Economic effort management in multispecies fisheries: the FcubEcon model

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Applying single-species assessment and quotas in multispecies fisheries can lead to overfishing or quota underutilization, because advice can be conflicting when different stocks are caught within the same fishery. During the past decade, increased focus on this issue has resulted in the development of management tools based on fleets, fisheries, and areas, rather than on unit fish stocks. A natural consequence of this has been to consider effort rather than quota management, a final effort decision being based on fleet-harvest potential and fish-stock-preservation considerations. Effort allocation between fleets should not be based on biological considerations alone, but also on the economic behaviour of fishers, because fisheries management has a significant impact on human behaviour as well as on ecosystem development. The FcubEcon management framework for effort allocation between fleets and fisheries is presented, based on the economic optimization of a fishery's earnings while complying with stock-preservation criteria. Through case studies of two European fisheries, it is shown how fishery earnings can be increased significantly by reallocating effort between fisheries in an economically optimal manner, in both effort-management and single-quota management settings.

Keywords: bioeconomic model, economically optimal management, effort management, mixed-fisheries management.

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Introduction

With the introduction of the 2002 reform of the Common Fisheries Policy in the European Union (EC, 2002), effort restrictions were given still stronger weight alongside single-species quota control and restricted entry to the fisheries in the form of capacity restrictions and limitations on days at sea (Frost and Andersen, 2006). The reason for including effort control alongside quota control is that in mixed fisheries, most fleets harvest several species jointly. Each species is managed with separate single-species quotas that are often exhausted at different rates. The Scientific, Technical and Economic Committee for Fisheries (STECF) of the EU has since 2002 produced mixed-fisheries advice including economic repercussions in terms of single-species assessment, mixed-fisheries assessment, and management plans (Vinther *et al.*, 2004; SEC, 2004a, b). By introducing control of sea days alongside quotas, it is assumed that overexploitation of some species may be prevented, at least to some degree. Whether this is actually the case depends on how restrictive is the effort limitation, because this is not directly related to specific quotas, but instead limits general quota uptake across the board.

Today, therefore, there is growing awareness among decision-makers that focus in management should be shifted towards taking fisheries métiers into consideration, defined as a catch composition in a certain area during a certain period. The aim of the development of the Fcube model (Fleets and Fisheries Forecast; ICES, 2006, 2009, Ulrich *et al.*, 2009) is to provide mixed-fisheries advice (Ulrich *et al.*, 2008), using fisheries métiers as the management basis. Fcube can be used to (i) estimate over- and underutilization of quotas in a single-species management setting and (ii) set effort limits, or the corresponding catch compositions, based on fisheries and areas, in addition to single-species considerations.

In both cases, Fcube bases its management decisions on a combination of fleet catchabilities and fish-stock-preservation considerations. The basic assumption is that the fishing mortality exerted on a specific fish stock by a fleet métier is proportional to the effort exerted by that métier (Ulrich *et al.*, 2008, 2009). This correspondence is used by Fcube to determine the effort needed by a fleet segment to catch each of its original single-species quotas. These efforts may not necessarily be similar, leading to the problem of which effort to use. When the fishery is managed by single-species quotas, this decision is taken by the fisher, but it is taken by the decision-maker in an effort-management setting. Fcube covers, here, the following choices of effort in terms of days at sea: (i) the minimum effort needed to catch all species, (ii) the effort needed to catch a specific species, (iii) the maximum effort needed to catch all species, or (iv) the effort needed to catch the most-valuable species. The two last approaches may seem economically optimal, but they will not necessarily lead to maximum profits for the fishers because of the costs of fishing, and as such cannot be used to model the consequences of a fisher's economic behaviour.

The FcubEcon approach introduced here, on the other hand, takes Fcube a step further, and it bases the final distribution of effort on economic considerations of the harvesting agents. FcubEcon bases effort distribution between fleets and métiers on maximizing the total profit of the fleet segments involved. The approach thus recognizes that fisheries management has a significant impact on human behaviour as well as on ecosystem development and must as such be based on solutions that take into account the behaviour and economic interests of humans, as well as resource preservation. The FcubEcon approach is also discussed in comparison with the mixed-fisheries assessment carried out by the STECF.

FcubEcon was developed in connection with the 6th European Framework Programme project AFRAME (a framework for fleet- and area-based management), under which the model was applied to three case studies: (i) the North Sea demersal fishery, (ii) the Greek Aegean Sea (eastern Mediterranean) coastal and demersal fishery, and (iii) the Spanish fishery in the so-called western area (Channel, Celtic Sea, Bay of Biscay). The first two of these case studies are considered herein.

The manuscript contains a presentation of the Fcube and FcubEcon models and an application of the models to the two case studies. A similar evaluation has been made for the Spanish case study, but because this shows many of the same trends as the other two studies, those results are omitted for the current exercise.

The Fcube model

The model was initiated during the ICES WKMixMan workshop (ICES, 2006), and further developed as part of the AFRAME project (ICES, 2007a, 2008; Ulrich *et al.*, 2009). It was developed within the FLR framework (Kell *et al.*, 2007). A more detailed description can be found in ICES (2009). Only the main features are summarized below.

The starting point for Fcube is $j = 1, \ldots, J$ fleet segments, dividing effort between up to $k = 1, \ldots, K$ métiers that target $s = 1, \ldots, S$ different species. It is assumed that single-species total allowable catches (TACs) and corresponding target fishing mortalities, $F_{s,y}^{\text{targ}}$, are proposed for year y. In a single-quota management (SQM) setting, these TACs will be binding, but they are not binding if the aim is to set a final effort limit for each fleet segment, in which case the TACs are only guidelines for the final catches.

The initial TACs, and hence the fishing mortalities, are divided between member states and fleet segments using catch shares (or relative stabilities), $\text{RS}_{j,s,y}$, which are generally based on landings in previous years. This gives the following partial target fishing mortalities of species s for fleet segment j:

$$F_{j,s,y}^{\text{targ}} = F_{s,y}^{\text{targ}} \text{RS}_{j,s,y}. \qquad (1)$$

The effort corresponding to this partial fishing mortality, i.e. the effort needed by fleet segment j to catch its proposed quota of species s, depends on the segment's average catchability for species s. By "average" is meant that the overall fleet segment catchability will be a function of its individual métier catchabilities, which generally differ. Therefore, the average catchability $q_{j,s,y}$ of segment j in year y is estimated as a weighted average of the individual métier catchabilities $q_{j,k,s,y}$, using the effort distribution among métiers as weights:

$$q_{j,s,y} = \sum_k q_{j,k,s,y} e_{j,k,y}. \qquad (2)$$

Here, the catchability $q_{j,k,s,y}$ of métier k in segment j in year y is the average of the métier catchabilities in the years preceding the management year (the default choice is 3 years), assuming approximate constant catchabilities in the short term. The annual catchabilities are estimated using historical catch, stock, and effort observations. The fraction of effort $e_{j,k,y}$ used by métier k of the total effort exerted by fleet segment j in year y is likewise estimated as an average of the effort fractions $e_{j,k,y-i} = E_{j,k,y-i} / \sum_k E_{j,k,y-i}$ in the years preceding the management year, again assuming that effort distribution among métiers is constant in the short term.

The catchability $q_{j,s,y}$ estimated in Equation (2) is used to estimate the average effort needed by segment j to catch species s in management year y:

$$E_{j,s,y}^{\text{targ}} = \frac{F_{j,s,y}^{\text{targ}}}{q_{j,s,y}}. \qquad (3)$$

Thus, fleet segment j looks at s different target efforts $E_{j,s,y}^{\text{targ}}$, one for each species. These efforts will most often be unequal, which means that it is not physically possible for the segment to comply with all quotas, if it is assumed that the different species are caught in fixed proportions. For SQM, the fisher must then decide whether to comply with all quotas or to overfish some, and decision-makers must set the final effort limit based on policy decisions in the effort-management case.

The final effort limit for each fleet segment will be based on the consideration of the sustainability of the fish stocks as well as of fishery economics. If stock sustainability is the primary concern, a decision may be made to set the final effort equal to the target effort corresponding to the most-threatened stock, e.g. North Sea cod, *Gadus morhua*. This will probably lead to underutilization of the catch potential of the remaining species in a mixed fishery. If, on the other hand, short-term maximization of landings value of the fishery is the main concern, a decision may be made to set the effort to correspond to the quota for the stock that is least threatened. This will invariably lead to overutilization and depletion of the remaining species, so is not a viable solution in the long term. A third approach, used in the original Fcube framework (ICES, 2008), is to aim the effort at catching the quotas of the most-valuable species. As such, the final target effort assigned to fleet segment j is a function $f()$ of the individual species efforts in the Fcube framework evaluated using Equation (3):

$$E_{j,y}^{\text{final}} = f\,(E_{j,s,y}^{\text{targ}} \quad | \quad s = 1, \ldots, S). \qquad (4)$$

This final effort is then distributed on métiers using historical effort distributions:

$$E^{\text{final}}_{j,k,y} = E^{\text{final}}_{j,y} e_{j,k,y}. \tag{5}$$

The métier efforts are used to evaluate the final average (over age classes) partial fishing mortalities for each métier:

$$F^{\text{final}}_{j,k,s,y} = q_{j,k,s,y} E^{\text{final}}_{j,k,y}. \tag{6}$$

The final average fishing mortality for species s is then given by

$$F^{\text{final}}_{s,y} = \sum_{j,k} F^{\text{final}}_{j,k,s,y}, \tag{7}$$

which is distributed on age classes c, assuming that the relative distribution of fishing mortality is constant in the short term:

$$F^{\text{final}}_{s,c,y} = \frac{F^{\text{final}}_{s,y}}{F_{s,y-1}} F_{s,c,y-1}, \tag{8}$$

where $F_{s,c,y-1}$ is the historical fishing mortality in the year preceding the management year (or an average of fishing mortalities over 2–3 years) and $F_{s,\ y-1}$ is the average of this over the age classes. The final age-disaggregated fishing mortalities in year y are then used to evaluate the final catch of species s in the applicable year:

$$C^{\text{final}}_{s,y} = \sum_{c} \text{wt}_{s,c} N_{s,c,y} \left(1 - \exp(-F^{\text{final}}_{s,c,y} - M_{s,c})\right) \frac{F^{\text{final}}_{s,c,y}}{F^{\text{final}}_{s,c,y} + M_{s,c}}, \tag{9}$$

where $N_{s,c,y}$ is the stock (in numbers) of species s at the beginning year y, $\text{wt}_{s,c}$ is the weight per individual in age class c of species s, and $M_{s,c}$ is the natural mortality. As $C^{\text{final}}_{s,y}$ is based on the final effort, it is not necessarily equal to the TAC. Whether the amounts caught exceeding the TACs are landed or discarded depends on the management system (SQM; EM, effort management):

$$L_{j,s,y} = \begin{cases} \dfrac{\sum_k F^{\text{final}}_{j,k,s,y}}{F^{\text{final}}_{s,y}} C^{\text{final}}_{s,y}; & \text{SQM}, \dfrac{\sum_k F^{\text{final}}_{j,k,s,y}}{F^{\text{final}}_{s,y}} C^{\text{final}}_{s,y} \le \text{RS}_{j,s,y}\text{TAC}_{s,y} \\ \text{RS}_{j,s,y}\text{TAC}_{s,y}; & \text{SQM}, \dfrac{\sum_k F^{\text{final}}_{j,k,s,y}}{F^{\text{final}}_{s,y}} C^{\text{final}}_{s,y} > \text{RS}_{j,s,y}\text{TAC}_{s,y}. \\ \dfrac{\sum_k F^{\text{final}}_{j,k,s,y}}{F^{\text{final}}_{s,y}} C^{\text{final}}_{s,y}; & \text{EM} \end{cases} \tag{10}$$

In single-species quota management, the quota of species s distributed to segment j is given by $\text{RS}_{j,s,y}\ \text{TAC}_{s,y}$. The catches taken by segment j of species s are given by $\sum_k F^{\text{final}}_{j,k,s,y}/F^{\text{final}}_{s,y} C^{\text{final}}_{s,y}$, and as long as these are less than the quota, the whole catch is landed. When the catch, however, exceeds the quota, only the quota is landed, and the balance of the catch is discarded. In the effort-management scenario, on the other hand, everything caught is landed.

Economic assessment of the Fcube results

The original Fcube framework does not include any evaluations of the economic outcomes of the different effort scenarios, although economic assessment of such scenarios is important, seeing that fisheries management has a significant impact on both human behaviour and ecosystem development. Therefore, the original Fcube framework has been extended to contain an economic assessment module.

First, the landings resulting from the chosen effort scenario [Equation (10)] are divided into individual métier landings:

$$L_{j,k,s,y} = L_{s,y} \frac{F^{\text{final}}_{j,k,s,y}}{F^{\text{final}}_{s,y}}. \tag{11}$$

These are used to calculate fleet revenues (landings values), using prices $p_{j,k,s,y+1}$ disaggregated down to métier level:

$$R_{j,y} = \sum_{k,s} L_{j,k,s,y} p_{j,k,s,y}. \tag{12}$$

The profit for segment j is then given by the landings values less the variable costs, VC, and fixed costs, FC:

$$P_{j,y} = R_{j,y} - \text{VC}_{j,y}(E^{\text{final}}_{j,y}, L_{j,y}, R_{j,y}) - \text{FC}_{j,y}. \tag{13}$$

The variable costs are a function of (i) the final effort exerted by the fleet segment (ice, provisions, and fuel used per effort unit), (ii) the total landings weight summed over all species (through landings costs), and (iii) the total landings value (through crew costs). The fixed costs comprise insurance, depreciation, and interest, along with maintenance.

It must be expected that the profit initially increases, but at some maximum point it starts to decrease as effort increases, in both effort- and SQM cases. In the former case, the landings, and hence the landings value, cannot keep increasing continuously as effort increases because fish is a limited resource and production must have decreasing returns to scale. Contrary to this, the variable costs will increase steadily with increasing effort. For SQM, profit will peak as the landings, and hence the landings value, are limited by quotas. From an economic perspective, it is important for decision-makers and fishers to know the level of effort that determines peak profit. This is exactly what the FcubEcon model does, as outlined below.

FcubEcon: the economic optimization scenario for Fcube

The original Fcube framework does not directly include a choice of effort based on the economic behaviour of fishers. As an approximation to this, Fcube includes the value choice of effort, where the final effort is given by

$$E^{\text{final}}_{j,y+1} = \sum_{s} E^{\text{targ}}_{j,s,y+1} \frac{R_{j,s,y}}{\sum_s R_{j,s,y}}, \tag{14}$$

i.e. a weighted average of the target species efforts, where the weights are given by historical landings value shares of the different species. This effort choice is said to illustrate the case where fishers primarily target the most-valuable species. As the value effort given in Equation (14) is, however, less than the maximum effort corresponding to the different single-species quotas, any effort between value effort and maximum effort will necessarily contribute to the landings value [Equation (11)], so the value effort does not result in the highest landings value in either SQM or EF. Moreover, although the most-valuable species are used to set the effort, this will, as discussed above, not necessarily yield the greatest profit for fishers, because the variable costs depend on effort, catch value, and catch weight. Therefore, it should be clear that neither the value choice of effort [Equation (14)] nor the minimum or maximum choices of effort [Equation (4)] reflect true economic behaviour, i.e. that fishers are expected to try to maximize their total profit by (i) targeting economically valuable species while trying to comply with the quotas and (ii) keeping their costs of doing so as low as possible. To do this they could also be expected to divide their final effort between fleet métiers optimally, if possible. Such re-allocation of effort can of course only take place if allowed by the fleet structure and management scheme making it possible to re-allocate species quotas between fleet segments (and thus to redefine the relative stability if applied across EU member states).

A management system using individual transferable quotas (ITQs) satisfies these conditions just as profit-maximizing behaviour among the fishers entails quota trade and minimization of fishing costs. The literature on ITQs is extensive, starting with the paper of Christy (1973).

The FcubEcon model has been developed to analyse an ITQ case because it distributes effort between fleet métiers and quotas between fleet segments, while maximizing total fleet profit, given certain constraints:

$$\max_{E_{j,k,y}} P(E_{j,k.y} \mid j = 1, \ldots, J; \qquad k = 1, \ldots K), \tag{15}$$

where P is the profit [Equation (13)]. The constraints may be that the catches of each species should be less than the corresponding TACs or that the catch of a specifically threatened species should be kept below the TAC for that species while the catches of other species are not constrained. The restrictions could also be expressed in such a way that landings must not exceed quotas. In that case, there could be discarding or illegal landings. Further, there may be constraints on effort (minimum and maximum) and profit.

The optimal distribution of effort and quotas between fleet métiers performed by FcubEcon is not possible for all fleets in the short term where the fisher has no alternative other than to stick to his fishing gear and quotas. Moreover, the fisher will face transaction costs and lack of transparency on the market for ITQs. However, FcubEcon indicates the "what is best" allocation of effort and catches, and although this allocation may not be possible in the short term, it points to how fleet structure and quota allocation could be changed in the long term to maximize the earnings of a fishery. As such, FcubEcon adds to the original Fcube, giving the possibility to make the choice of effort from an economic perspective.

FcubEcon, as opposed to Fcube, selects effort endogenously, but based on constraints set exogenously. Therefore, the value judgement inherent in both models is moved from directly focusing on the final effort (Fcube) to focusing on, for example, the original management proposal on which Fcube is based.

Case studies

To illustrate the differences between Fcube and FcubEcon, two case studies are considered here: (i) the North Sea demersal fishery and (ii) the Greek Aegean Sea (eastern Mediterranean) coastal and demersal fishery. Both cases compare the economic outcomes of ten scenarios of effort allocation based on (i) five single-species quota scenarios and (ii) five effort-management scenarios. In the former case, the single-species quotas are binding, and over-quota catches cannot be landed and sold, but have to be discarded, but in the latter case, all catches are landed and sold. Each case evaluates the total economic outcome for the fishing fleet for five effort-allocation scenarios:

(i) the effort needed to catch the most binding species quota (MIN);

(ii) the effort needed to catch the least binding species quota (MAX);

(iii) the effort set to a weighted average of the effort needed to catch each species, the weights being the value shares of each species [cf. Equation (13)] (VAL);

(iv) the effort set using FcubEcon, so evaluating the effort maximizing fleet profit, while restricting total landings under single-species TACs (OPT1), reflecting an ITQ case with no discarding of over-quota catches because no TACs can be exceeded;

(v) the effort set using FcubEcon, thus evaluating the effort maximizing the fleet profit, but with no restrictions on landings (OPT2), reflecting an ITQ case with discards of over-quota catches.

Both MIN and OPT1 scenarios comply with the total single-species TACs in each management case. In contrast, catches above the single-species TACs will be made in the MAX and VAL scenarios, and can be expected in the OPT2 scenario, in both management cases. All effort-allocation evaluations (Fcube and FcubEcon) use the basic assumption that the number of sea days per vessel cannot physically exceed 365. Moreover, FcubEcon has the additional constraint that the final profit of each fleet in the management year should be greater than or equal to zero.

The management year is set to 2007 in both case studies. The evaluations are therefore based on average biological and economic values for the period 2004–2006. Note that there has been no further development in Case Study 1 since the present work was conducted and that biological and fleet data are continuously updated to provide a proposal for timely mixed-fisheries advice in ICES (ICES, 2009).

Case Study 1: North Sea demersal fishery

This case study includes 19 fleet segments from the European demersal fishery, covering vessels from Denmark, Belgium, England and Wales, the Netherlands, Scotland, and Norway, each including one to eight métiers. The fleet segments are classified according to length and gear type and the métiers to mesh size. Biological data were extracted from ICES (2007b). Fleet data, including effort and landings by métier, were provided by the relevant national scientific laboratories. Economic data for the fleet segments were obtained from AER (2008) and are based on data from 2004 to 2006. However, because economic data are missing (or highly uncertain) for 7 of the 19 fleet segments, these are not included in the economic assessments and optimizations. All segments are, however, included in calculating the landings, to make comparisons with total TACs. For these segments, the effort is set equal to the average fleet effort over the period 2004–2006.

The model includes 11 stocks, of which 6 are subject to stock assessment, namely cod, haddock (*Melanogrammus aeglefinus*), plaice (*Pleuronectes platessa*), pollock (*Pollachius virens*), sole (*Solea solea*), and whiting (*Merlangius merlangus*). Further, five stocks (also called Functional Units) of Norway lobster (*Nephrops norvegicus*), hereafter Nephrops, are included for which TACs and fishing mortalities are estimated through proxies based on historical catches and landings. Tables 1 and 2 list the basic economic and biological data used in the model.

Table 1. Basic economic parameter values used in the North Sea case study (average 2004–2006; source AER, 2008).

Fishery	Cost per fishing day ('000€ per day)	Landings cost ('000€ per tonne)	Wages (% of landings value)
Belgian beam trawl (93)	1.25	0.40	0.32
Danish demersal seine (24)	0.19	0.13	0.53
Danish demersal trawl <24 m (53)	0.27	0.04	0.50
Danish demersal trawl 24–40 m (39)	0.76	0.01	0.35
Danish gillnet (150)	0.11	0.15	0.62
English beam trawl (38)	1.19	0.25	0.26
Dutch beam trawl <24 m (62)	0.61	0.27	0.37
Dutch beam trawl >24 m (142)	2.60	0.28	0.25
Scottish beam trawl (15)	0.39	0.47	0.30
Scottish demersal seine (33)	0.69	0.14	0.30
Scottish demersal trawl <24 m (185)	0.50	0.24	0.29
Scottish demersal trawl >24 m (43)	1.31	0.17	0.30

The number of vessels in each segment is given in parenthesis.

Table 2. Basic biological parameters used in the North Sea case study (average 2004–2006).

Species	Average fishing mortality	Average natural mortality	Biomass at the start of 2007 (t)
Cod[a]	0.5334	0.3143	336 578
Haddock[a]	0.2897	0.4500	1 562 587
Plaice[a]	0.4344	0.1000	470 271
Pollock[a]	0.2909	0.2000	576 765
Sole[a]	0.3779	0.1000	59 625
Whiting[a]	0.3079	0.369	127 900
Nephrops6[b]	2.23	–	–
Nephrops7[b]	2.36	–	–
Nephrops8[b]	2.86	–	–
Nephrops9[b]	1.86	–	–
NephropsOther[b]	–	–	–

[a]Data for cod, haddock, plaice, pollock, sole, and whiting from ICES (2007b).
[b]Data for Nephrops proxies (the numbers and "Other" refer to Fuctional Units) estimated by C. Ulrich.

Table 3 shows the total fleet profits in each of the ten scenarios described. For SQM, it is most profitable for the fleet segments to re-allocate their effort between métiers and quotas between segments by maximizing total earnings, while overfishing some of the TACs (OPT2). If fishers decide not to comply with single-species quotas, it is least profitable for them to keep fishing until the least restrictive quota is taken (MAX), but it will be profitable for them to change their métier use and to interchange quotas between fleet segments in an economically optimal manner, so resembling an ITQ management scheme. If this is not possible, the VAL scenario yields the greatest profit in this case. Note also that the MIN scenario complying with all quotas and TACs is actually more profitable than the MAX scenario in the SQM case, because the MAX scenario is costly to fishers. The OPT1 scenario, an ideal ITQ scheme, complying with all TACs but reallocating métier effort and fleet segment quotas, is more profitable than the MIN, MAX, and VAL scenarios. This shows that it may be possible, even in the traditional SQM case, to comply with overall TACs while securing significant earnings for the total fleet and attaining economic sustainability.

Table 3 further shows that in the effort-management case, it is most profitable to re-allocate effort between métiers according to economic optimization, while allowing catches above single-species TACs (OPT2). The OPT1 and MIN scenarios result in the same earnings as in the SQM case, a natural consequence of the two scenarios complying with all single-species TACs. For decision-makers, the question in this case is how to set the final effort, ensuring sustainability of the fish stock as well as the fishing fleets. It is still profitable for the total fleet to comply with all TACs if effort is re-allocated between métiers and quotas between individual fleet segments (OPT1), but if no stocks are threatened seriously by exceeding TACs (OPT2), more can be earned by the total fleet. Finally, if it is not possible to re-allocate effort between métiers, it is most profitable to set effort according to the least-threatened species (MAX).

Tables 4 and 5 show the total fleet catches together with the percentage over/underutilization of total TACs, a negative sign indicating overfishing. The total catches are the same in the three Fcube scenarios (MIN, MAX, VAL), independent of the management case, because the last only determines whether or not all catches can be landed, as discussed above. Likewise, the total catches will be the same for the two management cases in the OPT1 scenario, because catches are restricted to be below the total TACs, so optimal profit will not be affected by whether or not over-quota catches can be landed and sold. For the OPT2 scenario, however, the catches will be different for the two management cases, because the optimal profit depends on whether over-quota catches can or cannot be landed and sold, which

Table 3. Total fleet profits (million €) for each of the ten management scenarios of the North Sea case study.

Scenario	SQM	EF
MIN	42.3	42.3
MAX	−15.2	159.3
VAL	76.1	105.7
OPT1	104.4	104.4
OPT2	125	252.4

N.B. In the single-quota case, over-quota catches have to be discarded, whereas in the effort-management case, such catches have to be landed and sold.

Table 4. Total catches made under each effort-allocation scenario in the MIN-, MAX-, and VAL-management cases in the North Sea case study.

Species	TAC (t)	Catch under quota/ effort (MIN) scenario	Catch under quota/ effort (MAX) scenario	Catch under quota/ effort (VAL) scenario
Cod	19 957	19 738 (1%)	51 953 (−160%)	36 393 (−82%)
Haddock	54 640	29 385 (46%)	97 357 (−78%)	62 698 (−15%)
Nephrops6	5487	1232 (78%)	8278 (−51%)	4795 (13%)
Nephrops7	12 713	3566 (72%)	19 390 (−53%)	11 112 (13%)
Nephrops8	2887	800 (72%)	4500 (−56%)	2562 (11%)
Nephrops9	2111	635 (70%)	3572 (−69%)	2034 (4%)
NephropsOther	2944	649 (78%)	3234 (−10%)	1265 (57%)
Plaice	50 261	23 709 (53%)	71 628 (−43%)	49 822 (1%)
Pollock	123 250	92 486 (25%)	149 697 (−21%)	121 872 (1%)
Sole	15 020	7101 (53%)	20 644 (−37%)	14 125 (6%)
Whiting	23 800	13 494 (43%)	22 150 (7%)	17 804 (25%)

Numbers in parenthesis show over- and underfishing of the TAC as a % of the TAC, i.e. (TAC−Catch)/TAC.
The five Nephrops proxies refer to Functional Units.

Table 5. Total catch in each effort-allocation scenario in the OPT1 and two OPT2 management cases in the North Sea case study.

Species	TAC (t)	Catch under quota/ effort (OPT1) scenario	Catch under quota (OPT2) scenario	Catch under effort (OPT2) scenario
Cod	19 957	19 956 (0%)	26 854 (−35%)	81 782 (−310%)
Haddock	54 640	26 115 (52%)	54 639 (0%)	115 487 (−111%)
Nephrops6	5487	3637 (34%)	3679 (33%)	4014 (27%)
Nephrops7	12 713	11 737 (8%)	12 712 (0%)	23 426 (−84%)
Nephrops8	2887	2661 (8%)	2969 (−3%)	5358 (−86%)
Nephrops9	2111	2111 (0%)	2355 (−12%)	4286 (−103%)
NephropsOther	2944	2042 (31%)	2042 (31%)	2042 (31%)
Plaice	50 261	50 260 (0%)	50 261 (0%)	87 200 (−73%)
Pollock	123 250	122 306 (1%)	124 573 (−1%)	138 338 (−12%)
Sole	15 020	15 020 (0%)	15 019 (0%)	23 459 (−56%)
Whiting	23 800	15 145 (36%)	16 926 (29%)	20 902 (12%)

Numbers in parenthesis show over- and underfishing of the TAC as a % of the TAC, i.e. (TAC−Catch)/TAC.
The five Nephrops proxies refer to Functional Units.

again will affect the optimal effort, and hence the catch allocation between fleets.

Comparison of Tables 4 and 5 shows that no catches exceed the TACs in the MIN and OPT1 scenarios, as expected. It is, however, interesting that the underutilization of TACs is reduced in the OPT1 scenario compared with the MIN scenario, thus giving better utilization of the TACs along with higher earnings for the fishery. The MAX scenario, on the other hand, shows overutilization of all TACs, as expected. The most heavily exploited species is in this case cod, with an overutilization of the TAC of ~160%. The value scenario overutilizes cod and haddock TACs and complies approximately with the TACs of plaice and pollock, demonstrating that plaice and pollock are the most-valuable species. Finally, in the EF scenario OPT2, all TACs are heavily overutilized, especially cod, for which the catch is >300% of the TAC. Even for compulsory discarding (quota OPT2), cod is overfished by 35%. Therefore, these scenarios are not advisable when determining fleet segment effort in the effort-management case.

Case Study 2: Greek Aegean Sea coastal and demersal fishery

This case study includes four fleet segments in the Greek coastal and demersal fisheries of the Aegean Sea: coastal vessels 0–12 and 12–24 m, and trawlers 12–24 and 24–40 m. The former are divided into three metiers; gill- or trammel-nets, static bottom longlines, and seines. Data used in this case study analysis are taken from the Data Collection Regulation framework (EC, 2000, 2006), under which sample data on effort and landings have been collected in Greece since 2000. Economic cost data for the Greek fleet has been provided by the national fishery data collection programme for Greece. These have been aggregated into variable costs per fishing day, landings costs and wage costs, the average of which are shown in Table 6 over the period 2004–2006. The four fleets target hake, red mullet, and striped red mullet and catch other species. Basic biological data for the three target species are shown in Table 7 (IMAS–FISH, 2008). Other species are not target species and are therefore not included in the predictions of final effort in the Fcube and FcubEcon simulations, so they do not need biological data. Final catch values of other species are, however, needed to predict the total landings values of the coastal fleets in the projection year. The catches of other fish are therefore evaluated using the effort decision based on the three target species and a measure of catch per unit effort for other species, based on the value in 2006 (Table 8).

Currently, Greek fisheries are not regulated by TAC (except for bluefin tuna), so to run the model scenarios, a set of virtual TACs and their corresponding fishing mortalities were applied. These were estimated using forward projections based on target fishing mortalities.

Table 9 shows the total fleet profits in each of the five effort-allocation scenarios for each of the two management cases for the Greek case study. As for the North Sea case study, the

Table 6. Basic economic parameters used in the Greek case study.

Fishery	Cost per fishing day ('000€ per day)	Landings cost (% of landings value)	Wages (% of landings value)
Coastal 0–12 m	0.0143	10.72	6.57
Coastal 12–24 m	0.0372	12.91	11.65
Trawl 12–24 m	0.4777	31.86	15.08
Trawl 24–40 m	0.6501	32.13	11.36

Table 7. Basic biological parameter values used in the Greek case study (average 2004–2006).

Species	Average fishing mortality 2004–2006	Average natural mortality	Biomass in January 2007 (t)
Hake	1.103	0.48	27 290
Red mullet	0.765	0.31	8733
Striped red mullet	0.708	0.49	6884

Table 8. Values of catch per unit effort (kg per day at sea) for other species in the Greek case study.

Fishery	Coastal 0–12 m	Coastal 12–24 m	Trawl 12–24 m	Trawl 24–40 m
Demersal	–	–	310.52	391.92
Longline	1.08	7.33	–	–
Net	35.64	82.80	–	–
Seine	124.20	535.16	–	–

Table 9. Total fleet profits (million €) for each of the ten management scenarios in the Greek case study.

Management scenario	SQM	EF
MIN	350	350
MAX	438	462
VAL	423	440
OPT1	378	378
OPT2	567	593

MIN and OPT1 scenarios gave the same results for the two management cases. In both management cases, it was most profitable to re-allocate effort between métiers, if possible, by optimizing total fleet profit and overfishing the TACs to some degree (OPT2). Moreover, the OPT1 scenario is more profitable than the MIN scenario but not the MAX and VAL scenarios, in both management cases. The reason the last two are most profitable is the increasing quantity of other species caught when effort increases. As these other species are not regulated, they can all be landed and sold, leading to steadily increasing landings values as effort increases. However, the fact that OPT1 effort allocation is more profitable than MIN effort allocation again proves that it is optimal to rethink the effort allocation between métiers and quota allocation between fleet segments in the long term.

Tables 10 and 11 show the total fleet catches together with the percentage of over/underutilization of the total TACs. As explained for the North Sea case, total catches are similar in the three Fcube scenarios (MIN, MAX, VAL) as well as in the OPT1 scenario, independent of the management case.

Catches are the same in the two OPT2 scenarios, i.e. no more can be gained by catching more in the effort-management scenario, different from the North Sea case study. Further, there is no sign of severe overfishing of the TACs in most scenarios, except red mullet in the OPT1 scenarios and striped red mullet in the OPT2 scenarios. In this case study, therefore, it seems that it would be relatively easy to decide to exceed the TACs to some degree in the effort-management case to obtain greater profit, because the consequences for the stocks will not be too severe. Note here that the OPT1 scenario underexploits the TAC for red mullet to a greater degree than the MIN scenario, probably because there are few possibilities to re-allocate effort between métiers and quotas between fleet segments in this case study. This is due to there being fewer fleet segments and métiers available. In contrast, the earnings of the fleet are still higher in the OPT1 scenario than in the MIN scenario, and because they both comply with single-species TACs, the OPT1 effort-allocation choice is preferable.

Discussion

We have presented here the Fcube and FcubEcon models used for effort allocation between fleet segments and métiers in managing

Table 10. Total catches in each effort-allocation scenario in the MIN-, MAX-, and VAL-management cases of the Greek case study.

Species	TAC (t)	Catch under quota/ effort (MIN) scenario	Catch under quota/ effort (MAX) scenario	Catch under quota/ effort (VAL) scenario
Hake	9077	8914 (2%)	11 051 (−22%)	10 061 (−11%)
Other species	–	51 827	74 313	66 076
Red mullet	3076	2342 (24%)	3076 (0%)	2754 (10%)
Striped red mullet	1926	1897 (1%)	2315 (−2%)	2228 (−16%)

Numbers in parenthesis show over- and underfishing of the TAC as a % of the TAC, i.e. (TAC–Catch)/TAC.

Table 11. Total catches in each effort-allocation scenario in the OPT1- and two OPT2-management cases of the Greek case study.

Species	TAC (t)	Catch under quota/ effort (OPT1) scenario	Catch under quota (OPT2) scenario	Catch under effort (OPT2) scenario
Hake	9077	9076 (0%)	10 467 (−15%)	10 467 (−15%)
Other species	–	45 916	88 503	88 503
Red mullet	3076	1712 (44%)	3176 (−3%)	3176 (−3%)
Striped red mullet	1926	1925 (0%)	2712 (−41%)	2712 (−41%)

Numbers in parentheses show over- and underfishing of the TAC as a % of the TAC, i.e. (TAC–Catch)/TAC.

multispecies fisheries. Both models can be used to (i) assess the biological and economic outcomes of various effort allocations in the traditional single-species TAC management case and (ii) propose various effort-allocation scenarios in terms of EF. The Fcube model does this based solely on biological considerations, whereas the FcubEcon model bases effort allocation on biological and economic considerations. The two models have been compared by applying them to the North Sea demersal fishery and the Greek Aegean Sea fishery.

The applications of the two models demonstrate how the use of fleet economic assessment and optimization scenarios along with the Fcube approach to fleet-based management adds an extra dimension to the assessments and proposals made by Fcube. By including the economic assessment of the Fcube scenarios, valuable information is gained on whether the proposed distribution of effort, which might be advantageous from the perspective of biological stock preservation, is also viable from a fleet economics perspective. In addition to this, FcubEcon provides valuable information about how greater gains can be achieved by the fishery while complying with TACs, e.g. by applying ITQ schemes, thus acknowledging that fisheries management has a significant impact on human behaviour as well as on ecosystem development. It is, however, clear that the results obtained with FcubEcon were based on the assumptions of full flexibility, complete market transparency, and no transaction costs for individual vessels within a fleet to switch métiers and exchange quota shares. The reality is more complex, however, so the estimated economic gains cannot be achieved in the short term.

The use of FcubEcon also reveals the impact of management systems and discarding. In the short term, it is not profitable for a fisher to exceed the quota and to discard over-quota catches given that discard provisions are complied with. However, economic gains are achieved if discard restrictions are lifted, which, on the other hand, will jeopardize stock recovery. Management systems that allow trading of quotas, and hence effort re-allocation, improves the economic performance even under full compliance with TACs.

The management advice produced by STECF has to some extent been based on mixed-fisheries advice (Vinther *et al.*, 2004). Criticism of this type of fisheries-management advice cannot be neglected, and all the problems are not yet solved (Kraak, 2003; Kraak *et al.*, 2008). Our conclusion is that many problems still require solution, but the Fcube and FcubEcon models integrate biological and economic approaches and do so in a simpler manner than other approaches. Therefore, further development and use of the models could provide useful support in managing fisheries.

Currently, the potential for FcubEcon has not been explored fully. It is possible to vary the number of vessels in each fleet segment alongside the number of sea days, thus evaluating which segments are economically viable and which are not. Various constraints can be explored alongside compliance (or non-compliance) with TACs. Further, the linear relationship between effort and fishing mortality currently used in the model may be exchanged for a non-linear relationship, thus approaching a potentially more realistic production relationship between effort, catches, and costs. The last issue has been approached in the 6th Framework project CAFE (CApacity, F, and Effort) and is, among others, described in van Oostenbrugge *et al.* (2008).

Finally, it may be of interest to compare modelling results with reality, e.g. with actual observed effort allocations from the year before an assessment, to investigate how much the current situation should be changed to obtain an economic optimum. All these issues need to be examined in future development and evaluation of the FcubEcon model.

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