1,730	0.00	-1,816	0.00	80,313	4.24
Net/line	30,899	2.70	16,189	3.04	51,903	2.63	588,579	1.83
Purse seine	-12,315	0.00	-3,083	0.00	5,539	3.32	72,954	3.32
Trap	0	0.00	0	0.00	0	0.00	0	0.00
Trawl	251,746	1.60	33,092	3.88	147,947	1.79	782,707	1.51
Average, all	146,539	2.22	22,923	4.36	95,304	2.27	585,844	1.82

Notes: Coefficient of variation is calculated as standard deviation divided by average value, and measures the relative dispersion.

From Table 3, it can be observed that the average slack value from all observations is the highest for crew, followed by fuel, sales and ice and provisions. This indicates that fishermen have a tendency to have excess crew when they are fishing, or that any savings in fuel, etc. are reallocated into higher crew payments.

A number of negative slack values are observed in contrast to the theory. There can be several reasons for this. One could be that the estimated allocative efficient input use is not the correct one. The number of negative slack values within each fleet segment is given in Table 4.

Table 4 Number of negative slack values

	Fuel	Ice and provisions	Sales	Crew	Total
Danish seine	1				1
Multi-purpose		1	1		2
Net/line	8	10	9	2	29
Purse seine	1	1			2
Trawl	6	42	17	13	78
Total	16	54	27	15	112

If one illustrates the slack values of the different cost types against each other, as done in Figure 8, one observes a clear pattern that crew has the highest slacks compared to the other three inputs. The pattern becomes fuzzier when comparing the other slacks with each other, except when fuel and ice/provisions are compared.

Figure 8 Distribution of slacks on cost types

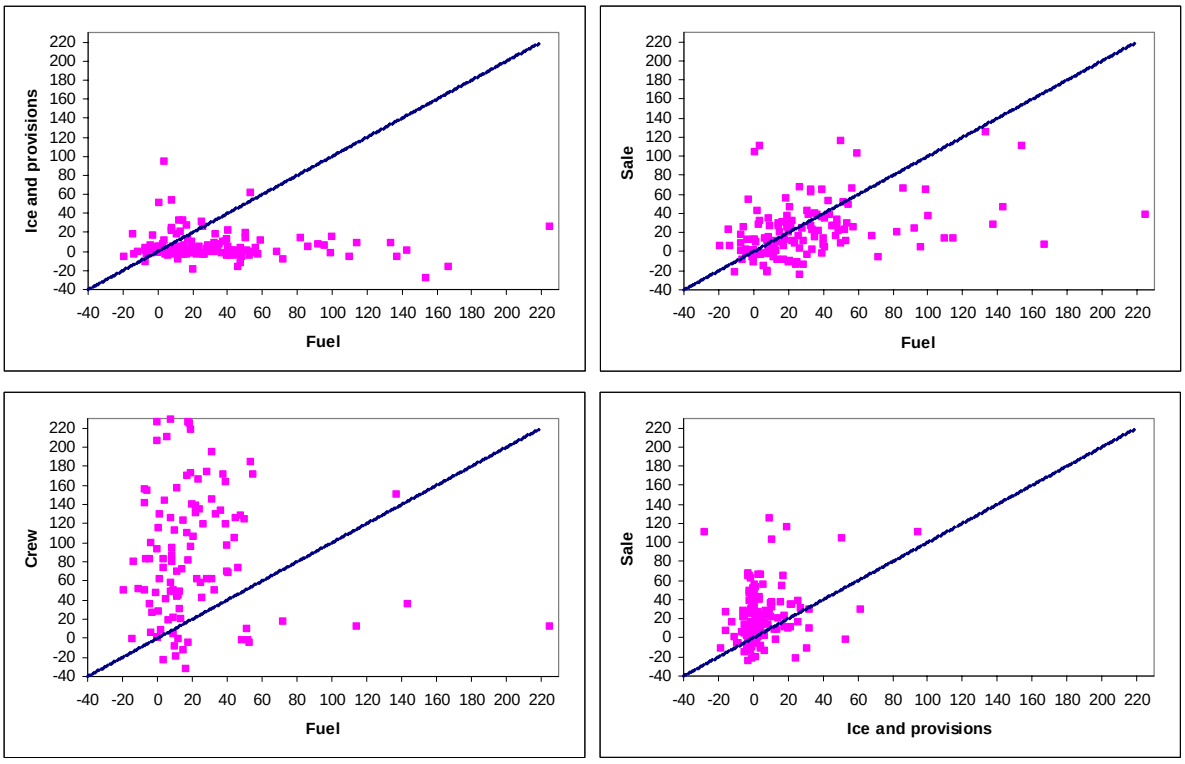
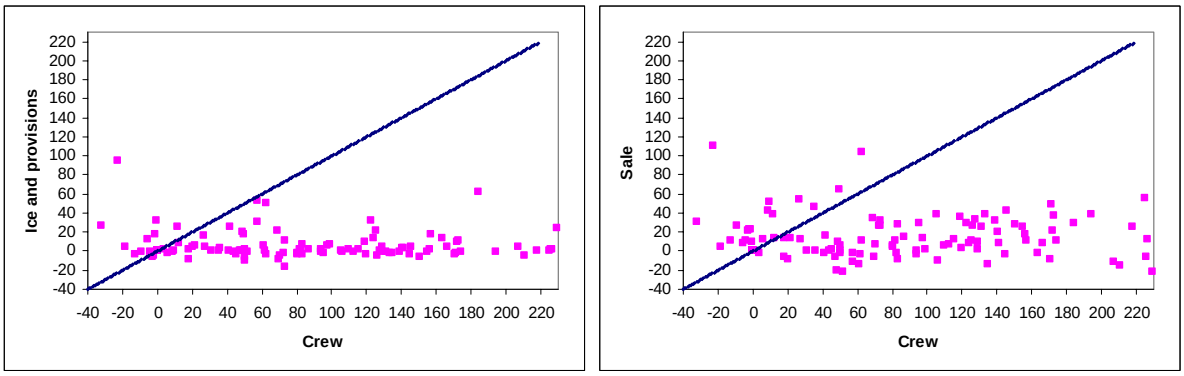


Figure 8 Distribution of slacks on cost types, continued



We have also estimated the more specific slack allocation models from Section 1.1. The values of the resulting relative importance factors are given in Table 5.

Table 5 Relative importance of input factors

	Nash Bargaining	Weighted Fairness	Fair Gains
Fuel	0.17	0.11	-66,113
Ice and provisions	0.03	0.70	-189,730
Sale	0.11	0.17	-117,349
Crew	0.69	0.03	373,192

It is observed that these utility function calculations support the previous findings. Excess resources or extraordinary savings go primarily to the crew.

Conclusion

In this paper we have made some initial attempts to extend and apply the idea of rational inefficiency to an uncertain environment. The idea is simple. Ex post evaluation of decisions that are planned under uncertainty ex ante may potentially lead to misleading conclusions. What appears to be inefficiency may in fact be a rational choice of extra resources ex ante to protect against the unknown future.

We have estimated the original rational inefficiency model for data from Danish fishery. This is to the best of our knowledge, except for an ongoing project by Asmild, Bogetoft and Hougaard (2004), the first attempt to implement the general ideas in Bogetoft and Hougaard (2003) in an actual application.

The results do not in general contradict the rational inefficiency hypothesis, and the allocation of slack across inputs reflects in a natural way the relatively strong bargaining power of the crew.

We have also speculated on some further development of the theory by including more specific state-contingent technologies and by suggesting ways to estimate combinations of such technological and behavioural assumptions.

Both the empirical and the theoretical discussions can easily be extended. One straightforward next step would be to test the extended state-contingent set-ups and the associated hypothesis on the same data.

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Part III

Industry Models of Fishermen's Behaviour and Individual Transferable Quotas

Quota Trading and Profitability: Theoretical Models and Applications to Danish Fisheries

by Jesper Levring Andersen and Peter Bogetoft

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 behavioural 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 potential gains to the industry from tradable quota under each of four sets of technological and behavioural characteristics.

Keywords

Data Envelopment Analysis (DEA), Individual Transferable Quotas (ITQ), reallocation, technical efficiency, allocative efficiency, fishery.

JEL-classification

C61, L51, Q22, Q28

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 (1966) and Dales (1968), and Montgomery (1972) 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). The seminal papers by Arnason (1990) and Kaufmann, Geen and Sen (1999) provide further insights into the use of ITQs within fisheries.

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 behavioural patterns are the result of the incumbent regime. The *technological adaptation* and *behavioural 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: Section 1 reviews some related literature. A brief introduction to DEA is given in Section 2. Section 3 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 Section 4. In Section 5, the usage of the framework is demonstrated on a dataset from Danish fisheries. The final section concludes the paper.

1. 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 (1995) and Brännlund, Chung, Färe, and Grosskopf (1998) study the Swedish pulp and paper industry using a DEA model with some non-discretionary inputs and some unwanted outputs (pollution). They use this model to estimate the cost of the existing transmission constraints at the individual units and the gains from reallocation of pollution rights.

A related approach is used in Bogetoft and Wang (2005) and Bogetoft, Thorsen and Strange (2003). 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 neighbours. 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 sector wide 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 behaviour or improve the result of strategic interactions with other firms on the market place, cf. Bogetoft and Hougaard (2003).

The fact that reallocation and individual efficiency improvement may not go hand in hand was first suggested in Bogetoft, Färe and Obel (2001). 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 (1986). There is also a recent revival of this literature known as *positive mathematical programming*, cf. Howitt (1995), where the calibration to the real world outcome is done using non-linear objectives to avoid "jumpy" behaviour.

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 modelling 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 (1979), Johansen (1977, 1978), Meijboom (1987), and Obel

(1981). 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. In one interpretation, therefore, 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.

2. 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), $v \in I=\{1,\ldots,V\}$, transform N inputs to M outputs. Let $x^v = (x_1^v,\ldots,x_N^v) \in \Re_0^N$ be the inputs consumed and $y^v = (y_1^v,\ldots,y_M^v) \in \Re_0^M$ the outputs produced in DMU^v, $v \in I$. Also, let T be the underlying production possibility set:

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

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:

[1] See for instance www.deazone.dk for an updated bibliography. Alternatively, Fried, Lovell, and Schmidt (1993), Charnes, Cooper, Levin, and Seiford (1994) give examples of Data Envelopment Analysis applications to different sectors.

[2] For textbook introductions to DEA, see Charnes, Cooper, Lewin, and Seiford (1994), Coelli, Rao and, Battese (1999) or Cooper, Seiford, and Tone (2000).

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

$$E^v = \text{Min } \{E \in \Re_0 \mid (Ex^v, y^v) \in T\} \text{ or } F^v = \text{Max } \{F \in \Re_0 \mid (x^v, Fy^v) \in T\} \qquad (2)$$

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 (1878, 1979) proposed the original constant returns to scale (*crs*) DEA model assuming A1, A2 and A3(crs). Banker (1984) developed the decreasing returns to scale (*drs*) model, while Banker, Charnes and Cooper (1984) 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:

$$T^*(s) = \left\{ (x, y) \in \Re_0^{N+M} \middle| \exists \lambda \in \Re_0^V : x \geq \sum_{v=1}^{V} \lambda^v x^v, y \leq \sum_{v=1}^{V} \lambda^v y^v, \lambda \in \Lambda(s) \right\} \tag{3}$$

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 (1984) 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 (1993). 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 (1990) and examined by Bogetoft (1996).

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.

3. 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 capital a typical non-discretionary good in the short run. Let the inputs and outputs of DMU^v be split up according to this classification:

$$(x^v, y^v) = (x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) \tag{4}$$

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:

$$\pi(x^v, y^v) = \pi(x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) = py_S^v - wx_S^v \tag{5}$$

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:

$$\Pi^{obs} = \sum_{v=1}^{V} \pi\left(x^{obs\ v}, y^{obs\ v}\right) = \sum_{v=1}^{V} \left[py_S^{obs\ v} - wx_S^{obs\ v}\right] \tag{6}$$

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 (1993) and Charnes, Cooper, Levin and Seiford (1994). Therefore, the *observed efficiency* of DMU^v can be calculated as:

$$E^{obs\ v} = \text{Min}\ \{E \in \Re_0 \mid (E\,x_S^{obs\ v}, E\,x_R^{obs\ v}, x_F^{obs\ v}, y^{obs\ v}) \in T\} \tag{7}$$

or

$$F^{obs\ v} = \text{Max}\ \{F \in \Re_0 \mid (x^{obs\ v}, F\,y_S^{obs\ v}, F\,y_R^{obs\ v}, y_F^{obs\ v}) \in T\} \tag{8}$$

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

$$\Pi^{new} = \sum_{v=1}^{V} \pi\left(x^v, y^v\right) = \sum_{v=1}^{V} \left[py_S^v - wx_S^v\right] \tag{9}$$

where (x^v, y^v), v=1,…,V, are the inputs and outputs in the new regime with transferable, regulated goods. The difference Π^{new}-Π^{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*:

$$\max_{(x_S, x_R, y_S, y_R, E)} \left[\sum_{v=1}^{V} \left(p y_S^v - w x_S^v \right) \right] - \Gamma\left[(x_S, x_R, y_S, y_R, E) \middle| (x_S^{obs}, x_R^{obs}, y_S^{obs}, y_R^{obs}, E^{obs}) \right] \tag{10}$$

s.t. $(E^v x_S^v, E^v x_R^v, x_F^{obs\,v}, y_S^v, y_R^v, y_F^{obs\,v}) \in T$ $\quad v = 1,\ldots,V$ (10.a)

$1 \geq E^v \geq E^{obs\,v}$ $\quad v = 1,\ldots,V$ (10.b)

$$\sum_{v=1}^{V} x_R^v \leq \sum_{v=1}^{V} x_R^{obs\,v} \tag{10.c}$$

$$\sum_{v=1}^{V} y_R^v \geq \sum_{v=1}^{V} y_R^{obs\,v} \tag{10.d}$$

where Γ 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 behaviour 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:

$$\max_{(x_S, x_R, y_S, y_R, F)} \left[\sum_{v=1}^{V} \left(p y_S^v - w x_S^v \right) \right] - \Gamma\left[(x_S, x_R, y_S, y_R, F) \middle| (x_S^{obs}, x_R^{obs}, y_S^{obs}, y_R^{obs}, F^{obs}) \right] \tag{11}$$

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

$$1 \le F^v \le F^{obs\,v} \qquad v = 1,\ldots,V \tag{11.b}$$

$$\sum_{v=1}^{V} x_R^v \le \sum_{v=1}^{V} x_R^{obs\,v} \tag{11.c}$$

$$\sum_{v=1}^{V} y_R^v \ge \sum_{v=1}^{V} y_R^{obs\,v} \tag{11.d}$$

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 Γ 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.

[3] See for instance Kirkley, Squires and Strand (1998), Sharma and Leung (1999) and Pascoe, Andersen and de Wilde (2001).

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

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 behaviour 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 (1984), where the output per input is maximal. This suggests that gains can be generated by giving more quotas to small units operating under 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 (2005).

[4] The partial ranking follows from the principle sometimes referred to as Le Châtelier Principle (cf. Samuelson (1974)). It states that gains cannot increase, when an extra restriction is imposed.

4. 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 behavioural 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 (1994):

$$\max_{(F^{v'},\lambda^{v'v})} F^{v'} \tag{12}$$

$$\text{s.t.} \quad \sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq F^{v'} \cdot CPY_m^{obs\,v'} \qquad M = 1,\ldots,M \tag{12.a}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{obs\,v'} \qquad n = 1,\ldots,\tilde{N} \tag{12.b}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \tag{12.c}$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1, \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \tag{12.d}$$

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 λ 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.

[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.

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:

$$\Pi = \max_{(\beta^v, \lambda^{vv}, VCPY^v)} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \beta^v \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^v \right) \tag{13}$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \geq \beta^{v'} \cdot CPY_m^{obs\,v'} \qquad m = 1,\ldots,M \tag{13.a}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \tag{13.b}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \tag{13.c}$$

$$\sum_{v=1}^{V} \lambda^{v'v} = 1, \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \tag{13.d}$$

$\vdots$

(13.a)-(13.d) repeated for each v' = 1,…,V

$\vdots$

$$\sum_{v=1}^{V} \beta^v \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \tag{13.e}$$

where β 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 β. 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:

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

s.t.

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

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

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

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

$\vdots$

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

$\vdots$

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

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 labelled Model EF -MC:

$$\Pi = \max_{(\lambda^{vv}, CPY^{v}, VCPY^{v})} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \frac{CPY_m^{v}}{F^{obs\,v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^{v} \right) \tag{15}$$

s.t.

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

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

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

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

$\vdots$

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

$\vdots$

$$\sum_{v=1}^{V} \frac{CPY_m^{v}}{F^{obs\,v}} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \tag{15.e}$$

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:

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

s.t.

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

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

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

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

$\vdots$

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

$\vdots$

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

Four industry models with different assumptions about production technology and behaviour 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 behaviour and technology.

5. 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. It must be emphasized that the intention is to illustrate the application of the framework, and thus not to provide precise estimations of the plausible tradability gains, if an ITQ system was implemented in Danish fisheries.

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 Food and Resource Economics Institute[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 (sand eel, 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 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) landings

[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.

and sale[9] 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 1998)[10].

Firstly, we estimate the level of technical efficiency for each vessel by solving the technical efficiency program[11]. Table 3 gives the descriptive statistics for the estimated scores.

Table 3 Output-orientated technical efficiency scores

	Mean value	Standard deviation	Maximum value
Technical efficiency score F	1.22	0.38	3.45

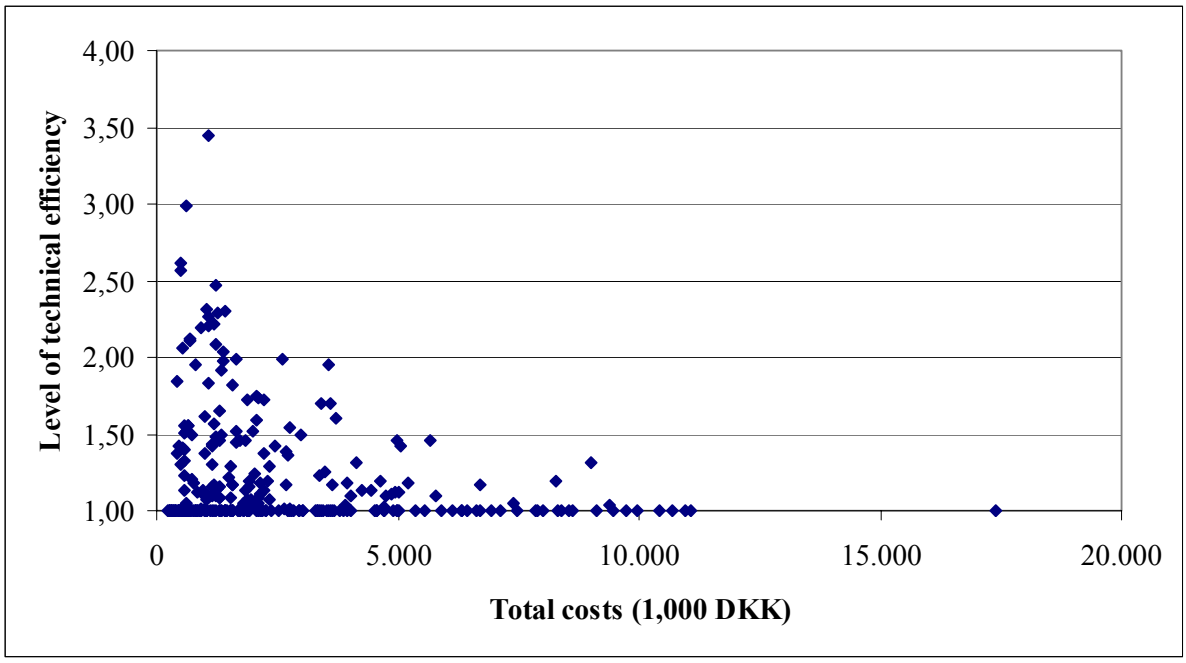
Interpretation of the results in Table 3 indicates that the vessels can increase their output by approximately 20% on average without increasing costs. For some vessels, the increase in output can even be more than three times their present output. The number of 100% technically efficient vessels is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

[9] This covers expenses for brokerage and harbor dues, collecting, sorting and auctioneering, packing chilling and freight and other landings costs.

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

[11] Due to the short run time horizon in the present analysis, we have as Grosskopf and Valdmanis (1987) chosen to assume that the production technology is characterized by variable returns to scale.

Figure 1 Technical efficiency as a function of total costs



With the above 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, defined as 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	685,563	38.65
Model EF-MC	683,065	38.15
Model EC-MC	720,515	45.72

We define gross profits as earnings minus fixed costs, i.e. catch value minus variable cost minus fixed costs. This measure shows 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	448,888	72.47
Model EF-MC	451,386	73.43
Model EC-MC	486,338	86.86

For both earnings and gross profits, we observe that over 50% of the expected gains in the most flexible model arise from simply reallocating quotas without allowing technological or behavioural 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, because the price of each species is assumed the same for all vessels. This implies that the reallocation of catches between different vessel types does not alter the catch value[12]. The variations are thus solely due to matching problems resulting in unused catch possibilities[13]. 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.

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

[12] Introducing an ITQ system may result in increased prices due to a lengthening of the fishing season, which result in better qualities of fish being landed, cf. Herrmann (1996).

[13] The assumption of unchanged and equal prices may therefore be an over-simplistic assumption, but is considered acceptable for current illustration purposes.

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[14].

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

[14] The angles have been calculated using $\mathrm{Cos}(\theta_{a,b}) = \left(\vec{a} \cdot \vec{b} / |\vec{a}| \cdot |\vec{b}|\right)$, 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.

modelled by DEA, there are no gains from specialization in the mix, cf. also Bogetoft and Wang (2005) for an extended discussion.

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 (ITQs) is an interesting instrument in the regulator's toolbox. It has attractive properties from a theoretical point of view. Changing an incumbent regulation to one based on ITQs, however, involves transition costs and it may take time before the effects are realized. It is therefore important to predict and analyze the potential economic gains from an ITQ system before it is implemented.

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 different economic sectors and different models of the production technologies. 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 behavioural 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 developed four sectoral models to capture the gains from introducing ITQs in fisheries. The models maximize industry profits without increasing the pressure on the harvested resources, and while respecting behavioural and technological restrictions on the individual vessels.

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 behavioural 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 fixed the catch composition entirely at the vessel level 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 in order to obtain results that are more realistic. As suggested by Korhonen and Syrjänen (2001), 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 behavioural 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.

It would also be relevant to investigate the transition path and the long run consequences from implementing an ITQ system. Grafton, Squires and Fox (2000) find that ITQs are often not used because there are high losses in the transition phase. Our analysis used a comparative static approach but by combining with the multi-level literature, it could potentially give information about the transition phase as well.

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Potential gains from using Individual Transferable Quotas to regulate Danish fisheries

by Jesper Levring Andersen and Peter Bogetoft

Abstract

Previous articles have shown that there are significant gains to be expected from implementing an Individual Transferable Quota system within fisheries. Andersen and Bogetoft (2003) developed a new approach to calculate expected tradability gains in such systems. Using Data Envelopment Analysis, linear programming problems were formulated to capture reallocation gains under two behavioural restrictions. This considers the ability to learn best-practice and to change output composition. In this paper, we extend the proposed method by focusing on a complex of restrictions, which can be included in order to obtain more realistic estimations, when applied to specific fisheries.

In order to illustrate the applicability, a dataset covering the entire Danish commercial fishery is utilised. Based on this, we estimate the tradability gains in the most flexible situation to be an increase in gross profits of around 90%. However, we also show that the potential gains are significantly reduced, if the flexibility in vessel behaviour is restricted. A series of policy implications is analysed including concentration, specialisation, market activity, price changes, etc. Attention has often been drawn to these effects when the implementation of Individual Transferable Quotas in fisheries is discussed. Finally, we analyse the consequences of exogenous chocks and changes in management practice in form of mesh size increases.

Keywords

Fishery, Individual Transferable Quota, behaviour, reallocation, tradability gains, regulation.

JEL-classification

Q22, Q28

Introduction

An important aspect of environmental and resource management is to analyse the consequences of new regulatory measures. For a decision maker, many criteria may be relevant to consider when performing such analysis, including biological, social and economic performance measures. Economists have traditionally focused on the latter, even though they acknowledge the importance of biological and social measures. Traditionally, such measures are included as restrictions in the optimisation of the economic measure.

One of the most popular regulatory instruments among economists is Individual Transferable Rights, when externalities are present. This instrument has been applied to regulate environmental problems, with the most prominent being the CO_2 Kyoto agreement. However, it has also been applied to regulate resources such as fish. Several management regimes within fisheries are based upon Individual Transferable Quota (ITQ), where fishermen are allocated the property right to a certain amount of catch and afterwards allowed to trade these rights. Making them transferable secures the highest possible profit.

The two most famous examples of ITQ management within fisheries are Iceland and New Zealand. Furthermore, other countries including Denmark are currently considering using this regulatory instrument for other species besides herring, which is currently regulated with ITQs. However, from an economic point of view the implementation of a new regulatory regime triggers a necessary investigation into whether the gains exceed the costs of doing so. Since the seminal paper from 1991 by R. Arnason about ITQs, there have been several attempts to estimate possible gains from implementing such a system in fisheries. The approaches to evaluate the gains are very different ranging from descriptive statistics to more complicated mathematical treatments[1].

Squires and Kirkley (1995) analysed the bottom trawl fishery in the continental slopes waters off Northern California and Southern Oregon. They estimated that an increase of around 50% in industry resource rents would be likely, if thorny heads and sablefish were jointly regulated using ITQs. Based on trip data covering Danish vessels from Esbjerg and Thyborøn primarily fishing in the North Sea and/or Skagerrak, Vestergaard (1998) estimated that short run rents would increase by 17% in a limited ITQ system covering cod, sole and saithe. Weninger and Waters (2003) considered the reef fish fishery in the northern Gulf of Mexico and their estimations of long run profits indicated a possible increase from $–4,646 to $6,640 million, resulting from a 49% increase in revenue and 75% decrease in costs[2].

[1] Grafton et al. (2000) review several methods to perform economic evaluation of ITQ systems.

[2] Other empirical analyses can also be found. One example is Lindner, Campbell and Bevin (1992), who use descriptive statistics to evaluate the generation of resource rent derived from regulating the entire New Zealand fishery with ITQs in 1986. Another example is the analysis of the Mid-Atlantic surf clam and ocean quahog fishery by Weninger (1998).

None of the above methods are however straightforward to apply in analysis of other fisheries. Andersen and Bogetoft (2003) therefore developed a flexible framework to estimate the potential gains from implementing an ITQ system. In this framework, different types of flexibilities were included to account for behavioural changes by the fishermen. These were individual learning and choice of output composition. In an illustrative application, we showed how profit gains from implementing an ITQ system are affected by the behavioural assumptions. However, the flexibility allowed in Andersen and Bogetoft (2003) may for many fisheries be an inadequate approximation of reality. The consequence is an overestimation of the tradability gains and thus regulatory decisions being made on the wrong basis.

In this paper, we therefore extend this approach by considering methods to make it more in agreement with the situation in an actual fishery. Based on these theoretical considerations, we estimate the potential gains from implementing an ITQ system in Danish fisheries. This is done using empirical data collected by the Food and Resource Economics Institute, which covers the total commercial fleet in Denmark. Furthermore, we consider how the framework can be utilised to address other topics within management of fisheries such as gear restrictions.

The paper is structured as follows: Section 1 gives a brief review of the framework presented in Andersen and Bogetoft (2003). In Section 2, the types of additional restrictions to make it more applicable in an actual fishery are discussed, while the applied dataset is described in Section 3. Using the previous sections, estimations of tradability gains under various levels of flexibilities are performed in Section 4. The estimations thus indicate the gains to be expected, if Danish fisheries were regulated by ITQs instead of the current regulation. Based on the empirical analysis, some policy implications are derived in Section 5 and some final remarks close the paper in Section 6.

1. Framework to estimate tradability gains

The framework presented in Andersen and Bogetoft (2003) used Data Envelopment Analysis (DEA) to model the fishermen's production structure. DEA is a non-parametric method, which can be used to estimate the empirical reference technology, when the underlying production possibility set is unknown. Using the best-practice observations, the empirical reference technology thus reflects the production frontier. Comparing actual production of a given fisherman with the production frontier, a measure of his efficiency can be obtained.

Efficiency measures can be derived in many ways. Here we opt for an output-oriented traditional Farrell (1957) measure. This measure seeks to identify the radial increases of all outputs that will make the fisherman technically efficient, i.e. produce at the frontier. The (in)efficiency F for vessel v (v=1,…,V) is thus determined as:

$$F^v = \text{Max } \{F \in \Re_0 \mid (x^{obs\ v}, Fy^{obs\ v}) \in T^*\} \tag{1}$$

where $x^{obs\ v} = (x_1^{obs\ v}, ..., x_N^{obs\ v}) \in \Re_0^N$ are the observed input use, $y^{obs\ v} = (y_1^{obs\ v}, ..., y_M^{obs\ v}) \in \Re_0^M$ are the observed outputs produced and T* is the empirical reference technology.

The empirical reference technology T* is the smallest subset of $\Re_0^{N+M}$ that contains or envelops the observed production plans $(x^{obs\ v}, y^{obs\ v})$ for all vessels $v \in V$, and satisfies certain technological assumptions specific to the given approach. It is thus constructed according to the minimal extrapolation principle (Banker, Charnes and Cooper 1984).

Different DEA models invoke different assumptions about the technology. Here we follow Banker, Charnes and Cooper (1984), and invoke free disposability and convexity of T*. The empirical reference technology hereby becomes the so-called variable returns to scale[3] DEA model:

$$T^* = \left\{ (x, y) \in \Re_0^{N+M} \middle| \exists \lambda \in \Re_0^V : x \geq \sum_{v=1}^{V} \lambda^v x^{obs\ v}, y \leq \sum_{v=1}^{V} \lambda^v y^{obs\ v}, \sum_{v=1}^{V} \lambda^v = 1 \right\} \tag{2}$$

Since these are polyhedral convex sets, the Farrell efficiency measurement programs become linear programming problems.

In Andersen and Bogetoft (2003), the basic principles from DEA were used to set up a profit-maximisation problem with individual restrictions for each vessel and industry restrictions for each output. Modelling the individual restrictions in the DEA set up, we were able to account for different flexibilities in the framework. These included the individual vessel's possibility to learn and to change its output composition. Depending on the analysed fishery, managers can allow for none, one or both of these flexibilities to exist, and thus evaluate the importance of these.

Inputs and outputs can be divided into three types of goods. These are standard (S), regulated (R) or fixed (F) goods. A standard good is defined as a good that can be bought and sold at perfect markets. A regulated good is currently not traded, but could in principle be transferred between vessels. Finally, a fixed good is defined as being produced and used locally, and is thus non-discretionary and non-transferable. For vessel v, we thus have:

$$(x^v, y^v) = (x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) \tag{3}$$

[3] Charnes, Cooper and Rhodes (1978,1979) proposed the original constant returns to scale DEA model assuming free disposability, convexity and free scaling of a given production plan, i.e. $(x,y) \in T^* \Rightarrow k \cdot (x,y) \in T^*\ \forall k \geq 0$. Banker, Charnes and Cooper (1984) also developed the decreasing returns to scale model by assuming free disposability, convexity, and free down scaling, i.e. $(x,y) \in T^* \Rightarrow k \cdot (x,y) \in T^*\ \forall k \in [0;1]$.

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 making the total number of inputs N equal to $N_S + N_R + N_F$ and the total number of outputs M equal to $M_S + M_R + M_F$.

If the individual objective of each fisherman is to maximise his profit π from the standard goods, we have for each vessel ($v \in V$) that:

$$\pi(x^v, y^v) = \pi(x_S^v, x_R^v, x_F^v, y_S^v, y_R^v, y_F^v) = py_S^v - wx_S^v \tag{4}$$

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

The observed industry profit Π^{obs} under the current regulation system can be found as:

$$\Pi^{obs} = \sum_{v=1}^{V} \pi\left(x^{obs\,v}, y^{obs\,v}\right) = \sum_{v=1}^{V} \left[py_S^{obs\,v} - wx_S^{obs\,v}\right] \tag{5}$$

Changing the current regulation system to one based upon individual transferable goods implies that the regulated goods become transferable. This gives the fishermen the possibility to change their production, which was previously limited by the regulated goods. The new industry profit Π^{new} therefore equals:

$$\Pi^{new} = \sum_{v=1}^{V} \pi\left(x^v, y^v\right) = \sum_{v=1}^{V} \left[py_S^v - wx_S^v\right] \tag{6}$$

where the use of inputs and outputs in the new management system with transferable regulated goods is given by (x^v, y^v), v=1,…,V. Note that the possible revenues and costs from trading the previously regulated goods cancel each other out at the industry level. The total gains from reallocation can therefore be calculated as the difference between observed and new industry profit, i.e. Π^{new}-Π^{obs}.

From a management perspective, it is important to be able to predict how fishermen will react, when previously non-transferable regulated goods are allowed to be transferred, and thus what their new input and output use will be. However, costs may arise, due to changed behaviour from one regulatory regime to another. A penalty function Γ is therefore introduced to reflect these costs. It is in this function assumed that transition costs increase, the more the new inputs, outputs and efficiency levels deviate from the historical levels.

Several behavioural changes can be a likely consequence of a new management system. In Andersen and Bogetoft (2003), we focused on individual learning and changes in output mix. If both are allowed to change, the new industry profit can be calculated by solving the following reallocation problem:

$$\max_{(x_S,x_R,y_S,y_R,F)}\left[\sum_{v=1}^{V}\left(py_S^v - wx_S^v\right)\right] - \Gamma\left[(x_S,x_R,y_S,y_R,F)\middle|(x_S^{obs},x_R^{obs},y_S^{obs},y_R^{obs},F^{obs})\right] \tag{7}$$

s.t. $$(x_S^v, x_R^v, x_F^{obs\,v}, F^v y_S^v, F^v y_R^v, y_F^{obs\,v}) \in T \qquad v = 1,\ldots,V \tag{7.a}$$

$$\sum_{v=1}^{V} x_R^v \le \sum_{v=1}^{V} x_R^{obs\,v} \tag{7.b}$$

$$\sum_{v=1}^{V} y_R^v \ge \sum_{v=1}^{V} y_R^{obs\,v} \tag{7.c}$$

where Γ is the penalty function. In the penalty function, we have furthermore used (x_S,x_R,y_S,y_R,F) to refer to the standard and regulated inputs, outputs and efficiency levels of all the vessels. The reallocation problem thus determines the optimal distribution of standard and regulated goods in order to maximise industry profit and minimise transition costs.

Several constraints are included. First, it is required that the reallocated production plans are within the production possibility set and therefore feasible under the assumed improvements in efficiency levels. The last two constraints secure that the total use of regulated inputs cannot be increased and that the total use of regulated outputs cannot be reduced.

The penalty function can be utilised to allow or exclude behavioural changes. This is facilitated by setting the penalty for individual learning and/or output mix changes to either zero or infinity. Changing the level of technical efficiency via individual learning is allowed, if the penalty is equal to zero, while it is not facilitated with an infinite penalty. Likewise can changes in the output mix be included or excluded through the penalty level. A distinction can thus be made between four basic models, which are separately characterised by the level of vessel flexibility, cf. Table 1.1.

Table 1.1 Four basic models

	Changes in output mix impossible ($y^{v\,obs} \neq \beta y^v \Rightarrow \Gamma = \infty$)	Changes in output mix possible
Individual learning penalty impossible ($F^v < F^{v\,obs} \Rightarrow \Gamma = \infty$)	- Technical efficiency fixed - Output mix fixed	- Technical efficiency fixed - Output mix changeable
Individual learning penalty possible	- Technical efficiency changeable - Output mix fixed	- Technical efficiency changeable - Output mix changeable

Note: β is a scalar and change in the size of catch is thus facilitated.

Depending on the specific model, the industry level tradability gains from implementing an ITQ system can be attributed to efficiency effects, scale effects and/or mix effects, cf. Andersen and Bogetoft (2003). Efficiency effects refer to less efficient vessels selling to more efficient ones, scale effects refer to vessels adjusting their production towards the most

productive scale size, while mix effects refer to vessels changing their output mix towards a more productive direction in the production possibility space.

2. Restrictions on vessel flexibility

The framework presented in the previous section assumed either none or complete flexibility in the possible vessel behaviour. It hereby models only rather extreme cases. To obtain more realistic estimations it is often necessary to include a series of further restrictions, before solving the industry programming problems. If not, regulatory decisions may be taken on the wrong basis, and thus result in a loss of welfare.

Several restrictions can be thought of. Here we focus on restrictions regarding:

- best-practice
- individual learning
- output mix

For instance, in a fishery where vessels use different gear types, it is not reasonable to assume that the best-practice frontier is the same for all these. Instead, a frontier could be determined for vessels using the same gear types, or gear types based on similar technology. Vessels may also be able to change their level of technical efficiency through individual learning, but it may not always be reasonable to assume that a fully technical efficient level can be achieved. In some situations, there may even be efficiency regress. Allowing vessels to completely change their output mix - or not to change it at all - can also be unrealistic, especially when vessels use different gear types, but sometimes also when the same gear types are used. The importance of the different restrictions must obviously be based on specific knowledge about the analysed fishery.

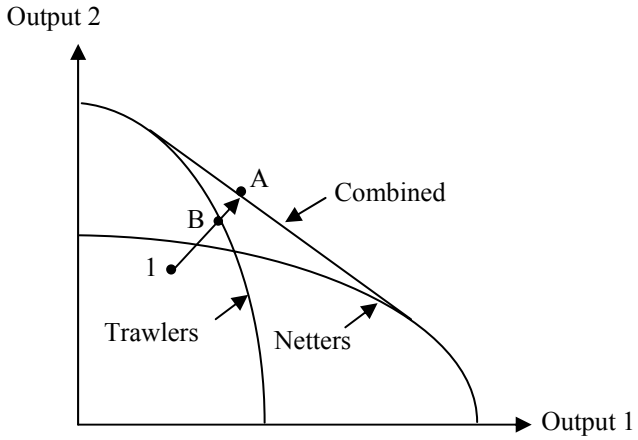
2.1 Restrictions on determination of best-practice frontier

Analysis of technical efficiency issues in fisheries (and other areas as well) is traditionally based on datasets consisting of production units, i.e. vessels in our case, using the same type of technology. However, an ITQ system can cover one or several outputs produced by vessels using distinctively different production technologies. For instance, the technologies used by a trawler and a netter differ, but because they catch some of the same species, they are regulated by the same ITQ system. Thus, when estimating the tradability gains in ITQ systems using the industry models, it can be necessary to account for differences in production technologies.

Figure 2.1 illustrates in a two-output situation, the difference between assuming that all vessels have the same best-practice frontier or group wise best-practice frontiers. If the best-

practice frontier is estimated using the combined observations for trawlers and netters, the frontier becomes the combined line due to the convexity assumption. However, if the estimation is performed group wise, i.e. for trawlers and netters separately, the best-practice frontier becomes the two individual lines. Trawler 1 will thus be compared to point B instead of point A, when evaluating its level of technical efficiency.

Figure 2.1 Comparing group wise with combined best-practice frontiers



A general way to formalise restrictions on the determination of best-practice frontier is to include a dummy vector for each vessel indicating which other vessels use the same production technology. Thus, the technological comparison vector D has the following form for vessel v′ (v=1,…,V):

$$D^{v'} = (d^{v'1},...,d^{v'v},...,d^{v'V}) \tag{8}$$

where $d^{v'v}$ has a value of 1 or 0 depending on whether the two vessels v′ and v use similar production technologies or not. The matrix $D=\{D^{v'v};v'\in V,v\in V\}$ is symmetric.

To specify the comparability is a potentially complicated exercise involving specific knowledge about the industry. Also, one may rely on statistical techniques. Cooper, Seiford and Tone (2000) for example present a statistical method to compare the production technologies of different vessel types within the framework of DEA. The method proceeds in three steps. In the first step, efficiency estimations are performed for the vessels within each of the two vessel types to be compared, and the non-efficient ones are projected to the respective efficient frontiers. Thereafter in step two, the now efficient vessels are merged into one dataset and a new estimation of efficiency is performed. The final third step uses a Wilcoxon-Mann-Whitney rank-sum-test to test whether the vessels can be considered to have the same production technology.

The comparison vectors can be included in the industry-programming problem presented in Section 1. Assuming for instance that individual learning and change in output mix is not

possible due to high costs, the programming problem assuming variable returns to scale becomes:

$$\Pi = \max_{(\beta^v, \lambda^{vv}, VCPY^v)} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \beta^v \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^v \right) \tag{9}$$

s.t.

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot CPY_m^{obs\,v} \cdot D^{v'v} \geq \beta^{v'} \cdot CPY_m^{obs\,v'} \qquad m = 1,\ldots,M \tag{9.a}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot VCPY_n^{obs\,v} \cdot D^{v'v} \leq VCPY_n^{v'} \qquad n = 1,\ldots,\tilde{N} \tag{9.b}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot FCPY_n^{obs\,v} \cdot D^{v'v} \leq FCPY_n^{obs\,v'} \qquad n = \tilde{N}+1,\ldots,N \tag{9.c}$$

$$\sum_{v=1}^{V} \lambda^{v'v} \cdot D^{v'v} = 1, \lambda^{v'v} \geq 0 \qquad v = 1,\ldots,V \tag{9.d}$$

$\vdots$

(9.a)-(9.d) repeated for each v' = 1,…,V

$\vdots$

$$\sum_{v=1}^{V} \beta^v \cdot \frac{CPY_m^{obs\,v}}{F^{obs\,v}} \leq \sum_{v=1}^{V} CPY_m^{obs\,v} \qquad m = 1,\ldots,M \tag{9.g}$$

where the subscripts indicate the outputs m and inputs n, while the superscript 'obs' specifies that observed values have been used. Furthermore, CPY denotes the catch per year in weight; VCPY the variable (discretionary) costs per year and FCPY the fixed (non-discretionary) costs per year. β is the radial output change parameter and the intensity variable $\lambda^{v'v}$ identifies the extent of which each included vessel v is used to construct the piecewise linear frontier approximation that envelops the data for a given vessel v′. As previously, F denotes the output efficiency level and P the output prices. Observe that there are $\tilde{N}$ variable inputs and $(N-\tilde{N})$ fixed inputs. Observe also that by including F and β, we do not allow the included vessels to alter their level of technical efficiency and output mix (relative catch composition).

The appeal of the above problem is that a vessel is only compared to vessels with similar technology, but still facilitating trades with vessels using other production technologies.

Instead of using dummy variables to account for technological differences, restrictions could be imposed upon the intensity variables or weights. The form of the included restriction would then be $\lambda^{v'v} \cdot (1-D^{v'v})=0$, $\forall v',v$, and the comparison vector D in the other equations can be removed. An extensive literature exists on this topic and an overview can be found in Allen et al. (1997).

2.2 Restrictions on individual learning

Changes in management are likely to influence the individual vessels level of technical efficiency. Depending upon the type of management change and the flexibility in vessel behaviour, this may result in either an improvement or deterioration in the individual vessels level of technical efficiency.

In the present context, the change from an unspecified ex ante management system to a system based upon ITQs is of primary interest. This change may allow skippers to utilise their skills better, resulting in improved levels of technical efficiency. However, deterioration may also be observed, if skippers seek to explore more profitable fisheries, in which they - at least in the short run - do not have much experience.

Assuming in the basic model from Section 1 that the level of technical efficiency can be changed, it results in all vessels becoming fully efficient. However, technical inefficiencies seem to be a persistent problem within fisheries as well as other production sectors. We will therefore show an easy method to impose restrictions upon individual learning such that vessels' technical efficiency may improve (or deteriorate), but not necessarily to a fully efficient level.

The method we use is a two-step procedure. In the first step, the expected new level of technical efficiency is determined, and in the second step this new level of technical efficiency is included in the reallocation problem. The expected change in technical efficiency due to individual learning is thus not calculated internally within the reallocation model, but is instead considered externally.

Using an output-oriented approach, the method implies that the observed level of technical efficiency for each vessel F^{obs} is firstly changed with a given percentage α giving rise to a new level F^{new} i.e.:

$$F^{new\,v} = \left(1-\alpha^{v}\right)\cdot F^{obs\,v}, F^{new\,v} \geq 1, \alpha^{v} \leq 1-\frac{1}{F^{obs\,v}} \tag{10}$$

This formulation allows for both improvement and deterioration in the level of technical efficiency. Improvement will be the outcome if α is between zero and one, while deterioration follows if α is below zero.

Individual learning can hence be permitted in the industry-programming problem by exchanging F^{obs} with F^{new}. For instance, in the programming problem given by equation set (9), the objective function, cf. equation (9), is changed to:

$$\Pi = \max_{(\beta^v, \lambda^{vv}, VCPY^v)} \sum_{v=1}^{V} \left(\sum_{m=1}^{M} P_m \cdot \beta^v \cdot \frac{CPY_m^{obs\ v}}{F^{new\ v}} - \sum_{n=1}^{\tilde{N}} VCPY_n^v \right) \tag{11}$$

while the industry restriction on total catches, cf. equation (9.g), is replaced by:

$$\sum_{v=1}^{V} \beta^v \cdot \frac{CPY_m^{obs\ v}}{F^{new\ v}} \leq \sum_{v=1}^{V} CPY_m^{obs\ v} \qquad m = 1,\ldots,M \tag{11.g}$$

Having described the way to impose restrictions upon individual learning in the reallocation models, the next step is to quantify the level of changes in efficiency. Managers must consider the potential of individual learning in order to impose relevant restrictions reflecting the actual potential for each vessel or subgroup of vessels. The more precise these restrictions are, the more trustworthy the estimated consequences become. Generally, the choice of approach depends among other things on the characteristics of the analysed fishery and the availability of usable data.

A simple but imprecise approach is to test the consequences of allowing different levels of individual learning. This can be viewed as a sensitivity analysis. A more appropriate but also more time-consuming approach is to first investigate the fishery in question. The natural starting point is to identify the reasons for the presence of technical inefficiency. A review of the relevant literature reveals that many factors influence the level of technical efficiency.

Weninger and Waters (2003) make a distinction between external and internal factors that influence the level of technical efficiency. Examples of external factors are variations in fish stocks (Campbell and Hand 1998), weather and regulatory restrictions (Pascoe, Andersen and de Wilde 2001). Internal factors include vessel/engine size (Pascoe and Coglan 2002), vessel age (Sharma and Leung 1998), skipper skills/experience (Kirkley and Squires 1998) and judgments by the crew (Weninger and Waters 2003). While some of these factors are almost costless to alter, others may only be altered at significant costs. It may also be relevant to consider the variation in efficiency over time in order to identify any relevant trends, as done in Andersen (2002).

Having identified the relevant reasons for inefficiency in a specific fishery, the next step is to evaluate which of these can be expected to change, and by how much, for each vessel or group of vessels due to the change in management system. Determination hereof may require discussions with technicians, regulators and fishermen in order to settle on the expected improvement level, i.e. individual learning.

2.3 Restrictions on changes in output mix

It is not a straightforward task for a fisherman to decide upon the most profitable output mix. As it was the case with individual learning, several factors may influence his choice of catch composition. Bockstael and Opaluch (1983) mention family traditions, preferences, fishery specific knowledge, skills and uncertainty about net returns for different output mixes. Besides these internal factors, several external factors can also be added. Examples hereof could be weather, refitting possibilities, regulatory and seasonality considerations. The restrictions may therefore not only be related to the vessel, but to individual species as well.

Investigations of vessels flexibility with respect to choice of output mix exist in the literature. For instance, Bjørndal, Koundouri and Pascoe (2003) analyse the UK beam trawlers and otter trawlers. Their findings indicate that flexibility increases with vessel size. Furthermore, the results indicate that the beam and otter trawlers can make some but limited adjustments between their two most important species, which are plaice and sole for the former, and cod and haddock for the latter. Squires and Kirkley (1991) analyse the multispecies Pacific coast trawl fishery and find, as Bjørndal, Koundouri and Pascoe (2003), that the flexibility for vessels to reorganise their output mix is low. Flexibility in the choice of output mix is also investigated by Jensen (2000) were an analysis of the Danish North Sea and Skagerrak pelagic trawl fishery indicates that some flexibility is present between choosing to catch regulated herring or other unregulated species, while no substitution possibilities is likely between regulated mackerel and other unregulated species.

The assumption of unlimited flexibility in the choice of output mix is thus questionable even in a longer time perspective. It is necessary to consider flexibility restrictions in the choice of output mix, when we calculate the tradability gains. This can be done by assuming that the fishermen can change their output mix, but within some boundaries indicating some reasonable proportions between the species caught. We thus have the following:

$$(1+\gamma_m^v)\cdot\frac{CPY_m^{obs\,v}}{\sum_{m=1}^{M} CPY_m^{obs\,v}} \geq \frac{CPY_m^{v}}{\sum_{m=1}^{M} CPY_m^{v}} \geq (1-\eta_m^v)\cdot\frac{CPY_m^{obs\,v}}{\sum_{m=1}^{M} CPY_m^{obs\,v}} \tag{12}$$

where γ and η denote the upper and lower allowed change in output composition of each species caught by vessel v.

The share of each species is thus allowed to vary within an upper and lower bound given as the observed share multiplied with the allowed change. To include these bounds in the industry programming problem given in equation set (9), equation (12) can be reformulated as the following two linear restrictions for each individual vessel in the analysis:

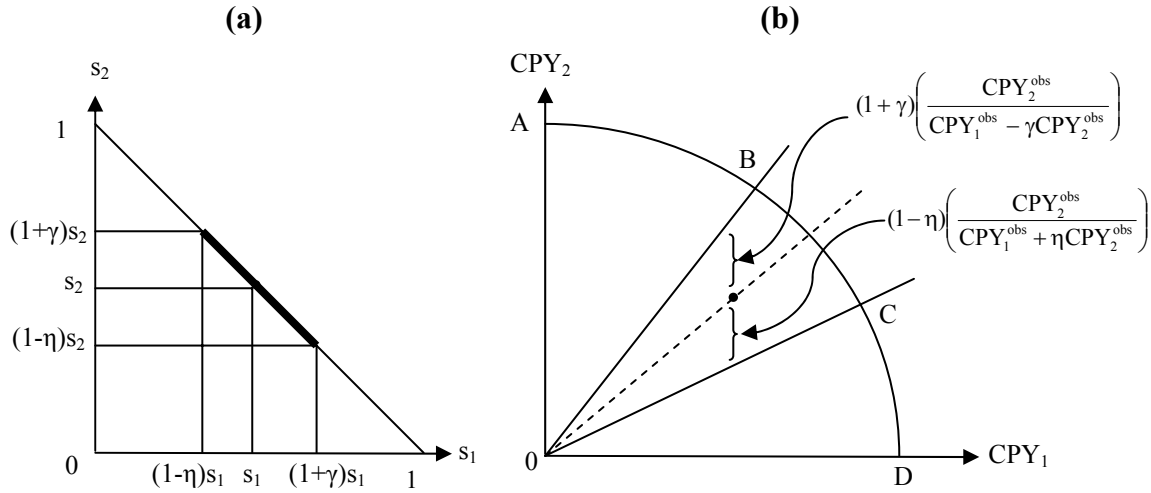
$$(1+\gamma_m^v)\cdot CPY_m^{obs\,v}\cdot\sum_{m=1}^{M}CPY_m^v \geq CPY_m^v\cdot\sum_{m=1}^{M}CPY_m^{obs\,v} \tag{13.e}$$

$$(1-\eta_m^v)\cdot CPY_m^{obs\,v}\cdot\sum_{m=1}^{M}CPY_m^v \leq CPY_m^v\cdot\sum_{m=1}^{M}CPY_m^{obs\,v} \tag{13.f}$$

The intuition behind the inclusion of restrictions on output mix can be graphically illustrated assuming two outputs and for easiness the boundaries to be the same for each species, cf. Figure 2.2. The boundaries can of course vary for each species and vessel, depending on the knowledge about the included vessels and their flexibility.

In Figure 2.2(a), the situation is analysed on a 'per output' level. For simplicity reasons we define the initial share of output 1 as $s_1=CPY_1/(CPY_1+CPY_2)$ and the initial share of output 2 as $s_2=CPY_2/(CPY_1+CPY_2)$ for vessel v. Allowing the shares to vary within the allowed bounds, vessel v can choose to produce at one point on the bold line, on which it is ensured that $s_1+s_2=1$.

Figure 2.2 Restricting change in output composition



The problem becomes more complicated when absolute catches are used to illustrate the situation, cf. Figure 2.2(b). Compared to the previous boundaries (1+γ) and (1-η) used in Figure 2.2(a), it is now necessary to correct these with a factor. However, the boundaries are still linear, because only observed values determine the factor. In the two extreme situations, catches can either be changed proportionally in size or decided freely. In the former, catches must thus be a point on the prespecified ray illustrated by the dotted line in Figure 2.2(b), while catches can be at any point within the area 0ABCD in the latter case. Be restricting the flexibility of choosing the output mix, the vessel can now only alter its output within the area 0BC. The boundaries of this area are determined by the choice of γ and η.

3. The Danish dataset

The Food and Resource Economics Institute has since 1995 published yearly account statistics for Danish fisheries. The publication is based upon information gathered from a representative part of the commercial fishing fleet[4]. In the statistics, the term fishing firm is used instead of fishing vessel, because some of the received information is from fishermen who own more than one vessel. However, considering that the majority of fishermen only have one vessel, we will continue to use the term vessel instead of firm in the following.

From the database, a dataset has been prepared to fulfil the objective of this paper, i.e. to calculate the tradability gains from implementing ITQs in Danish fisheries. The dataset is from 2002, which is the newest available year in the database. With exclusion of all vessels participating in licensed fisheries for blue mussels and common shrimps, the total number of vessels in the dataset is 308[5]. This number of vessels corresponds to approximately 20% of the total commercial fishing fleet in Denmark. The distribution of the 308 vessels with respect to gear type and length category is shown in Table 3.1. It is observed that a wide variety of gear types and lengths are represented in the dataset.

Table 3.1 Number of vessels

	<12m	12-15m	15-18m	18-24m	24-40m	>40m	Total
Beam trawl					4		4
Danish seine		3	6	15			24
Net/line	38	15	10	8			71
Multi-purpose	6	6	2	3	1		18
Purse seine						11	11
Trap	10						10
Trawl	5	33	29	39	50	14	170
Total	59	57	47	65	55	25	308

Note: A multi-purpose vessel is capable of switching between net, Danish seine and trawl.

To extend the gathered information to cover the whole Danish commercial fleet of 1,321 vessels, an enumeration factor (weight) is attached to each of the selected vessels. This factor is found by using a restricted least squares regression model. In the model, a restriction is included to secure that the number of vessels within each length category is equal to the number of vessels in the total population. Furthermore, the deviation from other restrictions such as distribution on homeports, fishermen's age and catch revenues is sought to be minimised. The statistic therefore reflects the commercial fleet with respect to key characteristics in the best possible way, given the included vessels.

The enumeration factor reflects each vessel's importance in the representation of the statistics. For instance, a vessel factor of 10 implies that 10 vessels on average have revenues

[4] A vessel is considered commercial, if it in 2002 had total catch revenue above 219,202 DKK (1 DKK≈ 7.43 €).
[5] In order to facilitate that vessels can lay-up, a fictitious vessel with zero revenues and costs is included in the dataset, bringing the total number of vessels to 309.

and costs like this vessel. For simplicity reasons, we have multiplied the revenues and costs of each selected vessel with the attached weight, instead of including bundles of similar vessels. The revenues and costs of the 308 vessels are thus able to describe the total revenues and costs of the 1,321 vessels in the total commercial Danish fishing fleet.

The average enumeration factor per vessel is displayed in Table 3.2. It is for instance observed that the average factor in the length category below 12 metres is higher compared to those for vessels above 40 metres. This does not however imply that the vessels below 12 metres are more important than the ones above 40 metres. The reason is that each of the small vessels represents a higher number of vessels in the total population compared to the larger vessels. Thus, the selection percentage is generally increasing with size.

Table 3.2 Average enumeration factor per vessel

	<12m	12-15m	15-18m	18-24m	24-40m	>40m
Beam trawl					1.75	
Danish seine		7.33	4.50	3.07		
Net/line	7.24	5.53	4.60	3.88		
Multi-purpose	6.83	6.50	5.00	3.00	4.00	
Purse seine						1.00
Trap	6.40					
Trawl	6.80	5.18	4.07	2.97	2.68	2.36

To obtain sensible results in the forthcoming estimations, it is necessary to reduce the initial number of 45 outputs. Based on the importance of the individual species and the technology used to harvest these, a deduction has therefore made between 9 outputs. These are as follows: 1) cod, 2) other codfish, 3) plaice, 4) other flatfish, 5) herring, 6) mackerel, 7) lobster and shrimp, 8) other consumption species and 9) industrial species. In Table 3.3, the economic importance of the different outputs is depicted.

Table 3.3 Relative catch revenue composition (%)

	Cod	Other codfish	Plaice	Other flatfish	Herring	Mackerel	Lobster and shrimp	Other species	Industrial species	Total catch value (1,000 DKK)
Beam trawl	5	4	66	25	0	0	0	0	0	87,636
Danish seine	35	6	48	11	0	0	0	0	0	190,565
Net/line	57	5	14	18	0	0	1	4	0	408,879
Multi-purpose	37	21	11	12	1	0	15	1	3	149,106
Purse seine	0	0	0	0	38	51	0	1	11	280,111
Trap	38	1	10	14	1	0	1	36	0	40,482
Trawl	10	5	3	5	9	4	19	0	44	2,294,872
Total	18	6	9	7	9	7	14	1	31	3,451,650

Some vessels are very dependent on a single species, while other vessels have a more diversified catch composition. For instance, beam trawlers have a high proportion of plaice, while net/line vessels have a considerable cod dependency. Danish seiners are on the other hand highly dependent upon cod and plaice, while trawlers have industrial species as their

main species with a series of other commercial species giving a significant contribution to the catch revenue.

Vessels obtain different prices for their landings for many reasons, with fish quality being one of the most important, cf. Table 3.4. There are many explanations of why a vessel is able to catch a high quality of fish, including gear type, fishing area and initial processing. Despite the observed variations for all species in price between the gear types, it is especially prominent for the industrial species. The background for this high variation is the fact that for instance netters and trappers only catch small amounts, which most often are used for consumption purposes, thus obtaining a higher price.

Table 3.4 Average prices (DKK/kilo)

	Cod	Other codfish	Plaice	Other flatfish	Herring	Mackerel	Lobster and shrimp	Other species	Industrial species
Beam trawl	19.93	22.02	13.68	34.42	0.00	0.00	18.40	16.54	9.88
Danish seine	18.11	9.92	12.91	11.43	0.00	3.45	24.94	16.41	15.30
Net/line	14.91	10.00	12.26	17.49	1.79	9.56	73.39	22.50	0.90
Multi-purpose	17.46	16.19	12.19	35.37	2.90	7.36	32.32	17.90	6.56
Purse seine	0.00	0.92	0.00	0.00	3.05	7.40	0.00	1.54	0.78
Trap	16.72	19.01	11.67	21.48	1.46	4.29	28.88	20.10	12.03
Trawl	15.15	8.46	12.64	17.50	2.63	6.03	48.96	8.52	1.00
Total	16.31	9.09	12.79	20.63	2.75	6.83	49.40	11.20	0.99

Vessel costs are divided into variable and fixed costs. The variable costs are subdivided into four types. These are: 1) fuel costs, 2) costs for ice and provisions, 3) sales costs[6] and 4) crew payments. Table 3.5 shows the relative distribution of the variable costs for the primary gears, which is the main reason for variation in the relative distribution as opposed to vessel size. Table 3.5 also includes the distribution of fixed costs, which are divided into 1) maintenance costs[7] and 2) other costs[8].

Table 3.5 Distribution of variable and fixed costs (%)

	Variable costs					Fixed costs		
	Fuel	Ice and provisions	Sales	Payment	Total (1,000 DKK)	Mainte-nance	Other costs	Total (1,000 DKK)
Beam trawl	36	1	17	46	56,808	66	34	13,917
Danish seine	7	2	17	73	129,255	62	38	39,867
Net/line	6	2	13	79	322,950	55	45	78,446
Multi-purpose	14	2	12	72	100,102	61	39	28,188
Purse seine	18	1	6	75	111,262	65	35	64,454
Trap	4	2	12	82	31,353	57	43	8,235
Trawl	19	4	15	61	1,325,960	64	36	399,046
Total	16	3	14	66	2,077,691	63	37	632,153

[6] Costs for brokerage and harbour dues, packing, chilling and freight and other unspecified landing costs.
[7] Costs for maintenance of hull, engines, winches, electronic equipment and repair of fishing gears.
[8] Costs for plant and equipment rent, insurance and administration.

Crew payments comprise the largest part of the variable costs, followed by fuel costs, sales costs and costs for ice and provisions. However, several interesting observations can be made. For instance, vessels using beam trawl are the most fuel intensive, while vessels using net/line and trap are the least fuel intensive. Beam trawlers do however have the lowest cost share for ice and provisions, while trawlers have the highest share. Vessels using Danish seine are the ones using the highest proportion of their variable costs for sales purposes, while purse seiners use the lowest. Finally, the highest share of crew payment is observed for the vessels using traps, while vessels using beam trawl have the lowest. With respect to the fixed costs, approximately two-thirds of the fixed costs are for maintenance, while other costs thus make up the rest. This distribution is relatively stable across the gear types.

In Table 3.6, the total revenues, variable and fixed costs are presented. Furthermore, earnings and gross profits are calculated. Earnings are defined as revenue minus variable costs, while gross profits are defined as earnings minus fixed costs. Gross profits thus indicate the amount left to rent, the invested capital and any excess payment to the vessel owners.

Table 3.6 Key economic total values in 2002 (1,000 DKK)

	Catch revenues	Variable costs	Earnings	Fixed costs	Gross profits
Beam trawl	87,636	56,808	30,828	13,917	16,911
Danish seine	190,565	129,255	61,310	39,867	21,444
Net/line	408,879	322,950	85,929	78,446	7,483
Multi-purpose	149,106	100,102	49,003	28,188	20,815
Purse seine	280,111	111,262	168,849	64,454	104,394
Trap	40,482	31,353	9,129	8,235	894
Trawl	2,294,872	1,325,960	968,911	399,046	569,865
Total	3,451,650	2,077,691	1,373,960	632,153	741,807

It is apparent from Table 3.6 that the trawlers give rise to the main part of the total earnings in the Danish fishing fleet. Over 75% of the total gross profits come from these vessels. These initial values will in the following be compared with the estimated values of the different models in order to evaluate the consequences of implementing an ITQ system.

4. Tradability gains from implementing an ITQ system in Danish fisheries

To illustrate the sensitivity of the estimated tradability gains with respect to restricting best-practice, individual learning and choice of output mix described previously, we apply the dataset presented in Section 3, thus assuming prices to vary between the gear types. The obtained results will thus indicate the expected range of gains had the Danish fisheries been regulated using an ITQ system in the Danish fishery in 2002.

This section will proceed in four steps. First, the consequences of restricting the best-practice frontier for the individual vessels will be analysed. Based on this, we will proceed with

separate investigations of restricting individual learning and changes in output mix. Finally, a comparison is made between different flexibility regimes.

In order to investigate the consequences of restricting the individual vessel's best-practice frontier, it is necessary to set up the comparison vector. For simplicity, we only analyse the situations where all vessels can be compared and where only vessels using the same gear type can be compared. The output-oriented level of technical efficiency assuming variable returns to scale in each of the two situations can be estimated using a traditional technical efficiency program, cf. Färe, Grosskopf and Lovell (1994). Descriptive statistics for the estimated levels distributed on gear types is displayed in Table 4.1.

Table 4.1 Estimated level of technical efficiency

	Best-practice:	Beam trawl	Danish seine	Multi-purpose	Net/line	Purse seine	Trap	Trawl	Total
Average	Unrestricted	1.00	1.09	1.36	1.32	1.01	1.20	1.30	1.28
	Restricted	1.00	1.02	1.11	1.00	1.00	1.00	1.19	1.13
Standard deviation	Unrestricted	0.00	0.15	0.46	0.46	0.02	0.28	0.50	0.46
	Restricted	0.00	0.07	0.26	0.00	0.00	0.00	0.39	0.32
Maximum	Unrestricted	1.00	1.61	3.01	2.77	1.08	1.81	3.56	3.56
	Restricted	1.00	1.25	2.07	1.00	1.00	1.00	3.32	3.32

When we only allow vessels using similar gear types to be compared, the average level of technical inefficiency is reduced as expected. The improvement in technical efficiency indicates that output can only be expanded by 13% on average, in contrast to 28% in the unrestricted case.

Including the new estimations of technical efficiency in the industry programming problems, it becomes possible to evaluate the economic consequences of restricting the determination of the best-practice frontier. For the two extreme assumptions about individual learning and changing output mix, Table 4.2 displays the effect on revenues, costs, earnings and gross profits.

Table 4.2 Impact of restricting best-practice frontier determination (1,000 DKK)

		2002-level	Technical efficiency and output mix fixed	Technical efficiency unrestricted, output mix fixed	Technical efficiency fixed, output mix unrestricted	Technical efficiency and output mix unrestricted
Best-practice unrestricted	Revenue	3,451,650	3,451,406	3,475,931	11,439,348	12,315,054
	Variable cost	2,077,691	1,672,854	1,485,976	1,561,004	1,485,411
	Earnings	1,373,960	1,778,552	1,989,955	9,878,344	10,829,643
	Gross profits	741,807	1,146,399	1,357,802	9,246,191	10,197,490
	Change (%)		54.54	83.04	1,146.44	1,274.68
Best-practice restricted	Revenue	3,451,650	3,366,479	3,422,133	3,467,546	3,483,018
	Variable cost	2,077,691	1,709,798	1,637,619	1,439,973	1,428,406
	Earnings	1,373,960	1,656,681	1,784,513	2,027,573	2,054,613
	Gross profits	741,807	1,024,528	1,152,360	1,395,420	1,422,460
	Change (%)		38.11	55.35	88.11	91.76

Looking at the models with best-practice as well as choice of output mix determined without any restrictions, we observe a very high increase in gross profit. From Table 4.2, it can be seen that the increase mainly comes from a rise in revenue. The primary reason is that the catch of industrial species in these models is allocated towards vessels obtaining high prices, e.g. Danish seiners and trappers. In reality, these reallocations are unlikely, because the high price for industrial species cannot be obtained for all catches, as discussed in the previous section.

If the determination of best-practice is restricted, but the output mix can be chosen freely, the reallocation of catches decreases significantly. Danish seiners can in this situation not be compared to trawlers and are thus restricted from obtaining the same catch/cost profile as these vessels. Such vessels can therefore not have a high share of industrial species in their catch and obtain the higher price. Despite this, gross profits are still above the level in 2002, and under the most flexible assumption about vessel behaviour, gains of 90% in gross profits are expected to be derived.

Comparison of the gross profits under assumption of unrestricted and restricted determination of best-practice is thus hampered when choice of output mix is unrestricted. However, a reduction is as expected observed in the models with the output mix fixed. The reduction is attributed to the lack of flexibility for the vessel's choice of catch/cost profile, thus resulting in lower revenues and higher costs in the restricted models. Had the output prices been assumed equal across vessel types, the tradability gains obtained with unrestricted output mix would have been almost unchanged in the models with different assumptions about the determination of best-practice.

Despite comparison problems, gross profits are influenced by restricting the determination of best-practice frontier. The next step is to evaluate the consequences of allowing individual learning, but not to the level where 100% technical efficiency is obtained. We illustrate this by decreasing inefficiency by 25%, 50% and 75% respectively[9]. When solving the reallocation problems, we assume that best-practice is determined on the basis of only similar production technologies. The consequences on revenues, variable costs, earnings and gross profits are displayed in Table 4.3.

[9] Technical efficiency is thus calculated as $F^v(\alpha=0.25) = (1-0.25)\cdot F^{obs\ v}$, $F^v(\alpha=0.50)=(1-0.50)\cdot F^v(\alpha=0.25)$ and $F^v(\alpha=0.75)=(1-0.75)\cdot F^v(\alpha=0.50)$. Thus, if α equals one, all vessels become fully efficient.

Table 4.3 Restricting improvement in technical efficiency (1,000 DKK)

			Assumption about technical efficiency				
		2002-level	Fixed	Improved by 25%	Improved by 50%	Improved by 75%	Unrestricted
Output mix fixed	Revenue	3,451,650	3,366,479	3,370,580	3,376,515	3,389,345	3,422,133
	Variable cost	2,077,691	1,709,798	1,689,079	1,669,156	1,649,834	1,637,619
	Earnings	1,373,960	1,656,681	1,681,501	1,707,359	1,739,511	1,784,513
	Gross profits	741,807	1,024,528	1,049,348	1,075,206	1,107,358	1,152,360
	Change (%)		38.11	41.46	44.94	49.28	55.35
Output mix unrestricted	Revenue	3,451,650	3,467,546	3,472,511	3,476,534	3,477,887	3,483,018
	Variable cost	2,077,691	1,439,973	1,439,481	1,437,473	1,432,467	1,428,406
	Earnings	1,373,960	2,027,573	2,033,029	2,039,062	2,045,420	2,054,613
	Gross profits	741,807	1,395,420	1,400,876	1,406,909	1,413,267	1,422,460
	Change (%)		88.11	88.85	89.66	90.52	91.76

Imposing restrictions upon individual learning does as expected result in levels of gross profits that range between the technical efficiency fixed and unrestricted cases. With output mix restricted, catches are allocated towards vessels with lower catch revenues, but also having lower costs. If output mix is unrestricted, catches are allocated towards vessels with higher catch revenues, but at the same time having lower cost. However, it can generally be concluded that the gains primarily originate from allocating catches towards vessels with lower cost.

As expected, the tradability gains rise with increasing levels of technical efficiency. With the output mix fixed, we observe that reallocation alone will result in increased gross profits of 38.11% compared to the 2002-level, rising to a total increase of 55.35% with all vessels being technical efficient. Allowing output mix to be determined without restrictions implies that the initial gross profits increase by 88%, but only rising by 92% in the fully technical efficient situation. Thus, the highest impact on gross profit from improved efficiency is observed with output mix fixed, but the highest level of gross profit is observed with output mix unrestricted.

Looking at the different levels of improvement, we observe "marginally increasing gross profits", i.e. the higher the technical efficiency level, the larger marginal increase in gross profits. This can be attributed to the fact that as inefficiency decreases, the catch/cost profile of the previously inefficient vessels becomes relevant with respect to allocation of catches, thus resulting in increased gross profits.

In the previous models, the flexibility with respect to output mix was observed to be of significant importance. Imposing restrictions upon the output mix is therefore most likely going to have a considerable impact on gross profits. To illustrate this, we have imposed boundaries of ±25%, ±50% and ±75% for changes in the output composition for each vessel. Solving the reallocation problem, we obtain the revenues, variable costs, earnings and gross profits shown in Table 4.4.

Table 4.4 Restrictions on changes in output composition (1,000 DKK)

			Assumption about output mix				
		2002-level	Fixed	Changeable by ±25%	Changeable by ±50%	Changeable by ±75%	Unrestricted
Technical efficiency fixed	Revenue	3,451,650	3,366,479	3,380,669	3,352,103	3,345,136	3,467,546
	Variable cost	2,077,691	1,709,798	1,636,445	1,551,495	1,508,017	1,439,973
	Earnings	1,373,960	1,656,681	1,744,224	1,800,608	1,837,119	2,027,573
	Gross profits	741,807	1,024,528	1,112,071	1,168,455	1,204,966	1,395,420
	Change (%)		38.11	49.91	57.51	62.44	88.11
Technical efficiency unrestricted	Revenue	3,451,650	3,422,133	3,395,408	3,393,338	3,388,755	3,483,018
	Variable cost	2,077,691	1,637,619	1,548,156	1,504,873	1,468,771	1,428,406
	Earnings	1,373,960	1,784,513	1,847,252	1,888,466	1,919,984	2,054,613
	Gross profits	741,807	1,152,360	1,215,099	1,256,313	1,287,831	1,422,460
	Change (%)		55.35	63.80	69.36	73.61	91.76

We observe that increasing flexibility with respect to choice of output composition results in rising gross profits. However, it is interesting to observe that the gains are primarily obtained when allowing the first and the last 25% increments of output flexibility. When the output flexibility is between 25% and 75%, it does result in higher gross profits, but the marginal increase is not as high as for the first and last 25%. Except for the situation with unrestricted output mix, the increase in gross profits comes from reduced variable costs and not increased catch revenues.

In the previous tables, only the total figures have been presented. However, these figures do not reflect the consequences for the different groups of gear types. We have therefore included Table 4.5, which shows the change in gross profits for each of the seven gear types in the analysed models.

Table 4.5 Change in gross profits compared to 2002-level (1,000 DKK)

Assumption about: Technical efficiency	Output mix	Beam trawl	Danish seine	Multi-purpose	Net/line	Purse seine	Trap	Trawl
Fixed	Fixed	0	3,132	4,253	62,887	2,537	3,404	206,510
Unrestricted	Fixed	0	7,615	1,321	89,157	2,280	3,325	306,857
Fixed	Unrestricted	1,996	3,984	23,091	149,437	-15,810	13,298	477,618
Unrestricted	Unrestricted	1,996	12,585	25,302	181,637	-31,342	13,298	477,178
Improved 25%	Fixed	0	4,068	4,253	66,810	2,421	3,404	226,587
Improved 50%	Fixed	0	5,044	2,276	71,941	2,482	3,404	248,254
Improved 75%	Fixed	0	6,320	2,276	78,942	2,420	3,404	272,192
Fixed	Changeable ±25%	1,069	6,806	7,518	81,860	6,193	4,021	262,799
Fixed	Changeable ±50%	1,544	7,384	8,389	96,244	9,774	4,358	298,957
Fixed	Changeable ±75%	1,766	7,327	11,105	109,345	9,821	4,932	318,865
Unrestricted	Changeable ±25%	1,046	9,217	-4,923	107,236	3,908	3,532	353,276
Unrestricted	Changeable ±50%	1,544	8,601	1,814	123,740	6,875	4,154	367,779
Unrestricted	Changeable ±75%	1,766	6,683	5,649	137,904	7,135	4,646	382,243
Improved 25%	Unrestricted	1,996	6,947	23,279	155,025	-15,810	13,298	474,335
Improved 50%	Unrestricted	1,996	8,422	23,334	160,926	-30,950	13,298	488,076
Improved 75%	Unrestricted	1,996	10,001	23,092	168,756	-31,342	13,298	485,659

Based on Table 4.5, the conclusion must be that all groups of gear types generally obtain increased gross profits compared to the 2002-level with some exceptions. For instance, when the output mix is fixed, the beam trawlers do not get higher gross profits, while the purse seiners obtain lower gross profits with an unrestricted choice of output mix.

It can also be observed from Table 4.5 that some gear types obtain a lower gross profit in a model with high flexibility compared to a model with low flexibility. The reason for this is the overall catch restriction for each of the included species limiting the total amount of catches taken. Thus, allocating catches to one gear type will necessarily imply that other gear types cannot take these.

Based on data covering Danish fisheries in 2002 we have thus applied the theoretical framework previously discussed under different assumptions of flexibility for the individual vessels. We have calculated the possible gains to be derived if Danish fisheries had been managed by ITQs in 2002. We have shown how the size of the tradability gains is influenced by the flexibilities and that almost all gear types earn higher profits. However, because of the included overall catch restriction, some gear types earn a lower gross profit compared to the 2002-level. It is also a general observation that the increases in gross profits are primarily driven by allocating catches towards vessels with lower costs and not vessels (gear types) obtaining higher prices.

5. Policy implications

In the previous section, we focused on the industry wide economic impacts of ITQs. However, when analysing the consequences of ITQs, a series of other effects are also relevant. Through time, discussions about ITQ systems have also included topics such as concentration, specialisation, market activity and price levels. These topics will be considered in this section. Furthermore, we will consider how to analyse the consequences of exogenous chocks and management changes. In order to limit the size of the included tables, we only analyse these topics under the extreme assumptions about the vessel's behavioural flexibility.

5.1 Concentration and specialisation

The accumulation of ITQs among fewer vessels is from a strict economic point of view not problematic, because marginal fishermen will sell the quota to more profitable fishermen, resulting in higher rent of the invested capital. However, there may still be reasons for evaluating the intensity of accumulation. One reason is that it can result in vessels obtaining market power, making them able to hamper the flexibility of the market, cf. Anderson (1991). Another is from a socio-economic point of view that small communities can become deprived of their primary source of income.

In order to approach the topic of accumulation, a distinction can be made between horizontal and vertical accumulation. The former, which we call concentration, refers to a situation where ITQs are distributed among fewer and larger vessels in certain regions. The latter refers on the other hand to a situation where ITQs are distributed among certain gear types. This type of accumulation we call specialisation.

The dataset does not allow us to investigate regional concentration. Nevertheless, larger vessels must locate themselves in larger ports to have sufficient water depths. Looking at the number of active vessels in the different length groups, we therefore get some indication about this possible development. The number of active vessels, i.e. vessels with quota, is presented in Table 5.1 for the different models.

Table 5.1 Distribution of active vessels on length groups

Assumption about: Technical efficiency	Output mix	<12m	12-15m	15-18m	18-24m	24-40m	>40m	Total
2002-level		414	315	201	202	145	44	1,321
Fixed	Fixed	377	274	201	200	145	44	1,242
Unrestricted	Fixed	365	287	201	199	145	44	1,242
Fixed	Unrestricted	400	234	159	178	138	44	1,153
Unrestricted	Unrestricted	389	289	196	198	132	41	1,245

Table 5.1 indicates some tendencies towards higher concentration. The total number of vessels is generally reduced by between 6% and 14%, and this reduction is primarily found for vessels below 15 metres. Due to the short time horizon used in the analysis, no increase in the number of vessels is observed. However, had the analysis been for a long time horizon, the possibility to build new vessels, and thus to change the fleet structure more significantly, could have been facilitated.

A distinction can be made between two types of specialisation. One is specialisation towards certain gear types and another is specialisation towards certain species.

Specialisation towards gear types is analysed in Table 5.2, where the number of active vessels is distributed among the different gear types. It is observed that no changes in the number of beam trawlers, Danish seiners and purse seiners are expected following implementation of an ITQ system. The number of vessels using the remaining gear types varies, depending on the assumptions made about individual learning and change in output mix.

Table 5.2 Distribution of active vessels on gear type groups

Assumption about: Technical efficiency	Output mix	Beam trawl	Danish seine	Multi-purpose	Net/line	Purse seine	Trap	Trawl
2002- level		7	95	103	435	11	64	606
Fixed	Fixed	7	95	77	417	11	43	592
Unrestricted	Fixed	7	95	75	407	11	43	603
Fixed	Unrestricted	7	89	103	430	11	64	449
Unrestricted	Unrestricted	7	95	103	435	11	64	530

Specialisation towards certain species is analysed in Table 5.3. Of course this requires that the output mix is allowed to change. The distribution of catch weights on the different species for the given gear types are provided.

Table 5.3 Output composition, catch weight (%)

	Assumption about: Technical efficiency	Choice of output mix	Cod	Other codfish	Plaice	Other flatfish	Her-ring	Mac-kerel	Lobster and shrimp	Other species	Indu-strial species
Beam trawl	2002-level		4	3	80	12	0	0	0	0	0
	Fixed	Unrestricted	3	3	80	14	0	0	0	0	0
	Unrestricted	Unrestricted	3	3	80	14	0	0	0	0	0
Danish seine	2002-level		27	8	52	13	0	0	0	0	0
	Fixed	Unrestricted	10	15	70	5	0	0	0	0	0
	Unrestricted	Unrestricted	10	15	70	5	0	0	0	0	0
Multi-purpose	2002-level		26	21	9	7	4	0	2	1	30
	Fixed	Unrestricted	11	76	6	6	0	0	0	0	0
	Unrestricted	Unrestricted	14	71	6	6	0	0	0	2	0
Net/line	2002-level		58	6	20	9	2	0	1	4	0
	Fixed	Unrestricted	65	0	23	12	0	0	0	0	0
	Unrestricted	Unrestricted	66	0	22	11	0	0	0	0	0
Purse seine	2002-level		0	1	0	0	37	20	0	1	41
	Fixed	Unrestricted	0	0	0	0	47	32	0	0	22
	Unrestricted	Unrestricted	0	0	0	0	47	39	0	0	15
Trap	2002-level		36	1	14	10	10	0	0	29	0
	Fixed	Unrestricted	31	0	1	8	0	0	0	61	0
	Unrestricted	Unrestricted	31	0	1	8	0	0	0	61	0
Trawl	2002-level		1	1	1	1	7	1	1	0	88
	Fixed	Unrestricted	2	1	0	1	7	1	1	0	88
	Unrestricted	Unrestricted	1	1	0	1	7	1	1	0	88

No significant changes are observed for the beam trawlers' output composition. Plaice is still the most important species. The Danish seiners specialise towards having a larger proportion of their catch weight being made up of plaice and other codfish, instead of cod and other flatfish. The flexible multi-purpose vessels also specialise significantly towards catching other codfish in place of all other species. The netters and liners seem not to specialise significantly, while the purse seiners focus more intensively on the pelagic consumption species, i.e. herring and mackerel, while reducing their dependency on industrial species. Instead of catching flatfish and herring, trappers are expected to increase their proportion of other species, while still catching a high proportion of cod. The trawlers on the other hand are not expected to specialise in an ITQ system.

To conclude, we find that had the Danish fisheries been regulated with an ITQ system in 2002, the larger vessels would make up a higher proportion of the active vessels, thus indicating tendencies towards concentration. With respect to specialisation, we observe that the preferred gear types depend on the flexibility assumptions. However, when analysing within each gear type, we find significant specialisation tendencies. Only beam trawlers and trawlers do not seem to specialise.

Should the regulatory authority find these effects undesirable, they can take measures against accumulation of ITQs. Possibilities are for instance the setting of a maximum amount of quota a vessel can own, or a minimum level that must be owned by vessels in specific harbours. By including these extra restrictions in the programming problem, regulators can get an impression of the economic losses such restrictions will give, enabling them to evaluate whether these are acceptable or not.

5.2 Market activity

High activity on the quota market is seen as important for the success of an ITQ system. The reasons are among others that 1) high activity indicates that gains are being derived and 2) high activity secures that "true" prices are obtained. In order to have a well functioning market, it is necessary for the regulators to set up the facilities for making low cost transactions. These facilities could for instance include: 1) low transaction costs, 2) a central market, where all trades take place[10], 3) security about ownership and length hereof for the ITQs, 4) setting up an independent board to deal with changes[11] and 5) type of actors and instruments allowed on the market[12].

Table 5.4 displays the traded amounts, including who are buyers and sellers. Looking firstly at the traded shares, we observe, not surprisingly, that when the output mix is restricted to the composition in 2002, the traded amounts are minor, and in some of the models there is more quota for sale than demanded on the market, resulting in unused quota. However, when the output mix can be chosen without restrictions, the traded amounts rise considerably, especially for cod, other codfish, herring and other species.

[10] Using a central market instead of a decentralised market makes it easier for the fishermen to find each other, thus reducing transaction costs. Furthermore the regulator has complete information about who owns what and how much.

[11] An independent board is necessary to avoid any doubts about changes in the total quotas, which may give rise to asymmetric information between the fishermen. Such asymmetric information will result in a non-optimal distribution of the ITQs.

[12] Besides fishermen, other actors can also be allowed to operate on the ITQ market. Non-governmental organisations and middlemen are common examples. Allowing the former can be problematic, because these are not necessarily willing to sell the ITQs at the market price, while the former can be beneficial, because they help fuel the market, reducing transaction costs. Different types of instruments such as futures, options, leasing and banking of ITQs can also be allowed on the market in order to increase the flexibility and reduce risk.

Table 5.4 Amount of quota bought and sold (tonnes)

	Assumption about: Technical efficiency	Choice of output mix	Beam trawl	Danish seine	Multi-purpose	Net/ line	Purse seine	Trap	Trawl	Unused	Traded share (%)
Cod	Fixed	Fixed	0	-115	-108	-1,612	0	-417	-113	-2,365	7
	Unrestricted	Fixed	0	29	-185	-242	0	-541	940	0	3
	Fixed	Unrestricted	-76	-2,336	-1,967	104	0	-152	4,427	0	12
	Unrestricted	Unrestricted	-76	-2,178	-1,440	1,817	0	-152	2,029	0	10
Other codfish	Fixed	Fixed	0	-19	-5	-176	0	-13	-1,647	-1,860	10
	Unrestricted	Fixed	0	0	-18	-133	0	-13	-2,330	-2,496	13
	Fixed	Unrestricted	-37	1,036	8,962	-1,342	-783	-14	-7,823	0	47
	Unrestricted	Unrestricted	-37	1,290	8,146	-1,340	-783	-14	-7,262	0	44
Plaice	Fixed	Fixed	0	58	-332	-621	0	-78	-41	-1,014	5
	Unrestricted	Fixed	0	174	-450	-437	0	-78	525	-265	4
	Fixed	Unrestricted	-441	2,638	-248	147	0	-327	-1,770	0	12
	Unrestricted	Unrestricted	-441	3,795	-313	456	0	-327	-3,170	0	18
Other flatfish	Fixed	Fixed	0	-35	-177	-252	0	-15	-132	-611	5
	Unrestricted	Fixed	0	-6	-229	-69	0	-18	322	0	3
	Fixed	Unrestricted	11	-1,092	-51	328	0	-75	879	0	10
	Unrestricted	Unrestricted	11	-1,009	-55	449	0	-75	679	0	9
Herring	Fixed	Fixed	0	0	-28	0	14	0	13	0	0
	Unrestricted	Fixed	0	0	-28	0	-58	0	85	0	0
	Fixed	Unrestricted	0	0	-558	-490	-6,088	-245	7,380	0	7
	Unrestricted	Unrestricted	0	0	-558	-490	-11,518	-245	12,811	0	11
Mac-kerel	Fixed	Fixed	0	0	0	0	28	0	-28	0	0
	Unrestricted	Fixed	0	0	0	0	-14	0	14	0	0
	Fixed	Unrestricted	0	3	0	-2	131	-10	-120	0	0
	Unrestricted	Unrestricted	0	2	0	-2	-125	-10	136	0	0
Lobster and shrimp	Fixed	Fixed	0	0	-32	-62	0	-7	100	0	1
	Unrestricted	Fixed	0	0	-112	-68	0	-7	187	0	2
	Fixed	Unrestricted	0	-2	-294	-180	0	-8	484	0	5
	Unrestricted	Unrestricted	0	-2	-294	-180	0	-8	484	0	5
Other species	Fixed	Fixed	0	1	-15	-8	0	53	-124	-93	4
	Unrestricted	Fixed	0	1	-16	20	0	48	-147	-95	4
	Fixed	Unrestricted	-3	1	-14	-840	-1,082	799	101	-1,038	70
	Unrestricted	Unrestricted	-3	4	222	-840	-1,082	799	822	-78	52
Indu-strial species	Fixed	Fixed	0	1	0	-1	-9	0	8	0	0
	Unrestricted	Fixed	0	2	0	0	-48	0	46	0	0
	Fixed	Unrestricted	0	-50	-4,341	-6	-25,491	0	29,888	0	3
	Unrestricted	Unrestricted	0	-50	-4,339	-6	-31,504	0	35,900	0	3

Looking at the models with unrestricted choice of output mix, we observe for cod that the most important actors on the market are trawlers buying quota from especially Danish seiners and multi-purpose vessels. The multi-purpose vessels and Danish Seiners do on the other hand buy quota for other codfish from trawlers and to some extent netters/liners. Danish seiners furthermore buy plaice from primarily trawlers, who in return buy other flatfish from them. Herring is primarily traded between purse seiners and trawlers, while only minor transactions of mackerel also take place between these two segments. Lobster and shrimp are bought by trawlers from multi-purpose vessels and netters/liners. Trappers buy significant amounts of quota for other species, but their buying does not correspond to the supply, thus resulting in unused quota. Industrial species are solely bought by trawlers, primarily from purse seiners.

5.3 Price levels

Having described the expected trade patterns on the market, the next step is to estimate the prices prevailing for the different species. Shadow prices are suitable for such analysis. These show the increase in earnings, if one extra unit of quota for each species were allowed for one year, i.e. the marginal willingness to pay. Table 5.5 gives the shadow prices for each of the included species assuming different levels of flexibility. In the situation with unused quota for sale on the market, cf. Table 5.4, the imposed catch restriction does not become limiting, and the shadow prices are in these cases therefore zero[13].

Table 5.5 Shadow prices for individual species (DKK/kilo)

Assumption about: Technical efficiency	Choice of output mix	Cod	Other codfish	Plaice	Other flatfish	Herring	Mac-kerel	Lobster and shrimp	Other species	Indu-strial species
Fixed	Fixed	0.00	0.00	0.00	0.00	1.09	3.55	18.61	0.00	0.42
Unrestricted	Fixed	0.59	0.00	0.00	1.51	1.16	3.73	40.14	0.00	0.48
Fixed	Unrestricted	8.58	2.52	1.63	10.49	2.16	3.07	40.12	0.00	0.46
Unrestricted	Unrestricted	9.64	3.15	3.76	10.17	2.22	3.35	41.58	0.00	0.51

From Table 5.5 it is observed that the shadow price varies significantly with the flexibility assumptions. Take for instance cod, an important species in Danish fisheries. With fixed levels of technical efficiency and output mix, there will be some unused quota. However, allowing all vessels to become technically efficient will result in the price of an extra kilo of cod quota to be 0.59 DKK, which is very low compared to a sales price of an average 16.31 DKK, cf. Table 3.4. In this model, the vessels with an interest in buying extra cod have high costs of catching an extra unit, which therefore reduces their willingness to pay for such an extra unit. In the situation with free choice of output mix within the given technology, it becomes possible for the low cost vessels to catch an extra unit of cod, which therefore results in a significant increase in the shadow price to around 9 DKK.

An obvious question is whether these prices are realistic. Currently, the Danish herring fishery is, as the only one in Denmark, regulated by ITQs. The system is installed for a test period of five years from 2003 to 2008, and the price in 2003 for a kilo of herring is around 7 DKK. Because the price given in Table 5.5 is the shadow price for a one year permit to catch an extra kilo, we can calculate the price for a five year permit using an 8% discount rate to be between 4.35 DKK and 8.86 DKK, depending on the flexibility assumptions. The estimated shadow prices do therefore not seem unrealistic, when comparing with the current prices[14].

[13] For some species there are buyers and sellers, but still also some unused quota, cf. 'other species' in Table 5.4. These trades will take place at a zero price, but information about the marginal profits for the buying vessels can be obtained by for instance including an extra restriction in the programming problem. This restriction limits the allowed total catch of 'other species' to be marginally below the level wanted by the buying gear type groups. However, this will not be investigated any further here.

[14] Ideally, we would have to compare the market price of a kilo of herring quota to the shadow price calculated in a system where only herring quotas are tradable.

Shadow prices can be used for many purposes by the regulatory authority. When discussing quota trades with for example other nations, they indicate which species should be bought and sold and at which proportions. For instance, in the situation with unrestricted individual learning and choice of output mix, the most valuable quota is lobster and shrimp. Thus, assume that Denmark wants to buy some quota of these species from the United Kingdom. The Danish negotiators should then at most be willing to trade with 4.3 kilo of cod (41.58/9.64), 11.1 kilo of plaice (41.58/3.76) or 81.5 kilo of industrial species (41.58/0.51), cf. Table 5.5.

5.4 Exogenous chocks

The regulatory authority can also analyse the consequences of different exogenous shocks on the economic gains, prices of the ITQs, etc. Several types of exogenous chocks can be relevant to consider, and this is relatively straightforward to do in the proposed framework. The method to apply is comparable to the two-step procedure used in Section 2.2. First, the new values are determined for the parameters expected to be influenced by the exogenous chock, and then the programming problems are solved again.

For illustrative purposes, we will focus on two likely examples. In the first example, we assume that the global price of cod increases by 10% for all gear types. Including a new price matrix in the programming problem and solving this, the key economic indicators become as shown in Table 5.6 together with the shadow prices in Table 5.7.

Table 5.6 Consequences of a 10% price increase for cod (1,000 DKK)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-price	Cod price +10%	2002-price	Cod price +10%	2002-price	Cod price +10%	2002-price	Cod price +10%
Revenue	3,366,479	3,434,832	3,422,133	3,481,926	3,467,546	3,531,846	3,483,018	3,543,716
Cost	1,709,798	1,749,168	1,637,619	1,663,367	1,439,973	1,464,830	1,428,406	1,450,437
Earnings	1,656,681	1,685,664	1,784,513	1,818,559	2,027,573	2,067,017	2,054,613	2,093,279
Gross profits	1,024,528	1,053,512	1,152,360	1,186,406	1,395,420	1,434,864	1,422,460	1,461,126

As expected the total revenues will increase following the 10% increase in cod price. However, the total costs will also increase, because the increased cod price makes it profitable to reallocate catches of cod towards vessels which have higher costs. As expected, it is primarily vessels with a high proportion of cod in their catches, which realise an increase in their gross profits, i.e. vessels using Danish seine, net/line or multi-purpose gear.

Turning attention to the shadow prices in Table 5.7, a considerable increase is observed for the one related to cod. However, for most of the other species, the shadow prices are expected to decrease. The reason is that the reallocations following the 10% increase in cod price result

in some catches of other species being allocated towards vessels with lower profitability for these species. This is however profitable, because these vessels are able to offset this by increased profits from the cod catches.

Table 5.7 Shadow prices following a 10% price increase for cod (1,000 DKK)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-price	Cod price +10%	2002-price	Cod price +10%	2002-price	Cod price +10%	2002-price	Cod price +10%
Cod	0.00	0.00	0.59	2.17	8.58	10.15	9.64	11.16
Other codfish	0.00	0.00	0.00	0.00	2.52	2.67	3.15	3.18
Plaice	0.00	0.00	0.00	0.00	1.63	1.36	3.76	3.46
Other flatfish	0.00	0.00	1.51	0.00	10.49	10.28	10.17	9.91
Herring	1.09	1.07	1.16	1.24	2.16	2.18	2.22	2.24
Mackerel	3.55	3.68	3.73	3.50	3.07	2.92	3.35	3.28
Lobster and shrimp	18.61	19.13	40.14	39.95	40.12	39.96	41.58	41.34
Other species	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Industrial species	0.42	0.41	0.48	0.46	0.46	0.45	0.51	0.50

In the second example, we assume that the fuel price increases by 10% due to some exogenous events. Thus, the values in the vector containing fuel costs are increased by 10%. After solving the new programming problems, we get the results presented in Table 5.8. Because a fuel cost increase influences all vessels equally, it will only lead to minor reductions in catch revenue. The total cost will on the other hand be increased, and logically this increase will be relatively larger for vessels using gear types that are fuel intensive, such as beam trawlers and trawlers.

Table 5.8 Consequences of a 10% price increase on fuel (1,000 DKK)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-price	Fuel price +10%	2002-price	Fuel price +10%	2002-price	Fuel price +10%	2002-price	Fuel price +10%
Revenue	3,366,479	3,364,119	3,422,133	3,422,055	3,467,546	3,466,983	3,483,018	3,483,017
Cost	1,709,798	1,735,703	1,637,619	1,664,334	1,439,973	1,463,288	1,428,406	1,450,438
Earnings	1,656,681	1,628,417	1,784,513	1,757,720	2,027,573	2,003,695	2,054,613	2,032,580
Gross profits	1,024,528	996,264	1,152,360	1,125,567	1,395,420	1,371,542	1,422,460	1,400,427

The influence on the shadow prices following a 10% price increase in fuel costs is more complex. The general trend is a decrease in shadow prices, but increases are observed for some species, especially herring, when comparing with unchanged fuel prices, cf. Table 5.9. To explain the increased shadow price for herring, we take the model assuming that technical efficiency is unrestricted and output mix is fixed as an example. The reallocation of herring catches is solely from purse seiners to trawlers. The increase in fuel costs influences, on average, purse seiners more than trawlers. Despite trawlers obtaining a lower price for

herring, the result is that profitability for catching one kilo of herring becomes higher for trawlers compared to purse seiners.

Table 5.9 Shadow prices following a 10% price increase on fuel (1,000 DKK)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-price	Fuel price +10%	2002-price	Fuel price +10%	2002-price	Fuel price +10%	2002-price	Fuel price +10%
Cod	0.00	0.00	0.59	0.55	8.58	8.38	9.64	9.64
Other codfish	0.00	0.00	0.00	0.00	2.52	2.48	3.15	3.14
Plaice	0.00	0.00	0.00	0.00	1.63	1.62	3.76	3.82
Other flatfish	0.00	0.00	1.51	0.28	10.49	10.41	10.17	9.77
Herring	1.09	1.03	1.16	1.24	2.16	2.17	2.22	2.24
Mackerel	3.55	3.75	3.73	3.50	3.07	2.91	3.35	3.28
Lobster and shrimp	18.61	17.42	40.14	39.96	40.12	39.82	41.58	41.34
Other species	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Industrial species	0.42	0.41	0.48	0.46	0.46	0.45	0.51	0.50

Other types of exogenous chocks can also be relevant to evaluate before one implements a system of ITQs. An obvious example within fisheries is changes in stock sizes. The stock level of the different species is influenced by many factors besides the actual fishing activity, including weather conditions, migrations, pollution, etc.

Accounting for changes in stocks have traditionally been troublesome, because of lacking knowledge about the size of these, and how they influence the fishermen's catch rates. In the presented framework, a short run time horizon has been assumed, thus excluding the possibility of such changes. Allowing for changes in stock sizes will necessarily influence a lot of the parameters in the model. If the stock size of e.g. plaice increases, vessels catching this species will obtain a higher catch with the same effort (costs). The total allowable catch will likely be increased, which furthermore will influence the prices of plaice in a downward direction, depending on the global demand situation. It is also likely that other vessels will start to catch plaice, increasing competition for the plaice quota. Changes in stocks may therefore have significant consequences, and the modelling framework is currently not set up to account for such exogenous shocks.

5.5 Management changes

In Section 2, we presented a method to account for individual changes in technical efficiency, and we applied this in Section 4 to a situation where the inefficient vessels had increasing levels of technical efficiency. However, one could also imagine situations where changes in management reduce fishermen's ability to catch fish, for instance through mesh size changes, closed areas, etc. These changes can either influence all vessels or only a specific gear type or vessel size. The framework can be set up to account for such changes.

In this section, we will analyse the consequences of increasing mesh size in the flatfish fishery, i.e. outputs of plaice and other flatfish. We assume for simplicity that the consequence hereof is that 10% of the flatfish escapes through the larger meshes, i.e. when previously 1 kilo was caught, only 0.9 kilo is now caught. For correct modelling of such regulatory changes, it will in practice be necessary to consult with biologists and gear technicians in order to use the right value of catch reduction following mesh size change.

To model this, a new variable G must be included in the programming problem, stating the reduction in catches. Because we use an output-oriented approach, G is assumed to be equal to or larger than one (if equal to one, no mesh size changes are made). The objective function given in equation (11) thus becomes:

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

where G is determined for each individual vessel v per output m.

The restriction on total catches cf. equation (11.g) is likewise converted to be as follows:

$$\sum_{v=1}^{V} \beta^v \cdot \frac{CPY_m^{obs\ v}}{G_m^v F^{new\ v}} \leq \sum_{v=1}^{V} CPY_m^{obs\ v} \qquad m = 1,\ldots,M \tag{14.g}$$

Because the individual vessel equations in the programming problem are not influenced, the estimated best-practice frontier is unchanged.

Having reformulated the industry programming problems to facilitate evaluation of mesh size changes, we reestimate all the models using the example of increased mesh sizes in the flatfish fishery with G equal to 1.1. The economic consequences of the larger mesh size are displayed in Table 5.10 for the different behavioural assumptions. It can be observed that the reductions in gross profits are expected to be between 60 and 80 million DKK. The highest reductions are observed when it is assumed that the output mix cannot be changed.

Table 5.10 Consequences of increased mesh sizes (1,000 DKK)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase
Revenue	3,366,479	3,305,603	3,422,133	3,360,626	3,467,546	3,447,927	3,483,018	3,464,173
Cost	1,709,798	1,726,013	1,637,619	1,652,414	1,439,973	1,486,211	1,428,406	1,468,928
Earnings	1,656,681	1,579,590	1,784,513	1,708,212	2,027,573	1,961,716	2,054,613	1,995,245
Gross profits	1,024,528	947,437	1,152,360	1,076,059	1,395,420	1,329,563	1,422,460	1,363.092

In order to explain the economic effects of such mesh size increases, it is beneficial to include Table 5.11, which displays the catches of flatfish and total catches under the behavioural assumptions. The table shows that catches of flatfish are significantly reduced with a fixed output mix, while catches of other species are only reduced to a minor extent. With the output mix unrestricted, only small reductions in the flatfish catches are observed, if any.

Table 5.11 Catch amounts with increased mesh sizes (tonnes)

	Technical efficiency and output mix fixed		Technical efficiency unrestricted, output mix fixed		Technical efficiency fixed, output mix unrestricted		Technical efficiency and output mix unrestricted	
	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase	2002-mesh size	Mesh size increase
Flatfish	34,029	30,600	35,383	31,587	35,654	34,824	35,654	35,654
Total	1,305,937	1,301,878	1,309,012	1,305,134	1,310,997	1,309,765	1,311,324	1,310,409

By increasing mesh sizes, each vessel will have to endure higher costs to obtain the same catch. However, at some point this is not economically viable, and catches are therefore reduced instead. This effect is also observed in the results above, where total catches and total revenues are reduced, while total costs increase. Allowing for flexibility in the choice of output mix, these effects are to some extent counteracted by reallocation towards vessels with the ability to catch the species at a lower cost. This implies that catches and thus catch revenues are reduced to a lesser extent than previously, but also that costs increase more. An increased mesh size will thus result in lower gross profits, and it is as expected that vessels using gear types such as beam trawl, Danish seine or net/line will primarily be influenced by this. The reason is that these vessels have a high proportion of flatfish in their catches.

Final remarks

Obtaining precise estimations of the economic consequences following regulatory changes is important in order to take economically sound decisions. In Andersen and Bogetoft (2003), we investigated a situation where the management system in a fishery is changed from a given unspecified one to one based on Individual Transferable Quotas. To perform such estimations, a series of industry models based on linear programming was set up in allowing the fishermen flexibility with respect to individual learning and choice of output mix.

In this paper, we have modified this framework in several ways. Firstly, we considered how to restrict the determination of the best-practice frontier in order to secure that vessels using the same technology (gear type) are compared, but still included in the industry programming problem together with vessels using other technologies. This can be achieved by including a comparison vector consisting of dummy variables equal to zero or one. Secondly, we focused on how to facilitate individual learning, but at the same time assuring that fishermen do not necessarily become fully technically efficient. To accomplish this, we proposed a method where the plausible efficiency increase following individual learning was calculated outside

the model and afterwards included herein. Finally, we considered how to allow for some flexibility in the choice of output mix instead of none or full flexibility. Upper and lower bounds can be utilised to restrict this type of flexibility.

To evaluate the consequences of these theoretical derivations, we applied a dataset covering the entire Danish commercial fishery in 2002, excluding licensed fisheries for mussels and shrimps. Based on these figures, we calculated gross profits to rise from 742 million DKK to 1,422 million DKK under the most flexible assumptions. Thus, had Danish fisheries been regulated by an ITQ system in 2002, gross profits could have increased by 92%. The gains are primarily derived, when the choice of output mix becomes flexible, and restricting this flexibility does thus also have the most pronounced effects compared to restricting individual learning.

Setting the restrictions are of course essential for obtaining realistic results. In this paper, we used some illustrative levels of these restrictions. However, to obtain more realistic restrictions and thus results, discussions with fishermen, managers, biologists and gear technicians could provide valuable knowledge. This is a resource demanding task, and has not been performed in this paper.

Finally, we focused on a number of policy implications, which can be important to consider before implementing an ITQ management system in fisheries. Previously, topics such as concentration, specialisation, activity on the market and price determination have been discussed in the literature. These topics were therefore also considered in this paper, and methods to investigate these were proposed. Furthermore, we displayed how the industry programming problems could be changed in order to investigate exogenous chocks and management changes. Based on this, examples were given in the form of increased prices of cod, increased fuel prices and increased mesh sizes in the flatfish fishery.

We have in the present paper modified a previously derived framework for calculation of tradability gains from implementing an individual transferable quota system within fisheries. Considering several different modifications, we have displayed the flexibility of the framework, and by applying it to a dataset, we have demonstrated its empirical capabilities. Furthermore, we have shown how it can easily be used to analyse a range of topics, including the consequences of management changes.

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