Capacity appraisal in the English Channel fisheries

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Abstract

The English Channel fisheries are characterised by multi-species, multi-gear, multi-métier vessels. Most of the vessels operating in the Channel are based in either France or the UK, although vessels from Belgium and other European countries are also active in the Channel. Many of the vessels are small scale, and are effectively artisanal. Six main gear types are used in Channel – trawl (both demersal and mid-water), beam trawl, dredging, lines, nets and pots. Many boats operate using several gear types over the year. Around 90 species are caught commercially, with most caught in different combinations depending on gear type used. As a result, the fishery is about as complex as any fishery in the world. The level of capacity utilization in the different UK fleet segments is examined using Data Envelopment Analysis. Target capacity is estimated for the fishery as a whole using a bioeconomic model.

1. Introduction

The measurement and management of fishing capacity has become a major international theme in fisheries management over the last few years. This is reflected in the number of international conferences and workshops dedicated to capacity measurement and management (e.g. FAO 1998, 2000) and the development of an "International Plan of Action on the Measurement of Fishing Capacity" (FAO 1999).

Capacity management requires some form of assessment of the current state of the fishery and the longer term desired state of the fishery. This essentially requires both a short term and long term assessment, the former providing information on current activity in the fishery and the latter on where the fishery should be in order to achieve the objectives of the fisheries management plan. For the purposes of deriving effective management plans, managers need to know the potential output from the current fleet, the target output in order to achieve the management objectives, and the fleet size and structure that is consistent with the 'optimal' levels of output.

The key short-term measure of capacity in the fishery is derived through estimating capacity utilization. From this, estimates of the harvesting capacity of the current fleet can be obtained. Capacity utilization (CU) refers to the ratio of actual to potential output. A measure of capacity utilization less than one implies that the same fleet, if fully utilized, could produce more than it is currently doing. Conversely, a smaller fleet if fully utilized could have taken the same level of catch. As a result, capacity under-utilization could represent the existence of

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over-capacity in the fishery, at least in the short term. However, as it is possible for capacity under-utilization to exist as a result of short term management imposed constraints, as well as short term market fluctuations (e.g. prices and costs), the existence of capacity under-utilization does not necessarily mean that over-capacity exists. Further, with highly variable stocks, some degree of capacity under-utilization may be desirable in 'average' or 'poor' seasons if it means that sufficient capacity exists to fully exploit the stock in 'good' seasons. The 'problem' of capacity under-utilization needs to be assessed taking these factors into account.

Nevertheless, the measurement of capacity utilization can provide valuable information relevant to capacity management. In particular, differences in capacity utilization across a fleet can have significant implications for management through effort controls, as in many cases these may form non-binding constraints (i.e. days at sea limits may not reduce effort if capacity is already under-utilized; fleet reduction policies may be ineffective if only those boats that are under-utilized are removed).

Several methods have been developed to estimate capacity utilization, with the most commonly employed being Data Envelopment Analysis (DEA). The DEA technique has been suggested as the preferred approach to capacity measurement in fisheries largely as a consequence of being able to measure capacity at the individual species level in a multispecies fishery (FAO, 2000). In fisheries, the technique has been applied to the Malaysian purse seine fishery (Kirkley, Squires *et al.,* 1999), US Northwest Atlantic sea scallop fishery (Kirkley, Färe *et al.,* 1999), Atlantic inshore groundfish fishery (Hsu, 1999), pacific salmon fishery (Hsu, 1999), the Danish gillnet fleet (Vestergaard *et al.,* 1999), and the total world capture fisheries (Hsu, 1999).

The estimation of target levels of capacity requires some form of bioeconomic model. Bioeconomic models are mathematical representations of the fishery that include the key biological relationships as well as economic factors that influence fisher behaviour and affect fishery profitability. Multi-objective bioeconomic models can be developed that enable 'optimal' output and fleet configurations to be estimated based on several conflicting objectives of management.

In this study, capacity utilization is estimated using DEA for a number of different UK fleet segments operating in the English Channel. Trends in capacity utilization over the period for different size classes of boats are examined. A multi-objective bioeconomic model of the fishery is also used to estimate the fleet configuration that best meets the fisheries management objectives in the long run. The level of overcapacity in the key fleet segments is assessed based on the long run results, while implications for capacity management are considered based on the short-term capacity utilization analysis.

2. The fisheries of the English Channel

The English Channel contains of a wide variety of fishing activities that are aimed at targeting a variety of species. Approximately 4000 boats operate within the English Channel, over half of which are UK boats (Tétard *et al.*, 1995). These broadly fall into 7 gear types: beam trawl, otter trawl, pelagic/mid-water trawl, dredge, line, nets and pots. In total, 92 species are landed by boats operating in the English Channel. However, the majority of the landed weight and value are made up of around 30 species.

The fleet is made up primarily of small vessels, with over two thirds of the fleet being less than 10 metres in length, and around half of these under 7m in length (Figure 1). A large proportion of the under 7m vessels operate essentially on a part time basis, fishing for generally less than half the number of expected full time days.

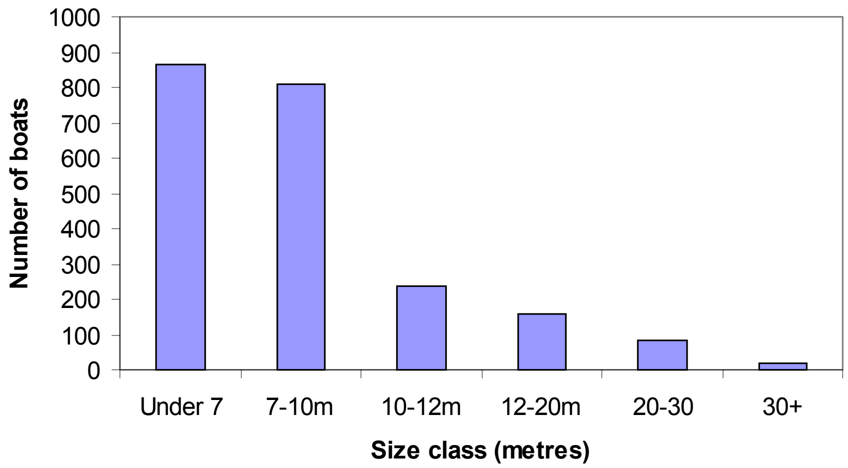

Figure 1. Size distribution of the UK Channel fishing fleet.

The boats are generally multi-purpose, operating with different gears over the year, and in some cases, using different gears in the same month. Fishing activity has been classified into a number of métiers based on gear used and area fished[2] (Tétard *et al.,* 1995). Boats may operate in different areas in the same month as well as with different gears, resulting in their activity being recorded in a range of métiers.

3. Assessment of capacity utilization

Capacity utilization in the main fleet segments was estimated using data envelopment analysis. The method involves comparing the level of output and inputs of different boats operating in the fishery. Details on the DEA methodology are given in Appendix A.

3.1 Data

An extensive database of fishing trip level log-book data from the fishery covering the period 1993-1998 was disaggregated into eight different fleet segments based on recorded fishing activity (beam trawl, otter trawl, scallop dredging, lining, netting, crab potting, whelk potting

[2] This classification was undertaken using cluster analysis to identify different activities within a given gear type.

and 'other' activities). The data had also been pre-classified into the different métiers by the UK Centre for Environment, Fisheries, and Aquaculture Science (CEFAS). Trip-level data were aggregated to provide monthly levels of output and effort by vessel over the period examined. In total, the combined data sets contain over 150,000 observations.

Many boats in the data set were multi-purpose, particularly the smaller ones, so the number of boats using a particular gear type varied from year to year and over the year. As many of the smaller boats (as well as larger boats that do not target quota species) are not required to complete logbooks, it was expected that much of the data may be unreliable. An assumption was made that boats that had consistently supplied data would be more reliable. To this end, only boats that used the gear for at least four months in a year and in at least three of the six years were allowed to remain in the data set, resulting in 20,250 observations (Table 1).

Table 1. Summary of consolidated data sets used in the analyses

	Total in data set		Average per boat per month				
Gear	**Boats**	**Number of Obs.**	**Catch[a] (Kg)**	**Value[b] (£)**	**Days fished**	**Deck area**	**Engine power (Kw)**
Beam trawl	101	6840	4801	10,352	6	160	422
Otter trawl	171	8215	1141	6454	12	56	155
Scallop Dredge	37	1553	14,806	21,860	11	143	375
Pots	28	916	6030	8121	9	43	95
Gillnets	51	2276	2618	3444	5	50	127
Longline	15	452	6270	2910	8	40	186

a) The catch has been weighted by revenue shares. b) Values have been inflated to 1998 values using a Fisher price index.

The key inputs used in the DEA analyses were days fished, 'deck' size (estimated as overall vessel length*breadth) and engine power (kW). Unbiased CU[3] was estimated using multiple outputs. For the multiple output measures, a composite revenue-based output measure, derived using revenue shares, was used for each main gear type. The 'other' catch (in weight terms) category was also derived using revenue shares, and all revenues were inflated to 1998 values.[4]

To address the problem of working with multi-purpose multi-métier fleet data, an additional input of days fished in other métiers in the same month was also included in the modified analysis.[5] Additional composite outputs were also created, both weight and revenue-based, to incorporate a measure of the catch generated in a particular month by a vessel's activity outside the particular métier being analysed.

[3] This is a more robust measure of capacity utilization as it takes into account differences in efficiency of the different fishermen, and also implicitly removes the effects of random variation in output. See Appendix A.
[4] Multi-output analysis was also carried out using individual outputs representing the catch of the top five species in terms of value. Catches of the remaining species were represented by a sixth composite category derived using revenue shares. However these results are not presented in this paper.
[5] This approach is further described in Tingley, Pascoe and Mardle (forthcoming).

3.2 Results

The results were produced using a linear programming model developed in GAMS (Brooke, Kendrick and Meerhaus, 1992). The model was run separately for each métier. Data on stock abundance was not available, however for the purposes of the secondary stage-analysis, with all vessels fishing in the same area, in the same month, being compared to each other to determine which vessels lie on the full efficiency or full capacity utilization frontier and for those that lie within it, how far inside it they are found. It was assumed that stock levels did not vary considerably during a given month, hence lack of stock abundance data was not perceived to be a significant problem.

The unbiased CU scores for each gear type in turn are shown in Figure 2. These have been disaggregated by vessel length categories to focus on small inshore vessels (less than 10m in overall length), medium-sized vessels (10 to 15.9m) and large vessels (greater than 16m).

Also presented in Figure 2 are the sample sizes used to provide average results for each vessel length category. For example, the average unbiased CU results for medium-sized otter trawlers was calculated from the results of between 102 to 151 vessels on average for each year, whilst results for the larger vessels were produced using data from between 13 to 21 vessels each year over the period 1993-98[6].

The results for the mobile gear types (otter trawl, beam trawl and scallop dredge) suggest that the medium sized vessels were operating more closely to maximum unbiased CU levels (i.e. 1) than the larger vessels. The difference was very significant for the beam trawl and otter trawl vessels across the whole period. The difference was less clear for scallop dredges.

The results are similar for the static gear potting vessels. Unbiased CU was highest for medium-sized potting vessels and generally lowest for smaller potters. As many of the smallest potters operate on a part-time basis, this result was not unexpected. However the smaller gillnetting vessels tended to have higher unbiased CU scores as compared to the largest gillnetters, which have the lowest scores. Attention should be paid to the numbers of vessels proving data for analysis in each length category.

While capacity utilization fluctuated from year to year, there appeared to be a general, gentle upwards trend in average annual unbiased CU for all major gear types between 1993 and 1998 (Figure 3). The rise between the years of 1993 and 1998 was 1% for beam trawlers, 2% for scallop dredgers, 4% for potters, 5% for otter trawlers and 9% for netters.

Overall, potters achieved the highest unbiased CU scores in four out of the six years studied (Figure 3). However, these annual scores are derived from the average of the 12 separate monthly analyses carried out for each gear type. They are not, therefore, directly comparable across gear types. During the four years when potters achieved the highest scores, they should be interpreted that, on average, more vessels achieved greater levels of unbiased CU as

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[6] All vessels were included in the same analysis, so the sample size of the group analyses is the sum of the sub-groups.

compared to those operating on the frontier (in each time period for that métier) than appears to have been the case in any other gear type.

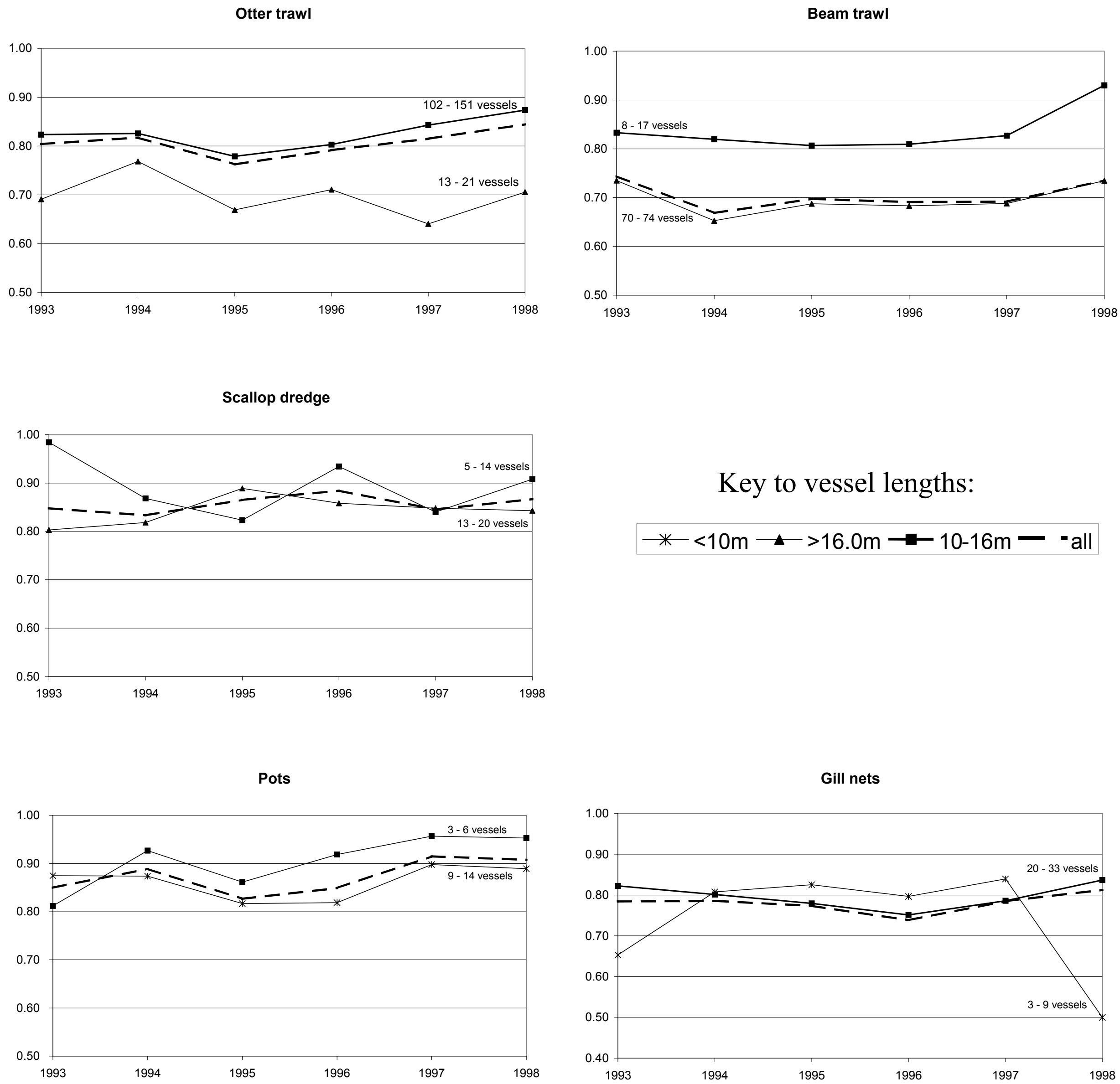

Figure 2. Unbiased CU results, single output revenue index, by gear type and vessel length category (1993-98).

Scallop dredgers appear to achieve the next highest consistent score, averaging between 85 and 90% of unbiased CU as compared to those dredgers operating on the frontier in each time period. Gill netters achieved consistently lower results of between 80 and 85% whilst beam trawlers appear to have the lowest average unbiased CU averaging a score of 78% over the period and 81% in 1998.

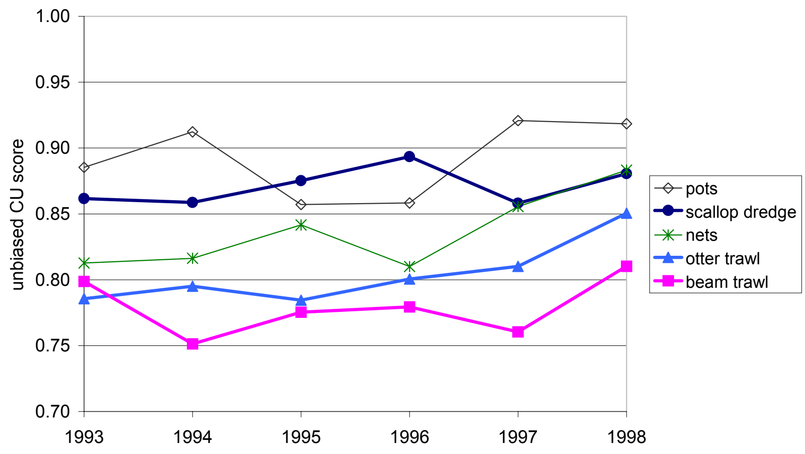

Figure 3. Average annual unbiased CU by major gear type (1993-98).

The numbers of vessels included in the analysis generally decreased between 1993 and 1998. As only records of vessels fishing a particular gear type for four or more months per year and for at least three years in the 1993-98 period were included in the analysis, their numbers used in the analysis provide a very crude measure of fishing effort. With the exception of scallop dredging and beam trawling, vessel numbers used in the analysis decreased between 1993 and 1998; by 28% of otter trawlers, 22% of potters and 32% for netters. Numbers of beam trawlers in the sample increased by only 3% over the period whilst numbers of scallop dredgers increased by 44%.

3.3.1 Distribution of capacity utilization

While on average the fleet is operating at below full capacity utilization, the distribution of CU in the fishery can also provide useful information for management. From Figure 4, it can be seen that for most fleet segments, most of the vessels are operating at or near full capacity, although a significant number are operating at low levels of capacity, reducing the overall average. Those boats operating at or near full capacity are therefore not able to increase their output above current levels. However, there also exists substantial latent effort in the fishery that could become active if economic conditions improved (i.e. prices increased) or new entrants to the fishery bought out the licenses of the relatively inactive vessels.

The distribution of CU in Figure 3 is only based on the boats that provided sufficient logbook data for the analysis. The fishery is characterised by a large number of part time vessels. As mentioned previously, survey estimates of fishing activity suggest that around 90 per cent of the under 7 metre vessels operate at less than 50 per cent of their potential days fished. As a result, the level of latent effort in the fishery is substantially greater than that indicated by the above analysis.

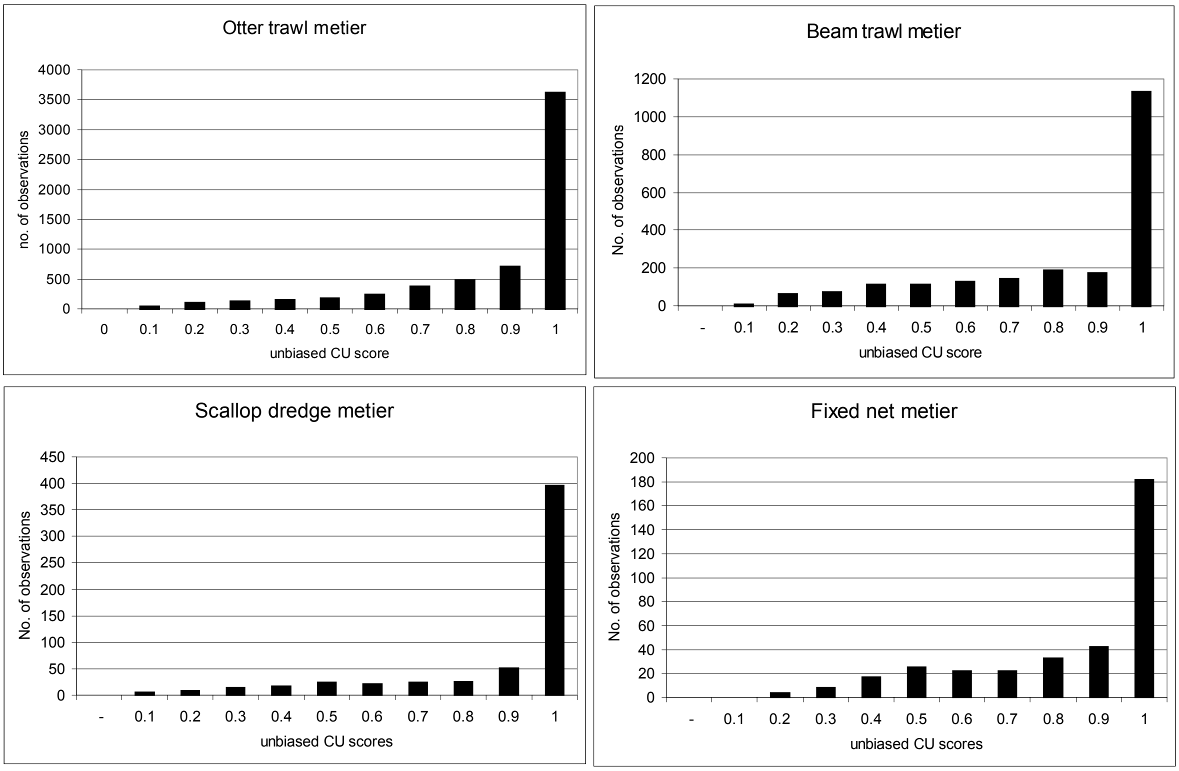

Figure 4. Distribution of unbiased CU in the UK Channel fleet.

3.3 Implications of the results

The results from the CU analysis indicate that the fleet as a whole was not fully utilized. In some fleet segments, there was the potential to increase output in the fishery through increased utilization (i.e. fishing more). Many boats were under-utilized to a high degree in all fleet segments, and there was considerable latent effort in the fishery due to part time fleet. As many of the part-time vessels are not included in the analysis due to lack of data, the level of latent effort in the fishery was even greater than suggested by the above results. There exists the potential, then for a considerable increase in fishing activity (effort) in the fishery, and corresponding increases in catch.

The other key result was that utilization appears to have increased as the number of vessels in the fishery has decreased. This could be due to a reduction in crowding pressure resulting in improved economic performance and an increase in fishing activity. Prices have also increased over the period so this would also be expected to have had an impact. Conversely, decommissioning programmes may have removed the boats with low CU, which consequently raised the average value. If this were the case, then the impact of the decommissioning programme in the fishery would have been less effective in reducing fishing effort than might be expected.

4. Multi-objective bioeconomic analysis

A multi-objective bioeconomic model was also used to determine the ‘optimal’ fleet configuration and size for the key fleet segments operating in the fishery assuming a long-run equilibrium position can be achieved. The model, described in Pascoe and Mardle (2001), include both the French and UK fleets operating in the Channel, as well as taking into account fishing activity of other EU Member States (which combined contribute around 5 per cent of the fishing activity). All commercial species caught in the Channel are included in the model, and for some species (e.g. crustaceans) several stocks have been included where these have been identified. The model includes a combination of age-structured biological models as well as surplus production models for some species. That is, all outcomes are sustainable in the long run (both biologically and economically). The model was also specified as an ‘optimization’ model, in that it produces the best outcomes given the objectives provided. The output of the model was the sustainable catch of each species, the fleet size and structure that produces that catch, and the relevant socio-economic measures of performance given the fleet structure and catch (e.g. profits, employment).

The model solution was based on the key management objectives in place in the fishery. Conservation objectives are over-riding, as all solutions are sustainable in the long run. The economic objectives were specified as maximising profits in the fishery, with each country having a separate profit target based on its own potential maximum profit (see Pascoe and Mardle 2001). Employment objectives were also included through setting target employment levels based on the current level of employment in the fishery. Finally, the EU principle of relative stability was imposed such that each country could not incur a greater proportion of benefit (or incur losses) than the other. The multiple objectives were incorporated into the model though the specification of an ‘achievement function’. The deviations away from the targets for each objective can then be minimized using a technique known as goal programming.

4.1 Multi-objective optimization

The model was run with the dual objectives of both increasing economic profits and maintaining employment. The economic profit objectives were taken as the maximum economic profits that could be achieved in each country (see Pascoe and Mardle 2001). The employment objectives were taken as the current level of employment in each country. The additional objective that each country can only incur the same proportion of the potential social cost was also imposed to ensure relative stability was maintained.

Essential to the achievement function was the definition of the weights associated with each goal. Different weights are likely to result in different optimal solutions. As deviations from all goals are unwanted, one method is to set all weights to unity since there is no need to differentiate their importance (Ignizio and Cavalier 1994).

A number of different weights were applied in the model. The model was run with equal weights being applied to both the profit and employment goals. The model was also run with a lower weight on economic profits and with a lower weight on employment. A common weight was used for both countries with each objective. This ensured that neither country was given preference relative to the other country.

As would be expected, the optimal fleet configuration depends on the relative weights given to the profit and employment objectives (Table 2). An optimal fleet with a higher weight on employment was characterized by a large number of smaller boats, particularly in the UK. Conversely, increased weight on economic profits results in the total capital (and employment) in the fishery decreasing. Comparing the current situation with the case in which employment was given greater weight than profits (i.e. $w_p=0.5,\ w_e=1$), economic profits could be increased from the current situation by 65 per cent with only an 8 per cent reduction in employment.

Table 2. Multi-objective optimization results.

	Current situation		Different weights on objectives					
			$w_p = 0.5; w_e = 1; w^s_e = 1$		$w_p = 1; w_e = 1; w^s_e = 1$		$w_p = 1; w_e = 0.5; w^s_e = 1$	
	UK	France	UK	France	UK	France	UK	France
Boat numbers								
• otter trawl	129	207	64	173	40	134		98
• beam trawl	92	86	74	65	65	63	92	56
• dredge	18	253	18	253	18	253	18	253
• trawl/ dredge		300		295		255		127
• pots	65	159	65	157	65	141	65	132
• nets		172		168		108		62
• lines		51		43		43		39
• net/line	137		122		122		122	
• whelk pots		44		42		38		25
• seaweed		59		59		59		56
• fixed gear		216		194		194		172
• misc.		127		126		119		79
• inshore mixed	1613		1613		1250		832	
Revenue (€m)								
• Channel fleet[a]	155.8	257.6	132.2	246.9	122.8	219.0	139.0	172.2
• External fleet	11.0	17.3	11.2	21.0	11.3	25.2	11.5	29.1
Profits[b] (€m)	-6.1	31.7	0.0	42.3	8.8	51.1	17.6	51.8
Capital[b] (€m)	195.5	319.2	149.1	260.4	113.9	182.1	114.3	102.1
Employment[b]	4343	4840	3978	4433	3216	3584	2198	2450

a) includes revenue from Channel fleet generated outside the Channel. b) Channel fleet only.

4.2 Trade-offs between employment and fishery profit

Comparing the results with the different weight combinations in Table 2, it is clear that there is a trade-off (as would be expected) between the level of employment and the level of fishery profits. A trade-off curve between the two objectives was estimated using the model. The level of employment in the fishery was set as a constraint and varied incrementally from 0 (zero) to 9200 (the current level of employment). The maximum sustainable profit that could be achieved given each level of employment was then estimated using the model (Figure 5)[7]. The additional constraint of relative stability was not imposed in estimating the frontier.

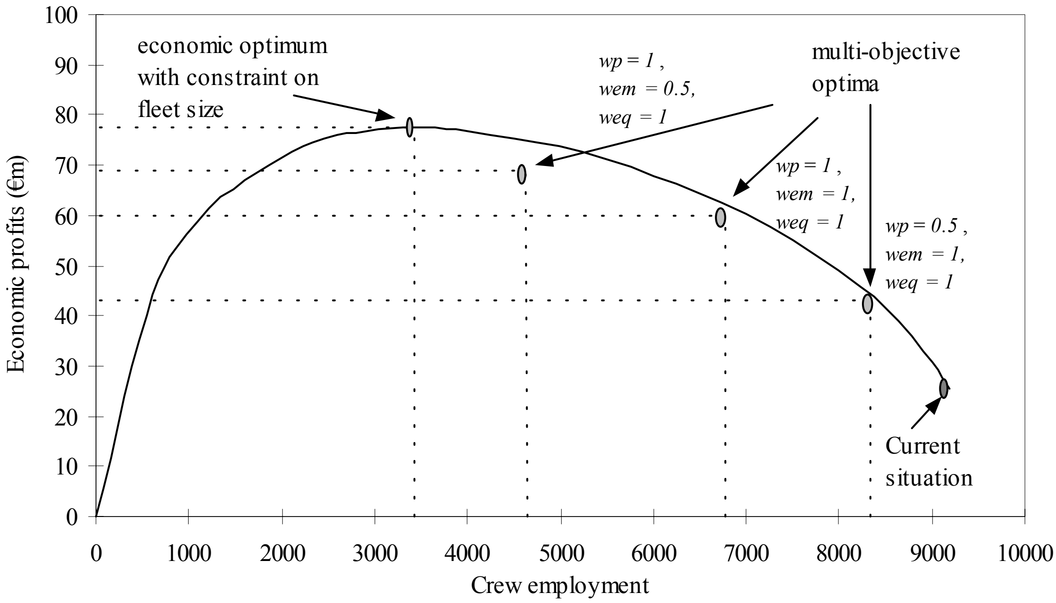

Figure 5. Economic profit and employment frontier.

From Figure 5, it can be seen that employment can be increased from the profit maximising level with a less than proportion decrease in profits. However, profits were estimated to decline sharply beyond the level of employment associated with the multi-objective optimum with equal weights (i.e. the slope of the tangent - equivalent to the marginal rate of transformation (MRT) - is equal to -1). At employment levels below this point, the slope of the tangent is greater than minus 1 (i.e. $0 > MRT > -1$), such that a one per cent increase in employment can be achieved with a less than one percent decrease in profits. Above this point, the MRT is less than -1 so that increased employment is achieved through a greater than proportional decrease in economic profits.

The level of profits and employment associated with all three multi-objective optima examined are interior to the profit-employment frontier. The relative stability constraint was estimated to prevent the fishery from achieving the greatest level of employment for a given level of economic profits (and vice versa). For example, for the optima with greater weight associated with profits, almost 10 per cent more economic profits could have been generated for the same level of employment. Conversely, an extra 1000 crew could have been employed for the same level of economic profits, an increase of more than 20 per cent. Hence, the

[7] The model was run as a single objective (profit maximisation) model only to derive this function. The level of employment was given as an equality constraint. That is, the model was used to estimated the maximum economic profits that could be achieved given a fixed total level of employment in the fishery.

equity considerations embodied in the stability constraint impose a cost in terms of forgone profits and/or employment in the fishery as a whole.

4.3 Extent of overcapacity

As noted previously, the extent of any overcapacity in the fishery will depend on the actual objective of fisheries management. From the above analysis, several different fleet configurations were identified based on different levels of importance given to each objective. Potentially, an infinite number of 'optimal' fleets can be identified, but only one will be truly optimal.

The percentage of overcapacity can be estimated by dividing the current fleet number by the 'optimal' fleet (Table 2). From this, it can be seen that the estimate of overcapacity varies substantially based on the objectives of management. For example, if maximising employment was the main objective, then there is no overcapacity in the inshore fleet, but if maximising profit was a main objective, then there was considerable overcapacity in the inshore sector.

Table 3. Extent of overcapacity in the UK fleet segments of the Channel fishery (%).

Fleet segment	Weights given to each objective		
	$w_p = 0.5$; $w_e = 1$; $w^s_e = 1$	$w_p = 1$; $w_e = 1$; $w^s_e = 1$	$w_p = 1$; $w_e = 0.5$; $w^s_e = 1$
otter trawl	102%	223%	inf
beam trawl	24%	42%	0%
dredge	0%	0%	0%
pots	0%	0%	0%
net/line	12%	12%	12%
inshore mixed	0%	29%	94%

5. Discussion and conclusions

The use of bioeconomic models for assessing the extent of overcapacity needs to be undertaken with some caution. Most optimisation models are sensitive to the data provided, and a small change in the main parameters may result in a different optimal solution. For example, if the price of the fish species targeted by the otter trawlers increased, then the optimal number of vessels in this segment may also increase. Similarly, if fuel prices decreased, the optimal number of all mobile gear boats (otter and beam trawlers and dredges) could increase. As prices and costs are likely to change in the future, the results of the models should not be seen as prescriptive, but indicative of the problem areas in the fishery.

Many biological parameters in the model are also subject to uncertainty. This again would affect the optimal fleet size and structure if errors are introduced into the model through inaccurate biological parameters.

The robustness of the results to uncertainty in biological and economic parameters can be examined through either sensitivity analysis or stochastic simulation. This was not presented in this paper in order to keep the analysis fairly simple, but a stochastic analysis of the model results was presented in Pascoe and Mardle (2001).

The results from the bioeconomic analysis largely confirm the results of the capacity utilization analysis. That is, that there exists overcapacity in the otter and beam trawl fleet segments. These groups were identified as having under-utilized their capacity in the short term CU analysis. Further, this suggests that fewer vessels can take the same or greater catches in the short term. The long run indicates that a more profitable fleet would develop as a result of reduction in these segments. The large reduction in the inshore fleet (in terms of total boat numbers) indicated by the bioeconomic analysis also raises the problem of part time fishing. As many of the smaller boats did not return logbooks, there was not sufficient data to estimate their capacity utilization. However, the model (using activity data collected through a survey of fishermen) estimated that there was considerable over-capacity in this fleet segment, largely as a result of the high proportion of part time fishers.

The above analysis demonstrates that CU can provide useful indicators as to the areas likely to be problematic for capacity management. However, CU does not tell you how much you may need to reduce capacity. Bioeconomic models can provide targets for capacity management, but the analyst needs identify the trade-offs that exist between objectives. The analyst must also be aware of the sensitivity of the models to prices, costs etc as well as potential errors in the underlying relationships before making firm recommendations to managers.

Appendix A. Capacity and capacity utilization measurement using DEA

The measurement of capacity of a firm (e.g. boat) can be described as its potential output given its fixed factors of production. Therefore, to measure this level of overall capacity, in practice the potential output of a firm is determined by a comparative analysis of the output levels achieved by other firms of similar size with similar activities. Differences in output between similar firms can be due to either differences in capacity utilization or differences in technical efficiency, both of which are relative measures. Capacity utilization is the level at which the firm operates given its level of variable input usage, which may be less than possible under normal working conditions. Technical efficiency on the other hand is the degree to which the potential output is achieved given the amount of both variable and fixed inputs employed. For example, in the case of a fishery, differences in the catch of two boats of the same size may be due to a difference in the number of days fished (capacity utilization), or a difference in the ability of the skipper in harvesting the resource (technical efficiency). Therefore, in order to determine the potential output of a boat under normal operating conditions, these effects need to be separated out.

DEA is a non-parametric approach to the estimation of capacity and technical efficiency. An advantage of DEA is that it is able to incorporate multiple outputs directly in the analysis. Further, the technique does not require any pre-described structural relationship between the inputs and resultant output, which allows greater flexibility in the frontier estimation. A disadvantage of the technique, however, is that it does not account for random variation in the output(s), and so attributes any apparent shortfall in output to either capacity under-utilization or technical inefficiency.

The following example takes a two-output example to demonstrate DEA for the estimation of capacity and capacity utilization. The illustrated example describes five boats (*j = {A,B,C,D,E}*) targeting. In terms of fixed input use, the fleet is homogeneous. Therefore, the level of catch is determined by the extent to which the fixed inputs are fully utilized. Figure A.1 shows the catch ($u_{j,m}$) achieved by the boats for both species ($m = \{1,2\}$). The production possibility frontier is defined by boats A, B C and D, which as they lie on the frontier are assumed to be operating at full capacity. However, boat E is producing less of both species relative to the frontier and is therefore assumed to be operating at less than full capacity. The production potential of boat E can be found by expanding the output of both species radially from the origin until it reaches the frontier (point E*). OE*/OE is the expansion factor (θ) by which output of boat E could be increased. Capacity utilization of boat E is given by OE/OE* (i.e. 1/θ).

The shape of the frontier will differ depending on the scale assumptions that underlie the model. Two scale assumptions are generally employed: constant returns to scale (CRS) and variable returns to scale (VRS). The latter encompasses both increasing and decreasing returns to scale. However, there are generally *a priori* reasons to assume that fishing would be subject to variable returns, and in particular decreasing returns to scale. Figure A.2 shows the differences between these alternative measures for the five boats in the example above. In the analysis in this paper, the frontier is assumed to follow the form of a VRS model where zero inputs equate to zero outputs. Hence, the frontier would go through the points OBCD and would not be defined by the standard VRS envelope ABCD as shown.

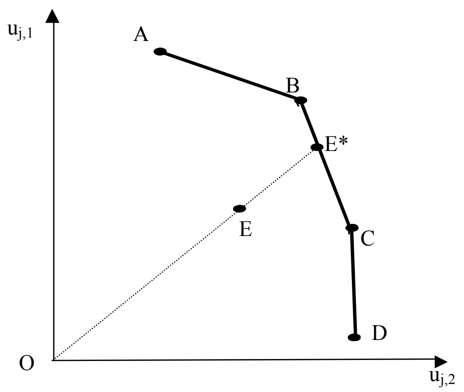

Figure A.1. Two output production possibility frontier.

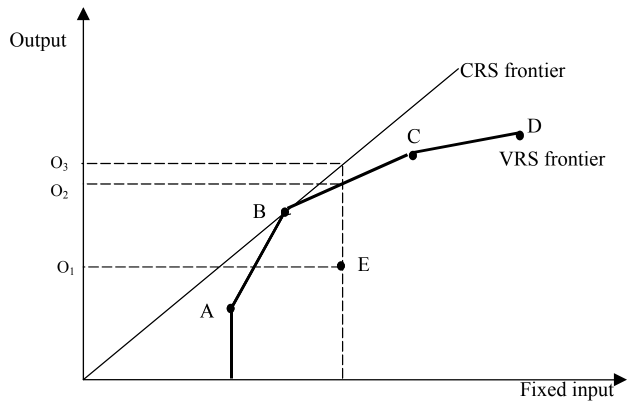

Figure A.2. CRS and VRS efficient frontiers.

The VRS DEA model is formulated as a linear programming (LP) model, where the value of θ for each vessel can be estimated from the set of available data. Following Färe *et al.* (1989, 1994) this DEA model of capacity output given current use of inputs is given as:

$$Max\,\theta_1$$

subject to

$$\begin{aligned}
&\theta_1 u_{0,m} \le \sum_j z_j u_{j,m} \quad \forall\, m \\
&\sum_j z_j x_{j,n} \le x_{0,n} \quad n \in \alpha \\
&\sum_j z_j x_{j,n} = \lambda_{0,n} x_{0,n} \quad n \in \hat{\alpha} \qquad (1)\\
&\sum_j z_j = 1 \\
&z_j \ge 0, \quad \lambda_{j,n} \ge 0 \quad n \in \hat{\alpha}
\end{aligned}$$

where θ_1 is a scalar showing by how much the output of each boat can be increased, $u_{j,m}$ is the output m produced by boat j, $x_{j,n}$ is the amount of input n used by boat j and z_j are weighting factors that determine the influence of each vessel j on the potential output of the vessel being considered (i.e. $z_j = 0$ for boats not on the frontier, and $z_j \ge 0$ for the vessels on the frontier). The value of θ_1 is estimated for each vessel separately, with the target vessel's outputs and inputs being denoted by $u_{0,m}$ and $x_{0,n}$ respectively. Inputs are divided into fixed factors (i.e. set α) and variable factors (i.e. set $\hat{\alpha}$). The measure of capacity output is calculated by relaxing the bounds on the sub-vector of variable inputs, $x_{\hat{\alpha}}$. This is achieved by allowing these inputs to be unconstrained through introducing an input utilization rate ($\lambda_{j,n}$). This is estimated in the model for each boat j and variable input n (Färe *et al.,* 1994). The restriction $\sum_j z_j = 1$ allows for variable returns to scale[8]. Hence, capacity utilization (*CU*) is defined as:

$$CU = 1/\theta_1 \qquad (2)$$

The measure of CU ranges from zero to 1, with 1 being full capacity utilization (i.e. 100 per cent of capacity).

Due to random variations in the catch being measured as under-utilization rather than stochastic error, the estimated capacity utilization may be biased downward (and capacity output biased upwards). Further, the observed outputs may not be produced efficiently (Färe *et al.,* 1994), and hence some of the apparent capacity under-utilization may be due to inefficiency (i.e. not producing the full potential given the level of fixed and variable inputs). If all inputs (both fixed and variable) are not being used efficiently, then it would be expected that output could increase without an increase in the level of variable inputs through the more efficient use of these inputs. By comparing the capacity output to the technically efficiency level of output, the effects of inefficiency can be separated from capacity under-utilization. As both the technically efficient level of output and capacity output can be upwardly biased due to random variability in the data, the ratio of these measures is a less biased (both statistically and theoretically) measure of capacity utilization.

[8] In contrast, excluding this constraint implicitly imposes constant returns to scale while $\Sigma z_j \le 1$ imposes non-increasing returns to scale (Färe *et al.,* 1989).

The technically efficient level of output requires an estimate of technical efficiency of each boat, and requires both variable and fixed inputs to be considered. The VRS DEA model for this technically efficient measure of output is given as:

$$Max\,\theta_2$$

subject to

$$\begin{aligned} &\theta_2 u_{0,m} \le \sum_j z_j u_{j,m} \quad \forall\, m \\ &\sum_j z_j x_{j,n} \le x_{0,n} \quad \forall\, n \\ &\sum_j z_j = 1 \\ &z_j \ge 0 \end{aligned} \tag{3}$$

where θ_2 is a scalar outcome showing how much the production of each firm can increase by using inputs (both fixed and variable) in a technically efficient configuration. In this case, both variable and fixed inputs are constrained to their current level. In this case, θ_2 represents the extent to which output can increase through using all inputs efficiently. The technically efficient level of output (u^*_{TE}) is defined as θ_2 multiplied by observed output (*u*). As the level of variable inputs is also constrained, $\theta_2 \le \theta_1$ and the technical efficient level of output is less than or equal to the capacity level of output (i.e. $u^*_{TE} \le u^*$). The level of technical efficiency is estimated as:

$$TE = 1/\theta_2 \tag{4}$$

Consequently, the unbiased estimate of capacity utilization (*CU**) is estimated by:

$$CU^* = \frac{CU}{TE} = \frac{1}{\theta_1} \Big/ \frac{1}{\theta_2} = \frac{\theta_2}{\theta_1} \tag{5}$$

As $\theta_1 \ge \theta_2$, the unbiased estimate $CU^* \ge CU$. The unbiased estimate CU* has been shown to be relatively insensitive to random error in the data (Holland and Lee 2002). Further details on the use of DEA in estimating capacity utilization in fisheries can be found in Kirkley and Squires (1999).

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