Economic and physical measures of capacity: A comparative analysis of Danish trawlers

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Abstract: The use of Data Envelopment Analysis (DEA) has been proposed as a possible tool to enable the measurement of fishing capacity worldwide. In fisheries the DEA approach has been limited to measuring physical capacity, where capacity is defined as the maximum amount of output that can be produced per unit of time, given existing plant and equipment and unrestricted availability of variable inputs. The physical (or technical) measure of capacity requires a set of physical input and output data, including variable and fixed input factors and production outputs. An economic measure of capacity can be defined as the maximum revenue attainable for the given inputs, using relevant outputs and output prices in the model. Due to a general scarcity of economic data, such analyses have yet to be seriously considered in a fisheries context. This paper considers Danish North Sea trawlers where detailed economic and physical vessel data are available. The economic and physical measures are compared and contrasted using statistical analysis. The two approaches and potential fishery management implications are discussed.

Keywords: Economic capacity, Physical capacity, Data Envelopment Analysis, Danish North Sea trawlers

1. INTRODUCTION

Fishing capacity has become a management topic of great significance in recent years. Problems stemming from ill-defined property rights and race-for-fish behaviour include overcapitalisation of the fishing industry and consistent overexploitation of the resource base. Under the initiative of the Food and Agricultural Organisation of the United Nations (FAO) and the International Plan of Action for the Management of Fishing Capacity, the use of Data Envelopment Analysis (DEA) has been proposed as a possible tool to enable the measurement of fishing capacity worldwide. Such estimates would give fishery managers valuable information on the commensurate level of fleet capacity that should be in place, given the availability of resources and the economic status of the fishing industry.

The DEA measurement approach to date has mostly concerned a physical measure of capacity (Johansen 1968, Färe *et al*. 1989, Färe *et al*. 1994). However, economists often propose that an economic measure of capacity should be applied, which requires the application of economic data. However, due to the general scarcity of economic data such analyses have yet to be seriously considered in a fisheries context. It is often considered that an economic dimension should be built into this kind of analysis since the main objective of fishers is often to maximise profits, and not necessarily to maximise output without regard to costs. Hence, profit maximising strategies are not captured, or indeed favoured, in the standard physical capacity approach, and may in fact be perceived as inefficient behaviour in a purely technical sense.

In this paper we take the first step towards a more appropriate portrayal of capacity by investigating a revenue maximisation approach. It is clearly the case that most fishers operate in order to maximise the value of catches, as an approximation of short run profit, rather than the mere catch volume. Firstly we discuss capacity definitions and the theoretical approaches to measuring efficiency and capacity of vessels. We then consider two optimisation models by using the economic and the physical approaches to measuring capacity. Results are compared and contrasted. A discussion of methodology application, potential implications for fishery management, and ideas for future research concludes the paper.

2. CAPACITY AND EFFICIENCY

2.1 Capacity Definitions

Capacity can be defined in several ways. Figure 1 below graphically depicts some of the various economic and physical capacity definitions in a generalised form. Klein (1960) states that the output level associated with optimal capacity is at the tangency point between the short-run average cost (SRAC) and long-run average cost (LRAC) curves. Berndt and Morrison (1981) suggest that the minimum point of the SRAC curve should represent optimal capacity. In physical terms, Johansen (1968) defines capacity as *"the maximum amount that can be produced per unit of time with existing plant and equipment, provided that the availability of variable factors of production are not limited"*.

Coelli *et al*. (2001) stress that these three capacity measures suggest that firms operate at a point where short-run profit is foregone. Hence, they suggest that the point of short-run profit maximisation be used as the preferred measure of capacity.

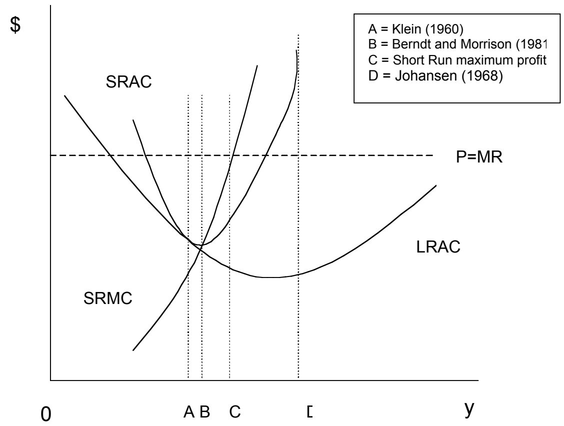

Figure 1: Measures of capacity (Coelli *et al*. 2001)

In 1999, the Food and Agricultural Organisation of the United Nations (FAO) agreed on an International Plan of Action for the Management of Fishing Capacity. The plan calls for all member states to achieve efficient, equitable and transparent management of fishing capacity by 2005, and to provide estimates of capacity of their fishing fleets by 2001. In this regard it has been concluded that the Johansen (1968) definition of capacity, with slight modification, can be shown to provide a suitable measure of capacity. Guidelines laid down by the FAO Technical Working Group on the Management of Fishing Capacity (FAO 1998), hence proposed that capacity should be viewed as a physical (technical) output, where:

"Fishing capacity is the maximum amount of fish over a period of time (year, season) that can be produced by a fishing fleet if fully utilised, given the biomass and age structure of the fish stock and the present state of the technology".

In order to measure capacity in this technical sense we can apply the standard approach to measuring production efficiency in industry.

2.2 Measuring Efficiency

In the simplest terms, technical efficiency (TE) is an indicator of how close actual production is to the maximal production that could be produced given the available factors of production (Farrell 1957). Alternatively, TE may be an indicator of the minimum levels of inputs or factors of production necessary to produce a given level of output relative to the levels of inputs actually used to produce that same level of output (Kirkley *et al*. 1999). In the case of fisheries, this interpretation is consistent with the FAO definition of fishing capacity described above.

In this paper we consider the output-orientated approach. Coelli *et al*. (1999) illustrate this measure by considering the case where production involves two outputs (y_1 and y_2) and a single input (x). If we hold the input quantity fixed at a particular level, we can represent the technology by a production possibility frontier (PPF) in two dimensions:

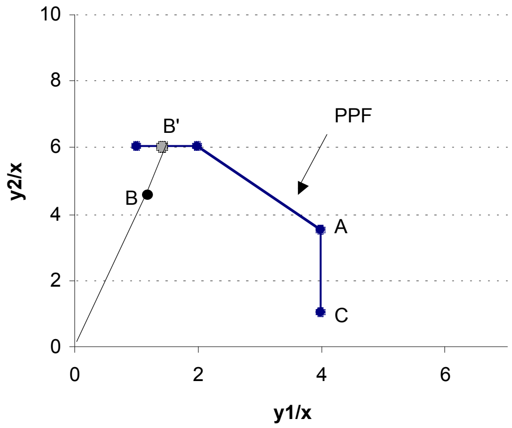

Figure 2: Technical efficiency from an output orientation (Coelli *et al*. 1999)

In Figure 2 we can see the PPF, i.e. the upper bound of production possibilities. Point *B* lies below the PPF and corresponds to an inefficient firm. Point *B´*, however, represents an efficient firm situated on the PPF. The distance defined by *BB´* represents technical inefficiency, and represents the amount by which outputs can be increased without requiring extra input. Coelli *et al*. (1999) hence define the measure of output-orientated TE as the radial measure ratio *0B´/0B*. For example, a TE score of 1.20 indicates that outputs may be increased by 20% whilst holding the current level of inputs fixed. A TE score of 1.0 represents a firm that is technically efficient and is on the frontier.

2.3 Measuring Capacity using DEA

An extension of the efficiency analysis by Farrell (1957) was undertaken by Charnes *et al*. (1978), who first applied Data Envelopment Analysis (DEA) to multiple input, multiple output processes. Since then, DEA has been used to assess efficiency in many different areas, ranging from the public sector to the fishing industry. It has also been applied to estimate optimal input utilisation, productivity, identify strategic groups, determine benchmarks and total quality programmes, and to estimate social and private costs of regulating undesirable outputs and capacity (Kirkley *et al*. 2000).

Färe *et al*. (1989) proposed that the DEA framework could be modified in order to estimate capacity as defined by Johansen (1968). Here, the capacity estimate refers to the maximum potential or frontier level of output that could be produced given the fixed factors and full utilisation of the variable factors. The DEA technique allows us to assess the efficiency of an existing technology relative to an ideal, 'best practice', frontier technology (Coelli *et al*. 1999). The frontier technology in this case resembles the optimal combination of inputs and outputs.

The DEA PPF, as depicted in Figure 2, is formed as a non-parametric, piece-wise linear combination of observed 'best practice' activities. Data points of all firms are enveloped with linear segments, and TE scores are calculated relative to the frontier. That is, TE scores of each firm are provided, representing their radial distance from the frontier. To be on the frontier, a firm must thus be producing the highest possible level of output for a given level of fixed inputs, and full utilisation of variable inputs (Ward 2000).

Firms that are not on the frontier are below it, either because they are using inputs inefficiently or because they are using lower levels of variable inputs relative to firms on the frontier. Inefficiency for any firm is thus determined by comparing it to the combination of firms on the frontier, which utilise the same level of input and produce the same or higher level of output (Walden and Kirkley 2000a). The analysis is accomplished by requiring solutions that can increase some outputs without worsening the other inputs or outputs (Charnes *et al.* 1996).

DEA is a non-parametric mathematical programming approach that uses the optimisation of an objective function given a series of constraints. The approach being non-parametric refers to the fact that it does not have to assume a particular functional relationship between the inputs and outputs. DEA is particularly well suited for estimating capacity in multi-species fisheries, as it can readily accommodate both multiple inputs (capital and labour) and multiple outputs (Ward 2000).

One of the drawbacks of DEA, however, is that it is unable to account for the stochastic nature of data. With DEA, all random deviations from the frontier are deterministically attributed to inefficiency, and do not account for data noise (e.g. catch rate fluctuations) or measurement error. The position of the frontier may hence be impacted by such an assumption, as the model assumes that the highest observed catch rates could always be duplicated (Ward 2000).

The DEA models used in this paper are written in the General Algebraic Modelling System (GAMS) language (Brooke *et al.* 1998).

3. MODEL SPECIFICATIONS

3.1 Physical Model

The estimation of capacity output can be obtained by solving a linear programming model. We designate the vector of outputs by y and the vector of inputs by x, with m outputs, n inputs, and j firms or observations. Capacity output and the optimum or full input utilisation values require us to solve the following problem:

$$\underset{\theta,z,\lambda}{Max}\,\theta_1 \qquad (1)$$

subject to:

$$\sum_{i=1}^{N} z_i y_{im} \geq \theta_1 y_{jm}, \forall m \qquad (2)$$

$$\sum_{i=1}^{N} z_i x_{in} \leq x_{jn}, n \in F_x \qquad (3)$$

$$\sum_{i=1}^{N} z_i x_{in} = \lambda_{jn} x_{jn}, n \in V_x \qquad (4)$$

$$z_i \geq 0, \forall i \qquad (5)$$

$$\sum_{i=1}^{N} z_i = 1 \qquad (6)$$

where θ_1 is the capacity measure, y_{jm} is the amount of output m produced by firm j, x_{jn} is the quantity of input n used by firm j, and z_i is the intensity variable for firm i.

Inputs are divided into fixed factors, defined by the set F_x, and variable factors defined by the set V_x. Equation (2) represents one constraint for each output, while Equation (3) constrains the set of fixed factors. Equation (4) defines a constraint for the variable inputs, allowing them to vary freely. Equation (5) is the non-negativity condition on the z variable and Equation (6) imposes variable returns to scale.

The model is run once for each firm in the data set. Capacity output is then determined by multiplying θ_1 by observed output. This is consistent with the Johansen (1968) definition of capacity because only fixed factors constrain production (Walden and Kirkley 2000b).

3.2 CU Observed

Capacity utilisation (CU) can be calculated using the observed output as follows:

$$CU(observed) = \frac{y}{\theta_1 y} = \frac{1}{\theta_1} \qquad (7)$$

Here, CU gives the fraction that the observed output constitute of the maximum obtainable output for the same firm, measured along a ray through the origin (cf. Figure 2). Thus the ray measure converts the multiple-output problem to a single-product problem by keeping all outputs in fixed proportions (Vestergaard *et al*. 2000). This corresponds to the Farrell (1957) measure of output-orientated technical efficiency due to the radial expansion of outputs. The CU_{OBS} scores range from 0 to 1, with 1 representing full capacity utilisation. Values of less than 1 indicate that the firm is operating at less than full capacity given the set of fixed inputs.

3.3 CU Färe

The CU_{OBS} measure might be downwards biased because the numerator in the measure, the observed outputs, may not necessarily be produced in a technically efficient manner (Färe *et al.* 1994). A technically efficient measure of outputs can be obtained by solving a problem where both the variable and fixed inputs are constrained to their current levels.

The outcome (θ_2) shows the amount by which production can be increased if production is technically efficient. Färe *et al.* (1994) show that this can be determined by solving another linear programming problem, which is similar to the capacity problem, but where the Equation (4) constraint for variable inputs is removed:

$$\underset{\theta,z}{Max}\,\theta_2 \qquad (8)$$

subject to:

$$\sum_{i=1}^{N} z_i y_{im} \geq \theta_2 y_{jm}, \forall m \qquad (9)$$

$$\sum_{i=1}^{N} z_i x_{in} \leq x_{jn}, n \in F_x \cup V_x \qquad (10)$$

$$z_i \geq 0, \forall i \qquad (11)$$

$$\sum_{i=1}^{N} z_i = 1 \qquad (12)$$

The $CU_{FÄRE}$ measure is then calculated as the ratio of the technically efficient output (θ_2 multiplied by the observed production for each output) and capacity output. That is:

$$CU(Färe) = \frac{\theta_2 y}{\theta_1 y} = \frac{\theta_2}{\theta_1} \qquad (13)$$

This technically efficient CU measure again ranges from 0 to 1. Values less than 1 indicate that output is less than potential output, even if all current inputs (variable and fixed) are used efficiently.

3.4 Economic Model

As often noted in fishery economics literature, fishing is an economic activity. Hence, it may be more appropriate to assume that fishers would pursue revenue maximisation rather than maximising physical output. According to Coelli *et al.* (1999) and Färe *et al.* (2000) the capacity output models, outlined above, can be adapted to represent a revenue maximisation problem. The problem can be formulated as follows:

$$\underset{y^*_{jm},z}{Max} \sum_m p_m y^*_{jm} \tag{14}$$

subject to:

$$\sum_{i=1}^{N} z_i y_{im} \geq y^*_{jm}, \forall m \tag{15}$$

$$\sum_{i=1}^{N} z_i x_{in} \leq x_{jn}, n \in F_x \tag{16}$$

$$\sum_{i=1}^{N} z_i x_{in} = \lambda_{jn} x_{jn}, n \in V_x \tag{17}$$

$$z_i \geq 0, \forall i \tag{18}$$

$$\sum_{i=1}^{N} z_i = 1 \tag{19}$$

where p_m is the output price for output *m,* and y^*_{jm} is the revenue maximising vector of output *m* produced by firm *j*, given the output prices p_m and the input levels x_{jn}. Following Coelli *et al.* (1999) we define total revenue utilisation, or economic utilisation (EU), of firm *j to be*:

$$EU_j = \frac{\sum_m p_m y_{jm}}{\sum_m p_m y^*_{jm}} \tag{20}$$

That is, EU is the ratio of observed revenue of firm *j* to maximum revenue, as calculated by the model. This measure is the economic equivalent of the CU_{OBS} score in physical terms, as described in Section 3.2.

The $CU_{FÄRE}$ measure is similarly calculated by running the economic model where both variable and fixed inputs are restricted to their current levels (as described in Section 3.3) and then taking the fraction between observed and technically efficient output as in Equation (13).

Graphically, we can view economic efficiency as shown in Figure 3. This resembles a similar case to that depicted in Figure 2, with the addition of the isorevenue line. Here, firm *A* is the only firm that has economic efficiency and all the other firms have some allocative inefficiency. Allocative efficiency in this case refers to selecting the mix of output (given the output prices that prevail), which produces maximum revenue for the given input levels (Coelli *et al*. 1999). Firm *B* represents a firm that also is technically inefficient.

Here, technical efficiency of firm *B* is given by *OB´/OB* and allocative efficiency is equal to the ratio *OB´´/OB´*. The economic efficiency measure of firm B is thus given by *OB´´/OB*, a combination of technical and allocative efficiency.

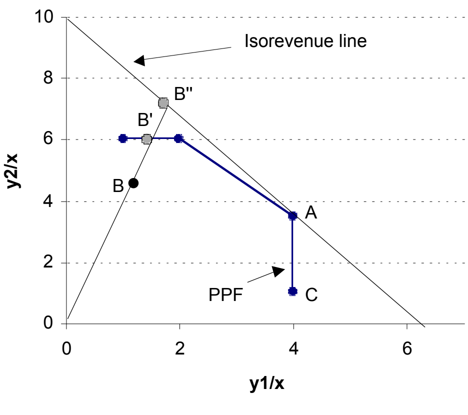

Figure 3: Economic efficiency (adapted from Coelli *et al.* 1999)

4. DATA

The dataset comprises 97 trawling vessels fishing in the North Sea in 1999. Trawl is the most used gear in Danish fisheries. In 1999 the trawling fleet segment fishing the North Sea had landings of 855 thousand tonnes in Danish ports, representing revenues of about €150 million (FD 2002). The dataset used is held in the FOI account statistics database and includes fixed inputs (tonnage, engine power and length), variable inputs (crew and days at sea), outputs (six species groups) and related output prices for 1999 (cf. Table 1). The species groups include crustaceans, codfish, flatfish, herring/mackerel, fish for reduction, and other species. Vessel output per day at sea is used in order to remove stochastic noise from the dataset.

Average output prices for each of the six species groups have been calculated for 1999. Here, average price has been calculated as the total revenue obtained by all vessels for a certain species group divided by the catch volume, referred to 'Fleet mean' in Table 1 below. This has helped to remove outliers that are observable if an average of all vessels' individual average price is used ('Vessel mean'), which are most noticeable for some vessels catching herring/mackerel and other species. Below we can observe the distribution of prices among vessels in the dataset, noting that the 'Fleet mean' prices have been used in the economic model.

Table 1: Average fish prices, Danish kroner (1999)

	Cru	Cod	Fla	H/m	FfR	Oth
Fleet						
Mean	57.66	14.31	15.90	1.52	0.64	14.21
Vessel						
Mean	57.06	14.93	15.75	3.66	0.64	17.12
Median	58.57	14.49	14.99	2.33	0.60	13.44
St. dev.	10.25	2.82	4.14	3.92	0.10	10.64
25%	54.28	13.05	13.35	1.50	0.58	9.22
75%	63.54	16.39	17.09	3.39	0.68	23.40
5%	38.79	11.29	12.39	1.00	0.55	5.64
95%	66.84	19.92	20.81	10.13	0.82	37.41
Obs	46	97	97	16	11	97

5. RESULTS

A summary of CU and EU scores and statistical interpretations can be viewed in Table 2 and Figures 4-6 below.

Table 2: CU and EU scores

	Observed		**Färe**	
	CU	EU	CU	EU
Mean	0.81	0.61	0.94	0.93
Median	0.88	0.62	1.00	1.00
St. dev.	0.21	0.21	0.12	0.12
25%	0.63	0.43	0.92	0.91
75%	1.00	0.75	1.00	1.00

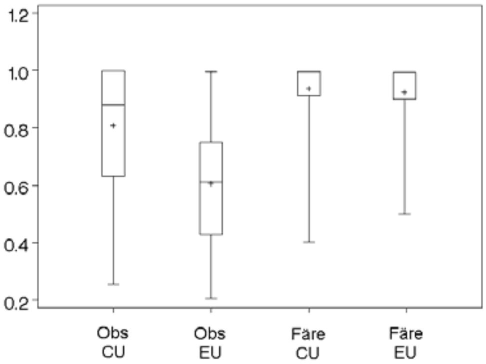

Figure 4: Box plots of CU and EU scores

The results indicate that EU_{OBS} scores are systematically lower than CU_{OBS} scores, as confirmed by Figure 5. This is to be expected, as it is clearly possible to be physically efficient without being economically efficient (cf. Figure 3). Both scores are fairly correlated and have a Spearman rank correlation coefficient of 0.74.

Contrary to this, both sets of Färe scores are approximately equal, cf. Table 1 and Figure 6, although there is more correlative noise among the scores, with a Spearman rank correlation coefficient of 0.53. Hence, a consistent linkage between the two sets of scores is less obvious.

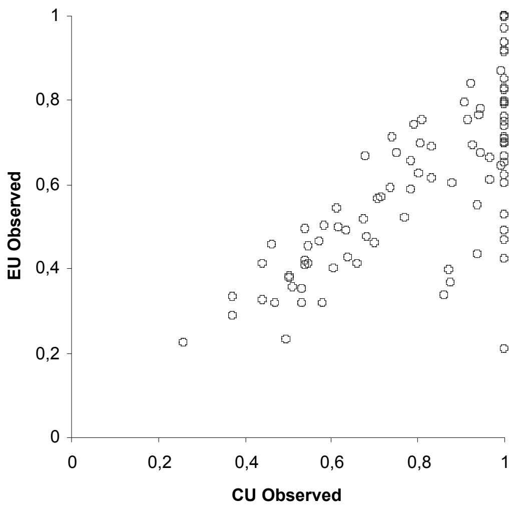

Figure 5: CU_{OBS} plotted against EU_{OBS} scores

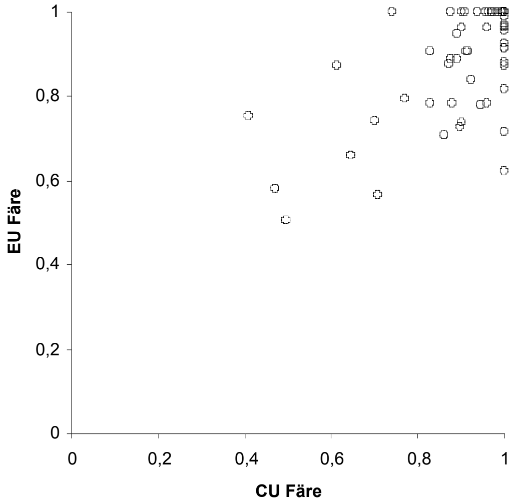

Figure 6: $CU_{FÄRE}$ plotted against $EU_{FÄRE}$ scores

These tendencies have been further analysed by the Wilcoxon signed-rank test. This is a statistical non-parametric method of testing the pair-wise equality of scores of two populations (e.g. X and Y). In this case, we can test whether the CU and EU scores of each vessel are the same. Both Observed and Färe scores are analysed in this manner.

The results of the Wilcoxon test support the correlation analysis. The CU_{OBS} and EU_{OBS} scores are shown to be different from each other with a 0.181 difference between medians, and a probability of less than 0.01% that they are equal. $CU_{FÄRE}$ and $EU_{FÄRE}$ scores are assumed to be equal with zero difference between medians, and a 58% probability that they are equal.
A detailed description of the composition of economic efficiency scores is given in the Appendix. Of the 97 vessels constituting the sample employed in this paper, six have EU_{OBS} equal to one (1.00). 29 vessels are Färe efficient but not economically efficient, meaning that the only 'increase' in output is given by the allocation of the outputs to the economically optimal combination. For the remaining 62 vessels the output increase combination is shown in Figure A3 in the Appendix. As expected, the total output increase for most vessels is a combination of efficient increase and economic allocation, while Färe increase has less importance, except for a group of approximately 5-15 vessels (cf. Figure A3).

It is concluded that (i) a large fraction of the vessels would be able to catch a higher amount by employing their given inputs in an optimal way, (ii) only a relatively small fractions of the vessels can achieve a higher output by changing the variable inputs, (iii) very few vessels are economically efficient. With regard to the last conclusion it should furthermore be remarked that a rather large fraction (38%) of the vessels are fully physically efficient, but not economically efficient, meaning that they would be able to gain a higher revenue had they aimed at a different catch combination.

As also shown in other studies (Vestergaard *et al.* 2000, Vestergaard *et al.* 2002), the use of the Färe approach results in higher utilisation scores than CU_{OBS}. This is because the approach is based on the assumption that the current mix of variable inputs for each vessel is efficient and cannot be expanded. Hence, there is less scope for increasing capacity output and the level of current capacity utilisation is therefore higher. The present analysis likewise shows that this is the case for both CU and EU scores, with the latter showing a greater discrepancy between Observed and Färe scores.

6. DISCUSSION

Why is it that we wish to find an economic measure of capacity, as opposed to the more standard physical approach? Further, why do we regard the inclusion of economic data as an imperative criterion to performance measurements of fishing vessels? We know that fishers are not purely interested in catching fish, but also wish to maximise their profits. They do so by implementing strategies that both seek to maximise the revenue of their catches whilst attempting to minimise the costs of securing that catch, although fisher behaviour may deviate from this generalised case. We thus maintain that an economic approach gives a more realistic portrayal of who is best placed to operate efficiently in the fishery under current conditions.

In this paper we have only taken the first step in this regard, namely by analysing the optimal mix of outputs for each vessel that will help to maximise its revenue. There are however many potential extensions of this paper. Firstly, the use of a larger dataset, and possibly different fleet segments, would assist us to verify the results of this analysis.

Secondly, a further step would be to formulate a profit maximisation problem based on Coelli *et al.* (2001). In such a case we would also need the specification of input prices, as well as the output prices defined in the economic model in this paper. With such data being readily available in the FOI database, this model approach should be relatively straightforward to define and execute.

Thirdly, we have used average prices to solve the economic capacity problem. It would also be feasible to use the individual prices obtained by each vessel. This may help to identify those vessels that enhance their economic efficiency levels by locating better market prices (time and place) or by delivering a product of superior catch quality. However, by using average prices we have reduced the effect of outliers in the efficiency analysis. That is, we have lessened the impact of a vessel that may only have caught one kilo of codfish but was fortunate enough to attain a far superior price than the prevailing average price. We also consider that it may be more appropriate to include more species groups in the analysis where differential prices are observed. Again, codfish is likely to receive different prices depending on size and quality. It may thus be appropriate to divide codfish into more output groups, e.g. grade 1 for direct consumption and grade 2 for filleting, and then applying differential output prices for each graded codfish output. Another way to solve this problem is by introducing 'environmental factors' (e.g. Coelli *et al.* 1999) that allows us to only compare vessels that have a similar mix of graded outputs.

An issue that should be considered when using this kind of approach to measuring capacity are the underlying principles of the analysis. The results we achieve, and our determination of who is efficient and who is not, much depends on our identification and inclusion of inputs. Our results may therefore be biased, according to whether we have been able to select the most appropriate inputs. Another example where bias might arise is where two vessels both have the same engine power, for example. One of the vessels decides to use it at is maximum output potential, whereas the other is more concerned with fuel efficiency and sails at more modest speeds. This further highlights the need for inclusion of economic data in order to determine the cost of using physical inputs at various levels.

We need to be very careful with the way we base our analysis on a certain set of inputs and thus, in general terms, we need be aware of the quality of data we are using, and assess how well that data portrays the fishery in question. With the FAO proposing that a tool such as DEA may be applied to capacity analysis on a worldwide basis, given that there is sufficient data, we should still be aware that efficiency of vessels is at least partly assessed on the back of our input assumptions.

It must be recognised that the undertaken analysis is for a particular dataset and hence these results cannot be viewed in a general context. For example, data errors and noise may influence the shape and position of the frontier, and the existence of outliers may also impact results. Therefore, conclusions drawn in this paper should be viewed with caution. It is also too premature to draw generalised conclusions regarding the management implications of economic and physical measures of fishing capacity. For management purposes we may, however, be able to identify in general terms what kind of vessel characteristics determine whether a vessel is likely to be efficient or not. What should also be emphasised is that this paper serves as a platform where physical and economic capacity measures can be directly compared for the same set of fishing vessels.

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APPENDIX

Composition of Economic Efficiency score

The observed economic utilisation EU_{OBS} is a measure of how much a given vessel may improve its observed revenue if it utilises its fixed and variable inputs optimally, i.e. (i) uses a technically efficient combination of fixed inputs, (ii) uses an optimal amount of variable inputs and (iii) catches an economically optimal output combination. There may be several reasons why a vessel is economically inefficient, i.e. where EU<1. Firstly, it may be technically inefficient, i.e. lie below the technical efficient frontier (defined by Equations 8 to 12), and thus also lie below the economically efficient frontier, as shown in Figure 3. Secondly, it may be Färe inefficient, i.e. technically efficient but not employing the variable inputs optimally, thus lying below the Färe frontier, and therefore also lie below the Färe economic frontier. Thirdly, it may be Färe efficient but still not economically efficient as it does not obtain the economically optimal output mix on the Färe frontier.

How far a Färe efficient output combination is from being economically efficient can be calculated by the allocative efficiency measure, which is the fraction between the optimal Färe output Y_{OBS} and the optimal economic output Y_{EC}:

$$AEU_{OBS} = \frac{y_{OBS}}{y_{EC}} = \frac{\theta_1 y}{y^*} = \frac{y/y^*}{y/\theta_1 y} = \frac{EU_{OBS}}{CU_{OBS}}$$
$$\Leftrightarrow \qquad EU_{OBS} = AEU_{OBS} \cdot CU_{OBS} \tag{A1}$$

The CU_{OBS} measure may further be separated into the technical efficiency measure and the Färe measure of efficiency by (cf. Equation 13):

$$CU_{FÄ} = \frac{y_{EFF}}{y_{OBS}} = \frac{y/y_{OBS}}{y/y_{EFF}} = \frac{CU_{OBS}}{CU_{EFF}}$$
$$\Leftrightarrow \qquad CU_{OBS} = CU_{FÄRE} \cdot CU_{EFF} \tag{A2}$$

where Y_{EFF} is the technically efficient output of the vessel, i.e. the output it obtains if it uses its given inputs optimally, but without changing the variable inputs. Equations (A1) and (A2) together give:

$$EU_{OBS} = AEU_{OBS} \cdot CU_{FÄRE} \cdot CU_{EFF} \tag{A3}$$

which shows the division of the observed economic efficiency discussed above. Table A1 shows basic statistical characteristics of the three measures AEU_{OBS}, $CU_{FÄRE}$ and CU_{EFF}. Figure A1 shows the corresponding box plots.

Table A1: Basic statistics of AEU_{OBS}, $CU_{FÄRE}$ and CU_{EFF} scores

	AEU_{OBS}	$CU_{FÄRE}$	CU_{EFF}
Mean	0.76	0.93	0.86
Median	0.77	1.00	0.99
St. dev.	0.16	0.14	0.19
25%	0.68	0.92	0.75
75%	0.87	1.00	1.00

Comparison of Table A1 and Figure A1 with Table 2 and Figure 4 indicates that it is especially the AEU_{OBS} score that contributes to the EU_{OBS} score, as AEU_{OBS} is mostly skewed away from unity, when compared with $CU_{FÄRE}$ and CU_{EFF}. Correspondingly, EU_{OBS} has an approximately normal distribution with a rather low mean of 0.61. CU_{EFF} also seems to have some influence on EU_{OBS} while $CU_{FÄRE}$ seems to have less importance.

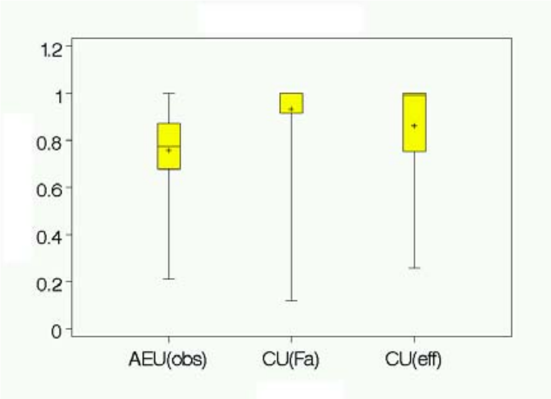

Figure A1: Box plots of the distributions of the AEU_{OBS}, $CU_{FÄRE}$ and CU_{EFF} scores

The question of the importance of the different parts constituting EU_{OBS} (cf. Equation A2) can also be investigated by alternative means. The reciprocal $\_{EC} = 1/EU_{OBS}$ is a measure of the total possible 'increase' in the output of the vessel in question, given physical as well as economic considerations. The total change in the output consists of a technical increase due to optimisation of fixed factors, a Färe increase due to possible variation of variable factors, together with an economic allocation to the combination of output that gives the highest revenue. This is illustrated in Figure A2 below.

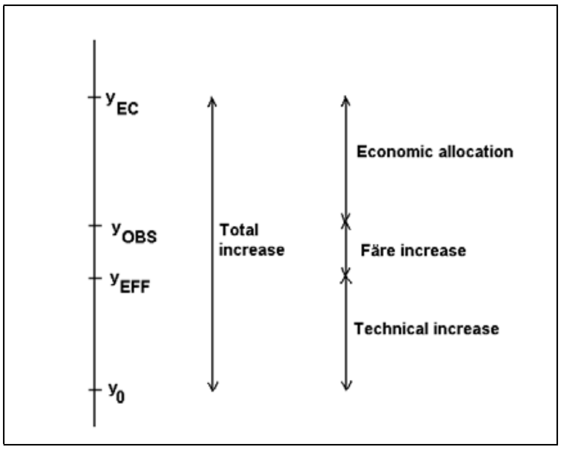

Figure A2: Illustration of the total possible increase in output for a given vessel

Given the factors AEU_{OBS}, $CU_{FÄRE}$ and CU_{EFF} it is straightforward to calculate how big a fraction each of the three output increments constitutes of the total output increase. The technical increase is given by:

$$\Delta_{TECH} = \frac{y_{EFF} - y_0}{y_{EC} - y_0} = \frac{\theta_{EFF} \cdot y_0 - y_0}{\theta_{EC} \cdot y_0 - y_0}$$
$$= \frac{\theta_{EFF} \cdot y_0 - y_0}{\theta_{AL} \cdot \theta_{FÄRE} \cdot \theta_{EFF} \cdot y_0 - y_0}$$
$$= \frac{(\theta_{EFF} - 1)}{(\theta_{AL} \cdot \theta_{FÄRE} \cdot \theta_{EFF} - 1)} \qquad \text{(A4)}$$

where

$$\theta_{EFF} = \frac{1}{CU_{EFF}} \qquad \theta_{FÄRE} = \frac{1}{CU_{FÄRE}}$$

$$\theta_{AL} = \frac{1}{AEU_{OBS}} \qquad \theta_{EC} = \frac{1}{EU_{OBS}} \tag{A5}$$

Likewise it may be shown that the Färe increase and the allocation ‘increase’ are given by:

$$\Delta_{FÄRE} = \frac{\theta_{EFF}(\theta_{FÄRE} - 1)}{(\theta_{AL} \cdot \theta_{FÄRE} \cdot \theta_{EFF} - 1)} \tag{A6}$$

and

$$\Delta_{AL} = \frac{\theta_{FÄRE} \cdot \theta_{EFF}(\theta_{AL} - 1)}{(\theta_{AL} \cdot \theta_{FÄRE} \cdot \theta_{EFF} - 1)} \tag{A7}$$

Figure A3: Output increase combination for vessels that are not Färe efficient

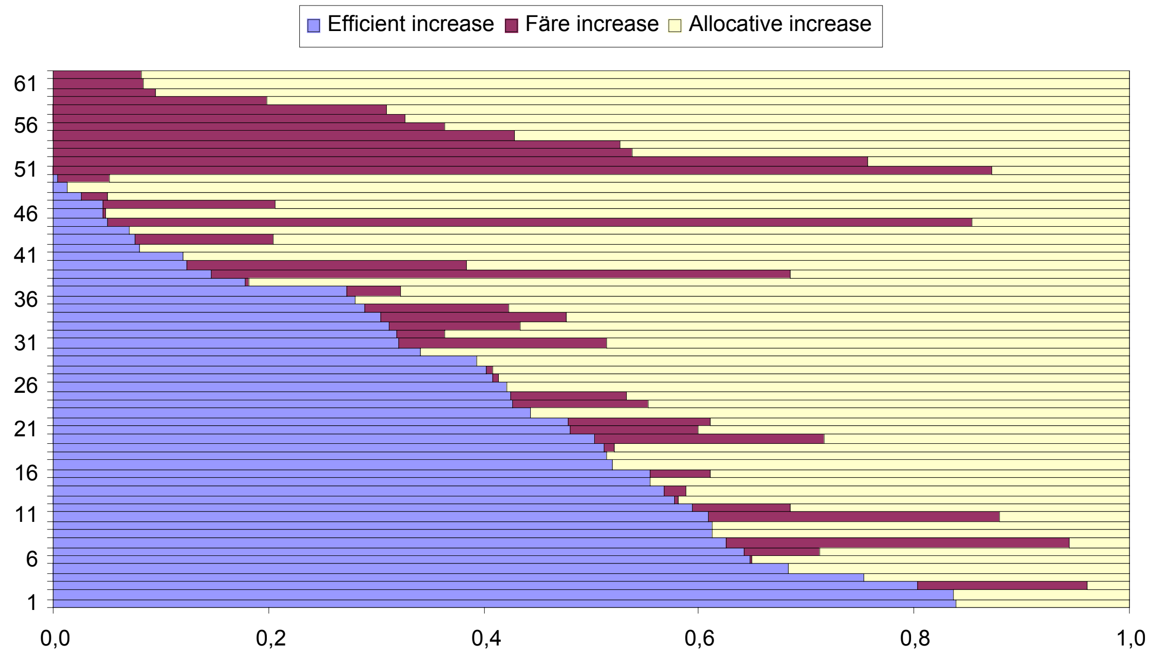

Figure A3: Output increase combination for vessels that are not Färe efficient