Economic response to harvest and effort control in fishery

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The authors have been greatly inspired by the wisdom of 'My fair lady', to which we are greatly indebted.

The Lord above gave man an arm of iron
So he could do his job and never shirk.
The Lord gave man an arm of iron-but
With a little bit of luck, With a little bit of luck,
Someone else'll do the blinkin' work!

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Foreword

This report constitutes a contribution to the EFIMAS project, Operational Evaluation Tools for Fisheries Management Options, under EU's sixth framework programme, priority 8.

EFIMAS is carried out as a multidisciplinary research project with the aim to improve the scientific foundation for fisheries management. The report outlines bio-economic models, which are designed to shed light on the efficiency of different management tools in terms of quota or effort restrictions given the objectives of the Common Fisheries Policy about sustainable and economic viable fisheries.

The report addresses the complexities of biological and economic interaction in a multispecies, multifleet framework and outlines consistent mathematical models. The work is carried out by Ayoe Hoff and Hans Frost, Thomas Thøgersen has forwarded valuable comments, and Elsebeth Vidø is responsible for the editing of the report.

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Søren E. Frandsen

1. Introduction

It is a well-known fact that the fish stocks in European waters are generally overexploited. While quotas are steadily decreasing and effort-regulations made more severe, the need for a deeper understanding of the actual effects, biological, environmental and economic, of different management systems is becoming even more pronounced. As the economic situation for the fishing fleets is worsened, it becomes increasingly important for stakeholders to make decisions based on a solid knowledge-base, and to have a high level of information on how a proposed management scheme is influenced by the present situation and will influence on the future situation for the fishing fleets and the environment.

The objective of the 6'th framework project 'Operational Evaluation Tools for Fisheries Management Options (EFIMAS)' (EFIMAS 2003, 2006), is 'to develop an operational management evaluation framework that allows evaluation of the trade-off between different management objectives when choosing between different management options' (EFIMAS, 2003). This will 'facilitate the exploration of management options in the decision process by developing an operational fisheries evaluation framework to consider plausible hypotheses about the dynamics of the stocks and fleets and explore the relative expected merits of different management options on basis of these hypotheses'.

The EFIMAS evaluation framework comprises an operational model, i.e. a model of the fishery that is managed, and a "model" of the management procedure. The operational model includes biological as well as economical aspects of the fishery, including how the development of the fishery affects the economical situation for the fishing fleets.

The aim of the present report is to construct a model that includes full feed back procedures between fish stocks and fishing fleets and that can work with two independent types of constraints such as output constraints in terms of TAC/quota and input constraints in terms of sea days and number of vessels. The model comprises aspects from models such as the EIAA, TEMAS, BIRDMOD, MOSES, MEFISTO, and ECONMULT, see SEC (2006). The report is organised is such a way that emphasize is put on developing a modelling framework that does not get stuck taking into account the above mentioned requirements of full feed back and several output and input constraints. Therefore concepts such as recursivity and causality have formed strong basis for the model construction.

The report thus presents two dynamic bioeconomic models, both of which are especially constructed to model the economic development of a number of fishing fleets, given the influence of different management procedures on the fish stocks. Both models cover the economic response of a number of fleet segments to the harvest of a number of fish stocks. The economic response is modelled through a selling/buying behaviour in the fishing fleet, i.e. whether capacity (in the present case represented by the number of fishing vessels) is bought or sold as a result of the economic outcome. The fleet responses are as such modelled through an investment/disinvestment function simulating economic behavioural response to the economic result in previous years of the fishery. This investment/disinvestment object and how to link this to a general bioeconomic fishery model, is the central contribution of the present work to the EFIMAS framework, as a key aspect of all management assessment should be the economic response of the fishery to the imposed management plan.

As mentioned above the two models consider two different management schemes, namely output control (quotas) in the AHF-Q model, and input (days at sea) control in the AHF-E model. It could be argued that both types of management should be included in the same model, as a combination of these two schemes has been the situation for a number of EU fishing fleets since 2004[1], where regulation of sea days was introduced alongside quotas and limited entry in terms of number of fishing licences. It must, however, be stressed that output (harvest) and input (effort) controls are interrelated, i.e. a given harvest will necessarily determine the effort used or, correspondingly, a given effort used will necessarily determine the harvest. It is thus important to acknowledge the issues of causality and recursivity in the modelling process. It is not possible to implement harvest and effort regulation as two independent management initiatives in the same model of a fishery unless models including constrained optimisation procedures are used.

It is often stated that fishermen do not comply with the management rules be it quotas or sea days. In the simplest case non-compliance is assumed to be a function of the profit from non-compliance landings minus the probability of being detected times the penalty. Non-compliance is included in the models under the assumption of full information. If the fishery is subjected to asymmetric information i.e. the fishermen have more information than the managers non-compliance becomes complicated to impute into the models, not least in terms of data implementation (Hatcher and Pascoe 2006; Astorkiza et al. 2006).

[1] Introduced in 2003, but not fully effective

The AHF models simulate a number of fleet segments exploiting a number of species. With an individual fleet segment is meant a collection of approximately similar (homogeneous) vessels, i.e. it is assumed that the vessels in the segment have approximately equal physical characteristics in terms of length, gear type, gross tonnages and engine power equalised to the average values of all vessels in the segment.

Finally, the models divide the concept fishing effort into sea days and capacity (fishing vessels) i.e. variable and semi-fixed components that refers directly to variable and fixed costs. That makes it possible to distinguish and model the short run and long run economic behaviour of the fishermen.

Section 2 and 3 give presentations of the AHF-Q model and AHF-E models, while section 4 gives a short discussion of how harvest and effort regulation can be included in the same model. Finally an example of an application of the AHF-Q model is presented in section 5.

2. The AHF-Q model: Economic fleet response to harvest control rules

This section presents the bioeconomic AFH-Q management assessment model that evaluates the dynamic response of a number of fishing fleet segments to harvest control rules (HCR).

In the AHF-Q model, harvest and stock growth is assessed through the well-known biological age-structured model (Mohn and Cook, 1992). Discard is included in the model through the assumption that discard is proportional to total harvest. The harvest control rule is included through individual quotas for each fleet segment, and non-compliance catches are assumed to be proportional to the quotas.

As mentioned above harvest and effort are interrelated, so in the AHF-Q model the number of sea days are calculated, given the HCR. Thus the recursive flow of the AHF-Q model goes from fish stocks to fishing mortality rates to fishing effort, and the causality implies that total allowable catch is determined before the effort executed to catch the quotas is calculated. This approach links to the EIAA-model ('Economic Interpretation of ACFM advice', SEC 2004).

The economic response of the fishing fleet segments to the HCR is modelled through an economic entry/exit function that evaluates how much the different fleet segments will invest/disinvest given previous years incomes from the fishery. The income includes profit from the fishery and possible decommissioning grants.

The description of the AHF-Q model is divided into two sections, the first giving the initialization[2] of the model in the start year, and the second describing the dynamic recursive model for the following years.

In appendix A is found a reference list of all parameters used in the description of the model.

2.1. Initialization of the model, year y=0

The total amount landed ${}^{k}L^{0,j}$ (measured in weight) of species j ($j=1,\dots,J$) by fleet segment k ($k=1,\dots,K$) in the start year $y=0$ is given by[3]:

[2] Sometimes also called calibration or conditioning.
[3] Assuming full information about non-compliance

$$ {}^{k}L^{0,j} = \min\{\sum_a ({}^{k}H_a^{0,j} - {}^{k}Dis_a^{0,j}) \quad , \quad {}^{k}Q^{0,j} + {}^{k}U^{0,j}\} \tag{1} $$

Where ${}^{k}H_a^{0,j}$ and ${}^{k}Dis_a^{0,j}$ is the maximum possible harvest and discard (measured in weight) of species *j* for fleet segment *k* in the start year as a function of age *a*. ${}^{k}U^{0,j} = {}^{k}u^{0,j} \cdot {}^{k}Q^{0,j}$ are the non-compliance landings of species *j* for fleet segment *k*, that are assumed to be proportional to the quota. The harvest is in the AHF-Q model given by a biological age-structured model, e.g. (Mohn and Cook 1992):

$$ {}^{k}H_a^{0,j} = N_a^{0,j} \left(1 - e^{-m_a^{0,j} - \sum_k \left({}^{k}f_a^{0,j}\right)}\right) \frac{{}^{k}f_a^{0,j}}{m_a^{0,j} + \sum_k \left({}^{k}f_a^{0,j}\right)} w_a^j \tag{2} $$

Where $N_a^{0,j}$ is the number of fish of age *a* in stock *j* in the start year, $m_a^{0,j}$ is the natural mortality for species *j* at age *a* in the start year, ${}^{k}f_a^{0,j}$ is the fishing mortality for age *a* fish in stock *j* taken by fleet *k*, and w_a^j is the weight of fish in stock *j* at age *a*.

${}^{k}Q^{0,j}$ is the quota of species *j* for fleet segment *k* in the start year. This is equal to the total quota $Q^{0,j}$ for species *j* in the start year times the fleet segment share ${}^{k}ss^{0,j}$, that gives fleet segment *k*'s relative share of the quota for species *j*:

$$ {}^{k}Q^{0,j} = Q^{0,j} \cdot \left({}^{k}ss^{0,j}\right) \tag{3} $$

The segment shares can be estimated from former years landings of species *j* for the different fleet segments (as in the EIAA model, SEC 2004).

The discard by fleet segment *k* of species *j* in age class *a* is assumed to be some fraction ${}^{k}d_a^j$ of the total harvest:

$$ {}^{k}Dis_a^{0,j} = \left({}^{k}d_a^j\right) \cdot \left({}^{k}H_a^{0,j}\right) \tag{4} $$

Thus $\sum_a \left[{}^{k}H_a^{0,j} - {}^{k}Dis_a^{k,j}\right] = \sum_a (1 - {}^{k}d_a^j) \cdot {}^{k}H_a^{0,j}$ is the maximum amount it is possible for fleet segment *k* to land of species *j*. If this is restricted by the quota share ${}^{k}Q^{0,j}$**,** only the quota plus possible non-compliance catch will be landed, as shown in equation (1).

Equation (1) gives the total landings aggregated over age-classes. The landings of species *j* by fleet segment *k* are disaggregated back to individual age classes by:

$$ {}^{k}L_{a}^{0,j} = \begin{cases} (1-{}^{n}d_{a}^{j})\cdot {}^{k}H_{a}^{0,j} & ; \ \sum_{a}(1-{}^{n}d_{a}^{j})\cdot {}^{k}H_{a}^{0,j} < {}^{k}Q^{0,j} \\ {}^{k}\eta_{a}^{j}\cdot \ {}^{k}Q^{0,j}\cdot(1+{}^{k}u^{j,0}) & ; \ \sum_{a}(1-{}^{n}d_{a}^{j})\cdot {}^{k}H_{a}^{0,j} \geq {}^{k}Q^{0,j} \end{cases} \qquad (5) $$

Where ${}^{k}\eta^{j} = ({}^{k}\eta_{1}^{j},...,{}^{k}\eta_{A_{MAX}}^{j})$ are the landings distribution vectors, i.e. how the landings made by fleet segment *k* of species *j* is distributed over age-classes.

The Catch Per Day in the start year ${}^{k}CPD^{0,j}$ of species *j* by fleet segment *k* is defined by:

$$ {}^{k}CPD^{0,j} = \begin{cases} \dfrac{\sum_{a}({}^{k}H_{a}^{0,j})}{{}^{k}NV^{0}\ \cdot\ {}^{k}D^{0}}; & \sum_{a}(1-{}^{n}d_{a}^{j})\cdot {}^{k}H_{a}^{0,j} < {}^{k}Q^{0,j} \\ \dfrac{{}^{k}Q^{0,j}+{}^{k}U^{0,j}+{}^{k}Dis^{0,j}}{{}^{k}NV^{0}\ \cdot\ {}^{k}D^{0}} & ; \ \sum_{a}(1-{}^{n}d_{a}^{j})\cdot {}^{k}H_{a}^{0,j} \geq {}^{k}Q^{0,j} \end{cases} \qquad (6) $$

I.e. the average catch of species *j* in the start year, which is equal to the maximum possible harvest or to the quota plus the non-compliance harvest plus discard[4], depending on whether the harvest minus discard are greater or smaller than the quota, divided by the total number of sea days for fleet segment *k* in the start year. The latter is equal to the number of vessels ${}^{k}NV^{0}$ times the average number of sea days ${}^{k}D^{0}$ per vessel, both for fleet segment *k* in the start year. ${}^{k}CPD^{0,j}$ will be used to evaluate number of sea days in the following years.

Finally the profit ${}^{k}\Pi^{0}$ of fleet segment *k* in the start year is given by the total value of the landed fish minus the total costs:

$$ {}^{k}\Pi^{0} = \left(\sum_{a,j} p_{a}^{0,j}\ \cdot\ {}^{k}L_{a}^{0,j}\right) - {}^{k}TTC_{V}^{0} - {}^{k}TTC_{F}^{0} \qquad (7) $$

Where $p_{a}^{0,j}$ is the price obtained of species *j* at age *a* in the start year, and ${}^{k}TTC_{V}^{0}$ and ${}^{k}TTC_{F}^{0}$ are the variable and fixed costs for fleet segment *k* in the start year.

[4] Assuming that some discard also takes place when only the quota is landed

2.2. The recursive model, y>0

For $y>0$ the model goes through the sequence described below for each year.

2.2.1. The Investment/Disinvestment function:

At the beginning of the year y the capacity of fleet segment k (represented by number of vessels in segment k) is adjusted according to an investment decision function $\mathbf{I^k}$. The investment decision in year y, taken ${}^kLAG$ years before year y, is a function of the projected average profit through ${}^kLGT+1$ year, which is given by:

$$ {}^k\overline{R}^y = {}^k\Delta \cdot \left(\frac{1}{{}^kLGT+1} \sum_{i=0}^{{}^kLGT} \Pi^{(y-1)-{}^kLAG-i} \right) \tag{9} $$

Where ${}^k\Delta$ is the discounting of the average future revenues, given by:

$$ {}^k\Delta = \frac{\left(1-(1+r)^{-{}^kLT}\right)}{r} \tag{10} $$

r is interest rate and ${}^kLT$ the expected lifetime of a vessel. Given this, the investment decision function is given by:

$$ \mathbf{I^k}(\vec{\Pi}) = \begin{cases} \dfrac{{}^kI^+ \cdot {}^k\overline{R}^y}{{}^kV_{IN}} & ; \quad {}^k\overline{R}^y \geq 0, \quad {}^k\overline{R}^y \geq {}^kG^y \\ -\dfrac{{}^kG^y}{{}^k\Phi^y} & ; \quad {}^k\overline{R}^y \geq 0, \quad {}^k\overline{R}^y < {}^kG^y \\ \dfrac{{}^kI^- \cdot {}^k\overline{R}^y}{{}^kV_{OUT}} & ; \quad {}^k\overline{R}^y < 0, \quad {}^kG^y = 0 \\ -\dfrac{{}^kG^y}{{}^k\Phi^y} & ; \quad {}^k\overline{R}^y < 0, \quad {}^kG^y > 0 \end{cases} \tag{11} $$

${}^kG^y$ is the total decommissioning grant for fleet k in year y, i.e. the total amount offered to the fleet in return of decommissioning of vessels. ${}^k\Phi^y$ is the decommissioning rate for fleet k in year y, i.e. the grant given per unit capacity[5] decommissioned.

[5] E.g. per gross tonnage or in the present case per vessel.

${}^{k}\Phi^{y}$ may in some cases be equal to V_{OUT}. If the projected profit ${}^{k}\overline{R}^{y}$ is higher than ${}^{k}G^{y}$ it pays off for the fleet to invest in new vessels, while if ${}^{k}\overline{R}^{y}$ is positive but less than ${}^{k}G^{y}$, the fleet profits from disinvesting by decommissioning. If the average profit is less than zero the fleet will always disinvest, either corresponding to ${}^{k}\overline{R}^{y}$ if ${}^{k}G^{y}$ equals zero, or else corresponding to ${}^{k}G^{y}$. ${}^{k}I^{+}$ and ${}^{k}I^{-}$ are the investment and disinvestment shares for the fleet, and denote how big a fraction of the average profit is used for buying vessels or is compensated for by selling vessels. ${}^{k}V_{IN}$ and ${}^{k}V_{OUT}$ are the investment price and disinvestment benefit per vessel in fleet segment k. ${}^{k}V_{IN}$ is typically lower than ${}^{k}V_{OUT}$, reflecting asymmetry in the investment/decommissioning incentives.

The decommissioning benefit ${}^{k}V_{OUT}$ will be a function of the decommissioning rate ${}^{k}O$, typically inversely proportional, ${}^{k}V_{OUT} \propto 1/{}^{k}O$, as this will lead to more vessels being decommissioned the higher the rate gets.

Altogether the fleet segment size is adjusted using the investment function and a possible effort control rule, i.e. that the number of vessels in fleet segment k must not exceed a maximum value[6] ${}^{k}NV^{MAX}$:

$$
{}^{k}NV^{y} = \begin{cases} {}^{k}NV^{MAX} & ; \; I^{k}({}^{k}\vec{\Pi}) > ({}^{k}NV^{MAX} - {}^{k}NV^{y-1}) \\ {}^{k}NV^{y-1} + I^{k}({}^{k}\vec{\Pi}) & ; \; I^{k}({}^{k}\vec{\Pi}) \le ({}^{k}NV^{MAX} - {}^{k}NV^{y-1}) \end{cases} \qquad (12)
$$

${}^{k}NV^{MAX} - {}^{k}NV^{y-1}$ is the maximum allowable investment in fleet segment k in year y. If the possible investment $\mathbf{I^{k}}({}^{k}\vec{\Pi})$ in year y exceeds this amount, the full investment is not performed, but the number of vessels in fleet segment k in year y is set to ${}^{k}NV^{MAX}$. If the investment is less than the maximum allowable amount, the number of vessels in fleet segment k in year y is equal to the number of vessels in year y-1 plus the investment or decommissioning.

2.2.2. Stock projection in year *y*

The stock (measured in numbers of fish) as a function of age in year y is given by the biological stock projection formula (Mohn and Cook 1992):

[6] NV^{MAX} can be set to infinity if effort control is not exerted through the number of vessels.

$$N_a^{j,y} \equiv \begin{cases} N_0^{j,y}(SSB^{j,y-1}) & ; \quad a=0 \\ N_a^y(Q^{j,y-1}, m_{a-1}^{j,y-1}, F_{a-1}^{j,y-1}, d_a^j, u^{j,y-1}); & a>0 \end{cases} \tag{13}$$

Where $m_{a-1}^{j,y-1}$ is the natural fishing mortality for stock j, $F_{a-1}^{j,y-1} = \sum_k \left({}^k f_{a-1}^{j,y-1} \right)$ is the total fishing mortality of species j in year $y-1$, $d_a^j = ({}^1 d_a^j, ..., {}^K d_a^j)$ is the vector of discard rates for each fleet segment, of fish of age a, $Q^{j,y-1}$ is the total quota of stock j in year $y-1$, $u^{j,y-1} = ({}^1 u^{j,y-1}, ..., {}^K u^{j,y-1})$ is the vector of non-compliance rates for each fleet segment, and the function $N_0^{j,y}(SSB^{j,y-1})$ is the recruitment in year y (i.e. the number of juveniles entering the stock in year y) as a function of the spawning stock biomass in year $y-1$. $N_a^y(\cdot)$ is given by:

$$N_a^{j,y}(Q^{j,y-1}, m_{a-1}^{j,y-1}, F_{a-1}^{j,y-1}, d_a^j, u^{j,y-1}) = N_{a-1}^{j,y-1} \cdot \exp\left(-m_{a-1}^{j,y-1} - \sum_{k;\, {}^k L^{j,y-1} < {}^k Q^{y-1}} {}^k f_{a-1}^{j,y-1} \right) - \sum_{k;\, {}^k L^{y-1} \geq {}^k Q^{y-1}} {}^k \eta_{a-1}^j \cdot {}^k Q^{j,y-1} \cdot (1 - {}^k u^{j,y-1}) / \left((1 - {}^k d_{a-1}^j) w_{a-1}^j \right) \tag{14}$$

For the fleet segments k for which the landings are less than the quota the reduction in the stock by harvest is given by $N_{a-1}^{j,y-1} \cdot \exp\left({}^k f_{a-1}^{j,y-1} \right)$. If on the other hand the maximum possible landings are higher than the quota, e.g. because a high number of sea days is allowed, only the quota plus possible non-compliance catch will be landed. This is equal to the total harvest minus the discard, i.e. ${}^k \eta_{a-1}^j \cdot \left({}^k Q^{j,y-1} + {}^k U^{j,y-1} \right) = {}^k H_{a-1}^{j,y-1} (1 - {}^k d_{a-1}^j)$, where the landings distribution factor ${}^k \eta_{a-1}^j$ is used to divide the quota on age-classes. ${}^k U^{j,y-1}$ is the non-compliance harvest of species j performed by fleet segment k. This is assumed to be proportional to the quota ${}^k U^{j,y-1} = {}^k u^{j,y-1} \cdot {}^k Q^{j,y-1}$. The total harvest, measured in weight, of age class $a-1$ is then ${}^k \eta_{a-1}^j \cdot {}^k Q^{j,y-1} \cdot (1 - {}^k u^{j,y-1}) / (1 - {}^k d_{a-1}^j) = {}^k H_{a-1}^{j,y-1}$. This is divided by the weight of age class $a-1$ to get the number of fish caught.

2.2.3. Landings in year *y*

The amount landed ${}^k L^{y,j}$ (measured in weight) of species j by fleet segment k in year y is given by:

$${}^k L^{y,j} = \min\{ \sum_a ({}^k H_a^{y,j} - {}^k Dis_a^{y,j}) \;\; , \;\; {}^k Q^{y,j} + {}^k U^{y,j} \} \tag{15}$$

Where ${}^{k}H_a^{y,j}$, ${}^{k}Dis_a^{y,j}$ and ${}^{k}Q^{y,j}$ are maximum possible harvest, discard and quota of species *j* for fleet segment *k* in the year *y*, and ${}^{k}U^{y,j}$ is non-compliance catch. As mentioned above, the latter is assumed to be a linear function of *Q*, ${}^{k}U^{j,y-1} = {}^{k}u^{j,y-1} \cdot {}^{k}Q^{j,y-1}$. Alternatively, *U* could be a function of the profit the year before including parameters for the probability of being detected and the magnitude of the penalty.

As for the start year harvest, discard and quota are given by:

$$ {}^{k}H_a^{y,j} = N_a^{y,j}\left(1-e^{-m_a^{y,j}-\sum_i {}^{i}f_a^{y,j}}\right)\frac{{}^{k}f_a^{y,j}}{m_a^{y,j}+\sum_i {}^{i}f_a^{y,j}}w_a^j \tag{16} $$

$$ {}^{k}Q^{y,j} = Q^{y,j}\cdot\left({}^{k}ss^{y,j}\right) \tag{17} $$

$$ {}^{k}Dis_a^{y,j} = \left({}^{k}d_a^j\right)\cdot\left({}^{k}H_a^{y,j}\right) \tag{18} $$

And likewise the landings of species *j* by fleet segment *k* are disaggregated back to age classes by:

$$ {}^{k}L_a^{0,j} = \begin{cases} (1-{}^{n}d_a^j)\cdot\ {}^{k}H_a^{y,j} & ; \ \sum_a (1-{}^{n}d_a^j)\cdot {}^{k}H_a^{y,j} < {}^{k}Q^{y,j} \\ {}^{k}\eta_a^j\cdot\ {}^{k}Q^{y,j}(1+{}^{k}u^{j,y}) & ; \ \sum_a (1-{}^{n}d_a^j)\cdot {}^{k}H_a^{y,j} \geq {}^{k}Q^{y,j} \end{cases} \tag{19} $$

2.2.4. Catch per day

The Catch Per Day (CPD) if species *j* by fleet segment *k* in year *y* is defined as:

$$ {}^{k}CPD^{y,j} = {}^{k}CPD^{0,j}\cdot\left(\frac{SB^{y,j}}{SB^{0,j}}\right)^{{}^{k}\chi}\cdot\left(\frac{\sum_a {}^{k}L_a^{y,j}}{\sum_a {}^{k}L_a^{0,j}}\right)^{-({}^{k}\beta)} \quad ; \ 0\leq {}^{k}\chi \ , \ 0\leq {}^{k}\beta \tag{20} $$

The catch per day equation is based on an inverse Cobb-Douglas production function, and the CPD in the start year is scaled by the relative change in biomass SB^j and the relative change in landings *L* for species *j* between year *y* and the start year.

2.2.5. Number of sea days

The average number of sea days used per vessel in fleet segment *k* in year *y* is evaluated by:

$$ {}^{k}D^{y} = \frac{{}^{k}W^{y}}{{}^{k}NV^{y} \cdot \sum_{j} {}^{k}CPD^{y,j}} \tag{21} $$

Where ${}^{k}W^{y}$ is the total weight caught, summed over all species, in year *y* by a vessel in fleet segment *k*. This is given by:

$$ {}^{k}W^{y} = \sum_{j} \begin{cases} \sum_{a} {}^{k}H_{a}^{y,j} & ; \ \sum_{a}\left[{}^{k}H_{a}^{y,j} - {}^{k}Dis_{a}^{y,j} \right] < {}^{k}Q^{y,j} \\ {}^{k}Q^{y,j} + {}^{k}U^{y,j} + \sum_{a} {}^{k}Dis_{a}^{y,j} & ; \ \sum_{a}\left[{}^{k}H_{a}^{y,j} - {}^{k}Dis_{a}^{y,j} \right] \geq {}^{k}Q^{y,j} \end{cases} \tag{22} $$

I.e. by the sum of the total weights caught for each species. If maximum possible landings (maximum possible harvest minus discard) of species *j* is less than the quota, the weight caught is equal to the harvest, while it is equal to the quota plus the non-compliance catch plus the discard if the maximum possible landings are higher than the quota.

2.2.6. Evaluation of price vector in year *y*

The price vector in the year *y* for species *j* is assumed to be a function of the quota for the species in year *y*:

$$ P^{y,j} = (p_{0}^{y,j}, ..., p_{a}^{y,j}, ..., p_{A_{MAX}^{j}}^{y,j}) = P^{0,j} \left(\frac{\sum_{k} {}^{k}Q^{y,j}}{\sum_{k} {}^{k}Q^{0,j}} \right)^{\alpha_{j}} \quad ; \quad \alpha_{j} \leq 0 \tag{23} $$

I.e. the price vector in the start year is scaled according to the quota change, and thus the change in demand, from the start year to year *y*. α_{j} is the price flexibility rate for species *j*, and A_{MAX}^{j} is the maximum age of species *j*.

2.2.7. Profit

The profit of fleet segment *k* in year *y* is finally given by:

$$ {}^{k}\Pi^{y} = \left[\sum_{a,j} p_{a}^{y,j} \cdot {}^{k}L_{a}^{y,j} \right] - \left[\frac{{}^{k}D^{y} \cdot {}^{k}NV^{y}}{{}^{k}D^{0} \cdot {}^{k}NV^{0}} \cdot {}^{k}TTC_{V}^{0} \right] - \left[\frac{{}^{k}NV^{y}}{{}^{k}NV^{0}} \cdot {}^{k}TTC_{F}^{0} \right] \tag{24} $$

Where the variable costs in year *y* are evaluated by scaling the variable cost in the start year by the total number of sea days in year *y*, and the fixed costs in year *y* are likewise evaluated by scaling the fixed costs in the start year by the number of vessels in year *y*.

2.2.8. Causality and the recursive procedure

If harvest control rules such as TACs and sea days are used in combination and if sea days become binding it is necessary to change the causality of the model as the number of sea days is a function the TACs. This is described in section 3 in which biomass and landings become a function of sea days.

To overcome the complexities of this model a simplified procedure could be applied taken into account the restrictions of both the TACs and the sea days. By use of a feed back loop the fleet segment shares and hence landings of the pertinent fleet segment are scaled down according to the sea days limitation in proportion to the number of sea days required to catch the TAC. This procedure is explained and used in section 5.2.

3. The AHF-E model: Economic fleet response to effort control rules.

This section presents the bioeconomic AHF-E management assessment model that evaluates the dynamic response of a number of fishing fleet segments to effort control rules, expressed through control of sea days.

In the AHF-E model, harvest is modelled via the Cobb-Douglas economic production function, as a function of stock biomass and effort, where the latter is expressed through the total number of sea days for the fleet segment in question. Stock growth is evaluated through a combination of the well-known biological age-structured model (Mohn and Cook, 1992) and the harvest given by the Cobb-Douglas function. The effort control rule is included through limitations on the number of sea days given to each vessel in the fleet segments.

It is thus seen that in the AHF-E model harvest is evaluated and limited through the allowed effort. Thus the recursive flow of this model goes from fishing effort to fish stocks and landing (catches), and the causality implies that effort in terms of sea days and capacity is determined before the landings. This approach links to the project 'Technical Measures – Development of an Evaluation Model and Application in Danish Fisheries (TEMAS)', a project performed in collaboration between the Danish Institute of Fisheries Research and the Institute for Fisheries Management and Coastal Community Development (Eigaard et al, 2004).

The economic response of the fishing fleet segments to the effort control driven fishery is modelled as in the AHF-Q model through the economic entry/exit function described above.

The description of the AHF-E model is divided into two sections, the first giving the initialization of the model in the start year, and the second describing the dynamic recursive model for the following years. The same notation is used as for the AHF-Q model. When the AHF-E model moreover uses the same equations as the AHF-Q model, these equations are not repeated but only referenced.

In appendix A is found a reference list of all parameters used in the description of the model.

3.1. Initialization of the model, year *y=0*

In the AHF-E model harvest is limited through a maximum limit on the effort, here the number of sea days. As such it is assumed that landings are equal to harvest, and that there are no quotas or discard. The harvest, and thus the landings, of species *j* by fleet segment *k* are evaluated using a Cobb-Douglas production function, with total stock biomass (*SB*) and effort (total number of sea days in fleet segment *k*, ${}^{k}D^{0} \cdot {}^{k}NV^{0}$) as inputs:

$$
\begin{aligned}
{}^{k}L_{a}^{0,j} &= {}^{k}H_{a}^{0,j} \\
&\equiv {}^{k}\eta_{a}^{j} \cdot {}^{k}H^{j}(SB^{0,j}, {}^{k}D^{0} \cdot {}^{k}NV^{0}) \\
&= {}^{k}\eta_{a}^{j} \cdot {}^{k}F_{CD}^{j}(SB^{0,j}, {}^{k}D^{0} \cdot {}^{k}NV^{0}) \\
&= {}^{k}\eta_{a}^{j} \cdot \left[{}^{k}\beta_{0}^{j} \cdot (SB^{0,j})^{{}^{k}\beta_{1}^{j}} \cdot ({}^{k}D^{0} \cdot {}^{k}NV^{0})^{{}^{n}\beta_{2}^{j}} \right] \; ; \; 0 < {}^{k}\beta_{1}^{j} + {}^{k}\beta_{2}^{j} \leq 1
\end{aligned}
\qquad (25)
$$

where the harvest has been distributed on age-classes using the landings distribution factors. ${}^{k}\eta_{a}^{j}$. ${}^{k}\beta_{0}^{j}$, ${}^{k}\beta_{1}^{j}$ and ${}^{k}\beta_{2}^{j}$ are Cobb-Douglas parameters. The condition $0 < {}^{k}\beta_{1}^{j} + {}^{k}\beta_{2}^{j} \leq 1$ ensures non-increasing returns to scale, which is ideally assumed to prevail. This assumption may however in some cases be violated, i.e. it may be seen that the sum of the parameters is greater than unity, see e.g. Skjold, Eide and Flaaten (1996), Danielsson et al. (1997) and Ussif, Sandal and Steinshamn (2005).

The profit in the start year is given by equation (7). In the present model the gross margin profit per sea day is also needed, as this will be used to scale the sea-days in the following years. This is given by:

$$
{}^{k}\Psi^{0} = \frac{\left(\sum_{a,j} p_{a}^{0,j} \cdot {}^{k}L_{a}^{0,j}\right) - {}^{k}TTC_{V}^{0}}{{}^{k}D^{0} \cdot {}^{k}NV^{0}} \qquad (26)
$$

3.2. The recursive model, *y>0*

For *y>0* the model goes through the sequence described below for each year.

3.2.1. Investment/disinvestment

The investment/disinvestment function is the same as in the AHF-Q model, i.e. follows equation (9) to (12), and the corresponding discussion.

3.2.2. Number of sea days

For $y>2$, the average number of sea days used per vessel in fleet segment k in year y is assumed to be given by:

$$ {}^{k}D^{y} = \min\left[{}^{k}D^{y}_{MAX} \quad , \quad {}^{k}D^{y\text{-}1} \left(\frac{{}^{k}\Psi^{y-1}}{{}^{k}\Psi^{y\text{-}2}} \right)^{\varphi} \right] \tag{27} $$

Thus the number of sea days in the previous year times the fraction between the gross margins per sea day ${}^{k}\Psi$ in the two previous years. The factor φ determines the strength of the influence of the gross margin fraction on the change in number of sea days, and hence includes the incentive of non-compliance.

For $y=1$ the number of sea days is set equal to ${}^{k}D^{0}$, i.e. the number of sea days in the start year.

The way sea days are calculated as a function of profit (cash flow) in previous periods makes room for linkage to Random Utility Modelling (RUM), which is also used in the EFIMAS framework (EFIMAS, 2003, 2006)

3.2.3. Stock in year *y*

The size of the stock of species j (measured in numbers of fish) as a function of fish age a in year y is given by:

$$ N_{a}^{y,j} \equiv \begin{cases} N_{0}^{y,j}(SSB^{y-1,j}) & ; \quad a=0 \\ N_{a-1}^{y-1,j} \cdot \exp\left(-m_{a-1}^{y-1,j}\right) - NH_{a-1}^{y-1,j}; & a>0 \end{cases} \tag{28} $$

With the same notation as in equation (13) $NH_{a-1}^{y-1,j}$ is the total harvest (measured in numbers of fish) in year y-1 of species j in year class a-1. This is given by:

$$ NH_{a-1}^{y-1,j} = \sum_{k} {}^{k}NH_{a-1}^{y-1,j} \tag{29} $$

I.e. the sum over all fleet segments *k* of the harvest (measured in number of fish) of species *j* in age class *a-1* taken by segment *k*. The latter is given by:

$$ {}^{k}NH_{a-1}^{y-1,j} = \eta_{a-1}^{j} \cdot {}^{k}H^{y-1,j} / w_{a-1}^{j} \qquad (30) $$

I.e. the total harvest (equation 25), measured in weight, in year *y-1* of species *j* by fleet segment *k*, distributed on age classes and divided by the age-class weight, to obtain the harvest measured in number of fish. The evaluation of the total harvest is discussed below.

3.2.4. Biomass

The spawning stock biomass (SSB) and total biomass (SB) of species *j* in year *y* are given by:

$$ SSB^{y,j} = \sum_{a=A_M^j}^{A_{MAX}^j} w_a^j \cdot N_a^{y,j} \qquad SB^{y,j} = \sum_{a=0}^{A_{MAX}^j} w_a^j \cdot N_a^{y,j} \qquad (31) $$

Where A_M^j is the maturity age of species *j*.

3.2.5. Landings in year *y*

As discussed above, the landings are assumed to be equal to harvest in the AHF-E model, as the limiting factor is effort (number of sea days). Thus the landings in year *y* of species *j* by fleet segment *k* are given by:

$$
\begin{aligned}
{}^{k}L_a^{y,j} &= {}^{k}H_a^{y,j} \\
&= {}^{k}\eta_a^j \cdot {}^{k}H^{y,j} \\
&\equiv {}^{k}\eta_a^j \cdot {}^{k}H^{j}(SB^{j,y}, {}^{k}D^{y} \cdot {}^{k}NV^{y}) \\
&= {}^{k}\eta_a^j \cdot {}^{k}F_{CD}^{j}(SB^{j,y}, {}^{k}D^{y} \cdot {}^{k}NV^{y}) \\
&= {}^{k}\eta_a^j \cdot \left[{}^{k}\beta_0^j \cdot (SB^{j,y})^{{}^{k}\beta_1^j} \cdot ({}^{k}D^{y} \cdot {}^{k}NV^{y})^{{}^{n}\beta_2^j} \right] \; ; \; 0 < {}^{k}\beta_1^j + {}^{k}\beta_2^j \le 1
\end{aligned} \qquad (32)
$$

3.2.6. Price in year *y*

The price vector in the year *y* for species *j* is given by equation (23).

3.2.7. Revenue and gross margin in year *y*

The profit of fleet segment *k* in the year *y* is given by equation (24), and the gross margin per sea day is given by:

$$ {}^{k}\Psi^{y} = \frac{\left(\sum_{a,j} p_a^{y,j} \cdot {}^{k}L_a^{y,j}\right) - {}^{k}TTC_V^{0} \cdot \frac{{}^{k}D^{y}}{{}^{k}D^{0}}}{{}^{k}D^{y} \cdot {}^{k}NV^{y}} \qquad (33) $$

Where the variable costs are also scaled according to changes in sea days.

Thus, the AHF-E model in many ways reminds of the AHF-Q model, with the difference being that in the former number of sea-days are determined *before* the harvest is evaluated, while in the latter the number of sea-days is evaluated *from* the harvest. In the next section this issue of causality is taken a bit further and it is discussed if and how it is possible to include harvest and effort regulation in the same model.

4. Causality

It was argued in the introduction that for reasons of interdependence between harvest and effort it is not possible to construct a model that accommodates control rules on harvest and effort at the same time. More precisely it is not possible to construct analytical recursive models, as the AHF-models given above, in which both harvest and effort control rules are included. It is however possible to include both effort and harvest control in optimisation models, i.e. models including optimisation rules, e.g. maximum profit from the fishery. In this case solutions with respect to the variables (harvest, sea days and capacity) will be numerous.

These models will have to be constructed by use of inequalities to allow for solutions. Such a model needs two main components:

a. An objective function
b. Constraints (delimit the set of feasible solutions)

The general mathematical formulation is as follows using the same notation as in Frost and Kjaersgaad (2003):

$$\text{(A)} \quad \text{maximise} \quad \boldsymbol{c}\begin{bmatrix}\boldsymbol{x}\\ \boldsymbol{y}\end{bmatrix} \tag{34}$$

subject to:

$$\text{(B)} \quad A\begin{bmatrix}\boldsymbol{x}\\ \boldsymbol{y}\\ \boldsymbol{q}\end{bmatrix} \leq \boldsymbol{a} \tag{35}$$

$$\boldsymbol{x} \in \Re_{+}^{n}, \boldsymbol{y} \in \Re_{+}^{m}, \mathbf{q} \in \Re_{+}^{k}$$

Where:

- $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{q}$ are non-negative vectors of number of vessels, number of seadays and quotas.
- $\boldsymbol{c} \in \Re^{n+m}$ and $\boldsymbol{a} \in \Re^{I}$ are parameters and A a $(n+m+k)\times I$ real valued matrix
- I is the number of constraints.

The use of this model type requires optimisation for each period of the entire simulation period, and this model type is suitable for studies that compare for example the current situation with the optimal situation given the objectives and constraints.

5. Application: Danish Gillnetters catching cod in the North Sea

5.1. Fishing mortality and stock

To illustrate the use of the AHF-Q model, an example has been constructed for the Danish gillnet fleet catching cod in the North Sea.

As is well-known, the cod-stock in the North Sea has been steadily decreasing since the early 1970'es and is at present at the lowest level observed over the last century (ICES, 2005). In 2005 the Spawning Stock Biomass (SSB) was ~50.000 tonnes, which entails that the stock may be suffering from reduced reproductive capacity (ICES, 2005). The stock should be at least B_{lim}=70.000 tonnes to be able to reproduce itself. The precautionary level for the North Sea cod is set to B_{pa}=150.000 tonnes. Correspondingly the precautionary level of fishing effort is set to F_{pa}=0.65 and the maximum level of fishing effort to F_{lim}=0.86 for cod in the North Sea. In 2004 the European Commission introduced a specific cod recovery plan for the North Sea (EC Council Regulation 423/2004) that formulate harvest control rules with reference to the limit and precautionary stocks and that aim to keep the SSB above 150.000 tonnes in the long run.

The Danish gillnet fleet is one of the bigger actors in the Danish North Sea mixed fishery, and has during the last decade landed over 50% of the Danish cod quota for the North Sea yearly (Andersen and Christensen, 2005, Yearbook of Fishery Statistics 2003). Danish gillnetters mainly target cod, plaice and sole, and the landings value of cod for this fleet segment has on the average constituted ~50% of the total landings value for the segment during the period 2002-2004. The Danish quota of cod in the North Sea constitutes ~20% of the north sea TAC for the European Union, and thus the gillnetters take ~50%·20%=10% of the EU TAC of cod in the North Sea. The Danish gillnet fleet will not as such have a significant influence on the state of the cod stock in the North Sea.

The example models the development of the cod stock in the North Sea given a re-covery scheme, and the parallel development of the Danish gill net fleet during this recovery plan. The model is based on the AHF-Q model described above, and starts from the situation of the cod stock and the fishery in 2003. The model recursive scheme is run for 30 years. Relevant data used in the model for initiation of the cod stock in 2003 is shown in table 1.

Table 1. **Status of Cod stock in the North Sea in 2003 (ICES Study Group on the Multispecies Assessment in the North Sea – SGMSNS – 2005[7], ICES Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak – WGNSSK - 2005[8]).**

Age Class	Stock ('000 fish)	Catch weight (kg) per fish	Fishing mortality rate	Maturity fraction	Natural mortality rate
1	13003	0.608	0.031	0.01	0.35
2	60677	1.173	0.158	0.05	0.25
3	12843	1.848	0.273	0.23	0.2
4	9127	3.255	0.291	0.62	0.2
5	1708	5.185	0.263	0.86	0.2
6	213	7.407	0.310	1.00	0.2
7	142	8.704	0.345	1.00	0.2
8	41	12.178	0.317	1.00	0.2
9	20	12.851	0.350	1.00	0.2
10	9	10.772	0.333	1.00	0.2
11	2	17.5051	0.500	1.00	0.2

The cod stock recovery scheme used in the model builds on a simple recursive model[9], aiming at keeping the spawning stock biomass above B_{pa} by setting the total fishing mortality accordingly. Thus at the beginning of each year the cod stock of the previous year is compared to B_{pa} and B_{lim} and a target for the total fishing mortality for the present year is set according to:

$$F_{target}^{y} = \begin{cases} F_{pa} & ; \quad SSB^{y-1} > B_{pa} \\ F_{low} + (SSB^{y-1} - B_{\lim}) \dfrac{F_{pa} - F_{low}}{B_{pa} - B_{\lim}} & ; \quad B_{\lim} < SSB^{y-1} < B_{pa} \\ F_{low} & ; \quad SSB^{y-1} < B_{\lim} \end{cases} \qquad (36)$$

Where F_{low} is a minimum fishing mortality used when the stock is below $B_{\lim}$ and consequently in danger of extinction. Thus the total fishing mortality is at all times kept below or equal to the precautionary level. In the present application $F_{low} = 0.1$ is used, meaning that the cod fishery in the North Sea is never shut down completely.

[7] http://www.ices.dk/icesworks/wgdetailacfm.asp?wg=SGMSNS
[8] http://www.ices.dk/icesworks/wgdetailacfm.asp?wg=WGNSSK
[9] Inspired by a model constructed by Martin Pastoors for plaice recovery in the North Sea (EFIMAS 2003, 2006)

The perceived fishing mortality of the previous year is estimated as the total catch weight (TW) of cod divided by the biomass (SB) the previous year, i.e. the harvest rate in the previous year is used as a first order approximation to the fishing mortality[10]:

$$F_{percieved}^{y-1} = \frac{TW^{y-1}}{SB^{y-1}} \tag{37}$$

Given the target and perceived fishing mortalities, a fishing mortality scaling factor is determined as:

$$f_{correction}^{y} = \begin{cases} 0.8 & ; \quad \dfrac{F_{target}^{y}}{F_{percieved}^{y-1}} < 0.8 \\ \dfrac{F_{target}^{y}}{F_{percieved}^{y-1}} & ; \quad 0.8 < \dfrac{F_{target}^{y}}{F_{percieved}^{y-1}} < 1.2 \\ 1.2 & ; \quad 1.2 < \dfrac{F_{target}^{y}}{F_{percieved}^{y-1}} \end{cases} \tag{38}$$

The limits *0.8* and *1.2* again secures that the fishery is neither shut down completely nor will suddenly explode, thus causing the stock to decrease rapidly again.

The actual total fishing mortality vector (including fishing mortalities for each age-class) for the present year is set to:

$$\overline{F}^{y} = \overline{F}^{y-1} \cdot f_{correction} \tag{39}$$

Stock and total cod landings in year *y* is estimated using equation (13)-(19), assuming no discard, and using the fishing mortality set in equation (39). The recruitment in

[10] A more correct formula for perceived fishing mortality is $F^{y-1} = -\log\left(SB^{y-1} / SB^{y-1}\right) - M^{y-1}$ (cf. Hilborn and Walters 1992, pp 354), but as this involves the natural mortality which may be rather uncertain, it has been chosen to use the harvest rate which is at the same time the first order Taylor approximation to solving the projected catch equation for *F*.

year y $N_0^y(SSB^{y-1})$ (equation 13) is modelled through a Beverton Holt recruitment function, given by:

$$R = \frac{\mu \cdot S}{\lambda + S} \qquad (40)$$

Where R is recruitment (in numbers) and S is stock (in weight). The parameters μ and λ are estimated from stock-recruitment data dating back to 1963.

5.2. Landings and fleet segment shares

For the gillnet fleet the capacity in year y (i.e. the number of vessels NV^y) is determined using the investment/disinvestment model (9)-(12). It is assumed that $LAG_I=1$ and that $LGT_I=2$. The fleet starts at $NV^0 = 379$ vessels, equal to the number of Danish gillnetters in 2003.

The landings of North Sea cod by the gillnet fleet are determined by:

$$L^y_{gillnetters,Cod,NS} = \left(\sum_a {}^{total}L_a^y \cdot w_a \right) \cdot CS \cdot FSS^y \qquad (41)$$

Where ${}^{total}L_a^y$ are the total landings of cod in the North Sea in year y, CS is the country share of the total TAC for cod in the North Sea (the relative stability for DK equal to 20.45%) and FSS^y is the fleet segment share of cod in the North Sea for gill netters in year y (i.e. how much the gillnet fleet takes of the total Danish landings of North Sea cod). FSS^y is estimated in two steps. First it is set by a base-value given by:

$$FSS^y_{BASE} = FSS^0 \cdot \left(\frac{NV^y \cdot D_{MAX}}{NV^0 \cdot D_0} \right) \cdot \left(\frac{\sum_a {}^{total}L_a^0}{\sum_a {}^{total}L_a^y} \right) \quad ; \quad FSS^0 = 0.49 \qquad (42)$$

I.e. the base FSS is firstly scaled according to the development of the fleet capacity (measured through the total number of sea days). D_{MAX} is the maximum number of sea days available per vessel in the fleet per year ($D_{MAX} \leq 365$), and $NV^y \cdot D_{MAX}$ is thus the maximum capacity available in year y. Secondly the base-value of FSS is scaled according to the development in the total landings of cod in the North Sea. *FSS* will decrease when the total landings and thus the Danish quota increase (through stock recovery), to keep the fleet segments landings within physically possible bounds. The start value of *FSS* is based on Danish catch data from the period 2003 (Yearbook of Fishery Statistics, 2003).

Total effort (days at sea) D^{y}_{BASE} for the gillnet fleet is estimated using equation (20)-(22). If the days at sea exceeds D_{MAX} this means that the fleet landings, and thus *FSS*, are set too high, and the base-value of *FSS* is then corrected. The new value of *FSS* is set to:

$$FSS^{y}_{Correct} = FSS^{BASE}_{y} \cdot \frac{D_{MAX}}{D^{y}_{BASE}} \tag{43}$$

This leads to corrected fleet landings evaluated through equation (41) and corrected days at sea evaluated with equation (20)-(22). This loop is run until the number of days at sea per vessel is below D_{MAX} , which is in the present example set to 365 days. In the start year the fleet is given 127 sea days per vessel, equal to the average number measured in 2003. For the evaluation of CPD (equation 20) the stock and landings scaling factors are set to: $\chi=0.8$ and $\beta=1$.

Price of cod from the North Sea in year *y* is evaluated using equation (23). For the quotas is used the total cod landings in the North Sea, evaluated as described above, as these are direct proxies for the quotas, given that they are evaluated using the target fishing mortality described above. The start price is set to 2.16 Euro/kg, equal to the average price of cod landed by the Danish gillnet fleet in 2003. The price flexibility is set to $\alpha = -0.2$.

The gillnet revenue from the cod landings in the North Sea in year *y* $\rho^{y}_{Cod,NS} = p^{y}_{Cod} \cdot L^{y}_{Gillnetters,Cod,NS}$ is evaluated as the product of the gillnet landings of cod (equation 40) times the price in year *y*. To estimate the change in capacity (number of vessels) from year to year via the investment/disinvestment function it is however necessary to have a measure of the total revenue of the gillnet fleet in year *y*, i.e. the revenue from all landings in all fishing grounds. This is estimated by:

$$\rho^{y}_{Total} = \left(\rho^{y}_{Cod,NS} \cdot \frac{1}{CCF^{y}_{NS}} \right) \cdot \frac{1}{CVF^{y}} = \left(\left[p^{y}_{Cod} \cdot L^{y}_{Gillnetters,Cod,NS} \right] \cdot \frac{1}{CCF^{y}_{NS}} \right) \cdot \frac{1}{CVF^{y}} \tag{44}$$

CCF_{NS}^{y} is the fraction that the gillnet cod catch (measured in weight) in the North Sea constitutes of the total gillnet cod catches (measured in weight) from all fishing grounds. Thus when the gillnet cod landings from the North Sea are divided by this factor a measure is obtained of the total gillnet cod catch (measured in weight) in all fishing grounds. And multiplying this with the cod price gives the total catch value of cod for the gillnet fleet. CVF^{y} is the fraction that the gillnet landings value of cod constitute of the total gillnet landings value. Thus when the cod landing value is divided by this factor a measure of the total landing value (revenue) for the gillnet fleet is obtained.

In 2003 CCF_{NS} was equal to $CCF_{NS}^{0} = 0.2$ (Yearbook of Fishery Statistics, 2003). It is in the model assumed that this fraction increases if the gillnet landings of cod in the north sea increases (e.g. due to stock recovery). Thus CCF_{NS}^{y} is modelled according to:

$$CCF_{NS}^{y} = \frac{1}{1 + A \cdot \exp\left(-0.1 \cdot \frac{L_{Gillnetters,Cod,NS}^{y}}{L_{Gillnetters,Cod,NS}^{0}}\right)} \quad ; \quad A = \exp(0.1)\left(\frac{1}{CCF_{NS}^{0}} - 1\right) \qquad (45)$$

Which is equal to CCF_{NS}^{0} when $L_{Gillnetters,Cod,NS}^{y} = L_{Gillnetters,Cod,NS}^{0}$ and will go towards unity as $L_{Gillnetters,Cod,NS}^{y}$ increases.

In the period 2002-2004 CVF^{y} was on the average $CVF^{0} = 0.49$. In the present model it is assumed that this fraction remains constant throughout the years, i.e. that the fleet will also still takes other species even though the cod stock in the north sea recovers.

Finally the gillnet profit in year *y* is evaluated using equation (24) but with the revenue given by equation (44).

5.3. Results

The model described above has been run over a successive period of 30 years starting in 2003. The model firstly predicts that the Cod stock in the North Sea will recover, given the simple recovery scheme described above. This is seen in figure 1 that shows the spawning stock biomass (SSB) and recruitment (R) as a function of time in the modelling period. The precautionary level B_{pa}=150.000 tonnes is emphasized with a thick line. It is seen that SSB and R quickly rises while the fishing mortality is still very low, and then both fall towards the precautionary level, as is the aim with the recovery scheme. The fishing mortality (averaged over age classes) and fishing mortality correction factor (equation 38) are shown in figure 2. It is seen that the fishing mortality stays more or less constant (low) in the first 5 years, while the SSB recovers some, but that the model then allows the fishing mortality to rise for 15 years while the SSB is high, after which period the fishing mortality starts to fall and will oscillate slightly around an equilibrium level.

Figure 1. Development of spawning stock biomass (SSB) and recruitment (R) during the modelling period. The precautionary level Bpa=150.000 is emphasized with a thick line.

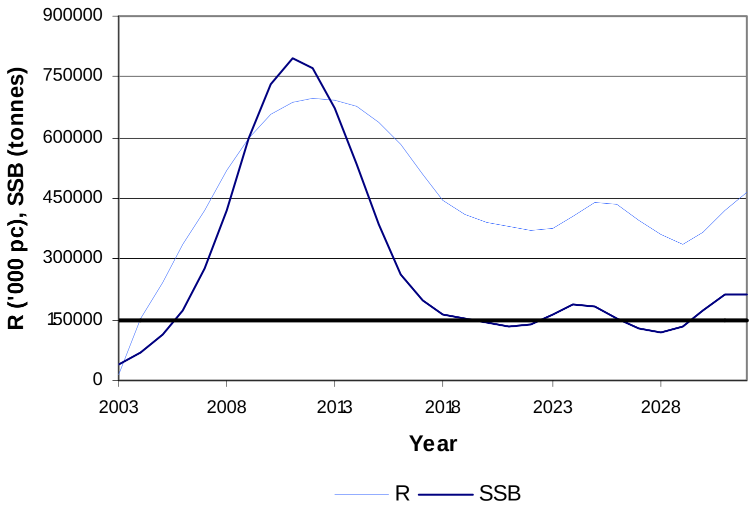


Figure 2. Average (over age classes) fishing mortality and fishing mortality correction factor (equation 39) during the modelling period.

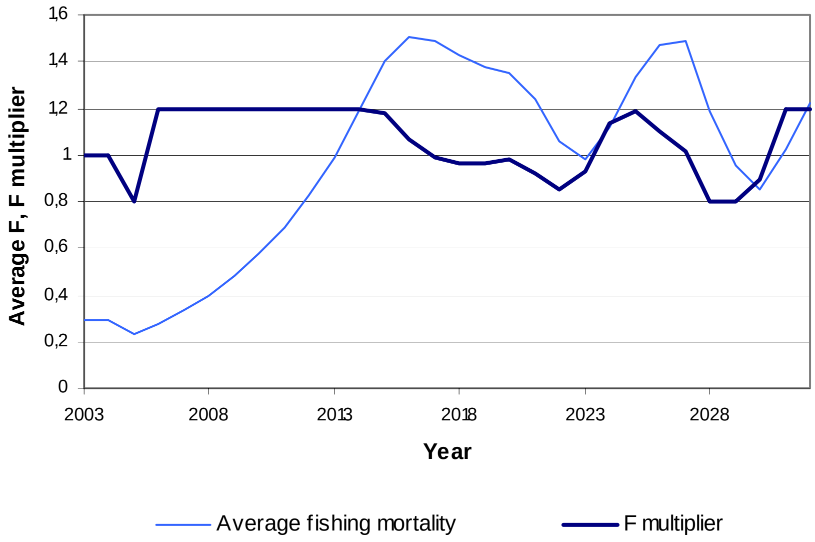


Figure 3 shows the logarithm of the total catches of cod in the North Sea, and of the gillnet catches of cod in the North Sea. It is seen that the total catches starts to fall before the fishing mortality (figure 2) peaks, thus following the pattern of SSB shown in figure 1. That the fishing mortality peaks later than total catches and SSB is caused by the lag in the fishing mortality correction procedure. The gillnet catches approximately follow the same pattern as the total catches.

Figure 4 shows the development in capacity (number of vessels) and effort (number of sea days per vessel) for the Danish gillnet fleet during the modelling period. It is seen that the capacity increases steeply while the stock and thus catches increase, and that the capacity reaches a peak a couple of years later than the stock peaks, because of the lag in investment. The capacity then drops and levels out at equilibrium of around 300 vessels, when the stock and catches reaches equilibrium. The sea days per vessel on the other hand only oscillates slightly during the period between 100 and 200 days. This difference in development pattern between capacity and effort illustrates how the AHF-Q model evaluates capacity independent of effort.

Figure 3. Logarithm of total and gillnet catches of Cod in the North Sea

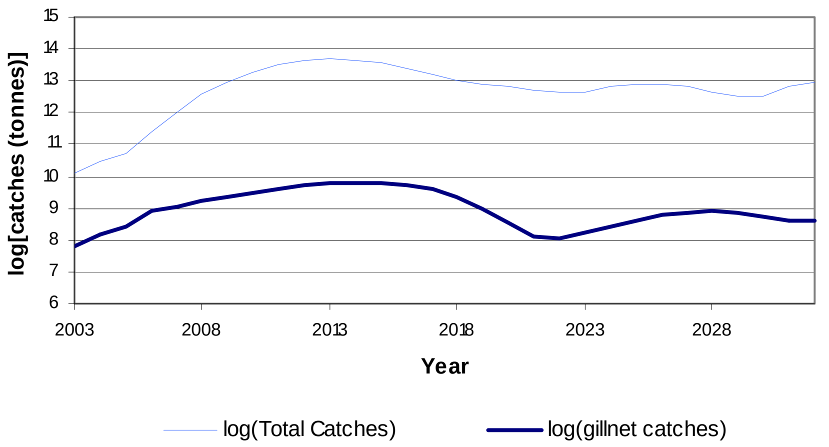
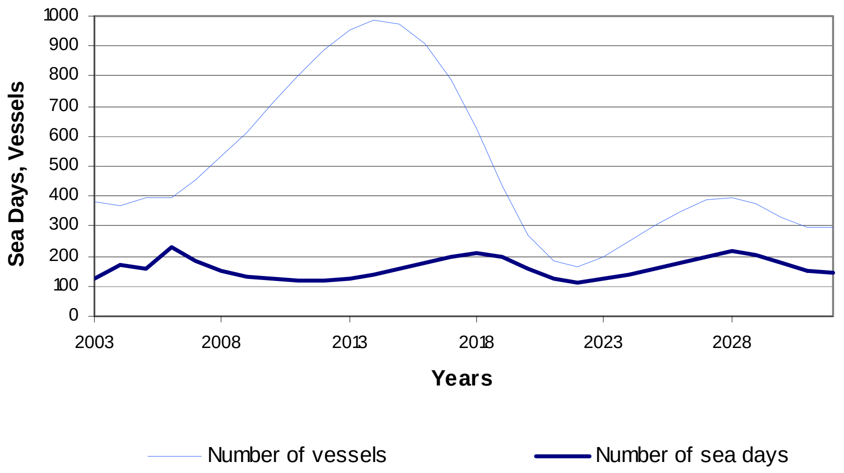
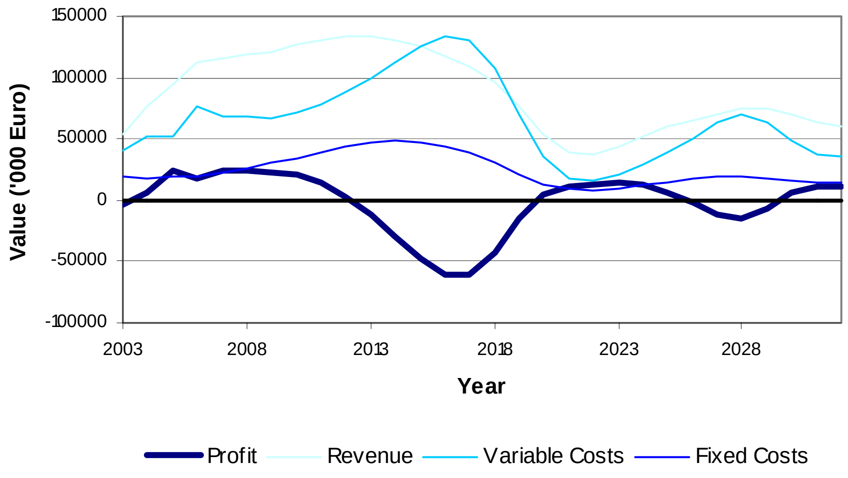


Figure 4. Capacity (number of vessels) and Effort (number of sea days) for the Danish gillnet fleet during the modelling period.



Finally figure 5 shows profit, revenue, fixed and variable costs for the gillnet fleet during the modelling period. It is seen how the profit goes from being approximately zero to significantly positive in the peak period where the stock recovers and fleet increases, then takes quit a steep fall to negative profit when the capacity and thus variable costs peaks while landings and thus revenue has started to fall. Finally the profit levels out around zero when the stock has recovered and the system reached equilibrium.

Figure 5. Profit, Revenue, Fixed and Variable Costs for the Danish gillnet fleet during the modelling period.



5.4. Discussion and conclusion

In is clear that the model presented above is a simplification of the actual dynamics between fish stocks, management plans and fishery. It has been made clear during the construction of the model that the results are extremely sensitive to the calibration of the model. The model, however, still gives a plausible indication of the possible development of a depleted fish stock under a recovery scheme, given that the fleets participating in the fishery of the stock comply with the scheme. And, at the same time, it is interesting to follow the resulting development of one of the fleet segments catching part of the stock during the recovery scheme, even though it may be unrealistic that the fleet size is allowed to vary by more than 150% during a period of 15 years.

It should be noticed that the loop used to bring number of sea days per vessel below the maximum allowed level may not be the most optimal way to approach this problem. On the contrary it would be more correct to switch to the AHF-E model when the number of sea days given by the AHF-Q model is too high. An example is at present developed using this approach.

In all the value of the model exercises must be found in the fact that they provide management with information, which allow managers to intervene in a sensible way.

Appendix A: Notation used in the AHF-Q and AHF-E models

${}^{k}L^{0,j}$	The total amount landed (measured in weight) of species *j* by fleet segment *k* in the start year *y=0.*
${}^{k}L^{y,j}$	The total amount landed (measured in weight) of species *j* by fleet segment *k* in year *y*.
${}^{k}H_{a}^{0,j}$	The maximum possible harvest (measured in weight) fleet segment *k* can take of species *j* at age *a* in the start year *y=0*.
${}^{k}H_{a}^{y,j}$	The maximum possible harvest (measured in weight) fleet segment *k* can tae of species *j* at age *a* in year *y*.
$NH_{a}^{y,j}$	Total harvest (measured in number of fish) in year *y* of species *j* at age *a*.
${}^{k}W^{y}$	Total weight caught by fleet segment *k* in year *y*.
${}^{k}Dis_{a}^{0,j}$	The discard (measured in weight) made by fleet segment *k* of species *j* at age *a* in the start year *y=0*.
${}^{k}Dis_{a}^{y,j}$	The discard (measured in weight) made by fleet segment *k* of species *j* at age *a* in year *y*.
${}^{k}Q^{j,0}$	The quota (weight) of species *j* for fleet segment *k* in the start year *y=0*.
${}^{k}Q^{y,j}$	The quota (weight) of species *j* for fleet segment *k* in year *y*.
$Q^{j,y}$	The total quota (weight) of species *j* in year *y*.
${}^{k}U^{y,j}$	The over quota landings (weight) of species *j* for fleet segment *k* in year y due to non-compliance.
${}^{k}u^{y,j}$	Quota proportionality factor for non-compliance landings
$SSB^{j,y}$	Spawning Stock Biomass of species *j* in year *y*.
$SB^{0,j}$	Biomass of species *j* in the start year *y=0*.
$SB^{y,j}$	Biomass of species *j* in year *y*.
$N_{a}^{0,j}$	The number of species *j* at age *a* in the start year *y=0*.
$N_{a}^{j,y}$	The number of species *j* at age *a* in year *y*.
A_{MAX}^{j}	Maximum age of species *j*.
$m_{a}^{0,j}$	The natural mortality for species *j* at age *a* in the start year *y=0*.
$m_{a}^{j,y}$	The natural mortality for species *j* at age *a* in year *y*.
${}^{k}f_{a}^{0,j}$	The fishing mortality for species *j* at age *a* taken by fleet segment *k* in year *y=0*.
${}^{k}f_{a}^{j,y}$	The fishing mortality for species *j* at age *a* taken by fleet segment *k* in year *y*.
$F_{a}^{j,y}$	Total fishing mortality for species *j* at age *a* in year *y*.
w_{a}^{j}	The weight of species *j* at age *a*.
${}^{k}ss^{0,j}$	Fleet segment share of species *j* for fleet segment *k* in the start year *y=0*.
${}^{k}d_{a}^{j}$	The fraction discarded of the total harvest made by fleet segment *k* of species *j* at age *a*

${}^{k}\eta^{j}$	$= ({}^{k}\eta_{1}^{j}, \ldots, {}^{k}\eta_{A_{MAX}}^{j})$ The landings distribution vector for fleet segment *k* of species *j*, i.e. how the total landings are distributed over age-classes.
${}^{k}CPD^{0,j}$	Catch Per Day for fleet segment *k*'s landings of species *j* in the start year *y=0.*
${}^{k}CPD^{y,j}$	Catch Per Day for fleet segment *k*'s landings of species *j* in year *y.*
${}^{k}NV^{0}$	Number of vessels in fleet segment *k* in the start year *y=0*.
${}^{k}NV^{y}$	Number of vessels in fleet segment *k* in year *y*.
${}^{k}D^{0}$	Days at sea per vessel in fleet segment *k* in the start year *y=0*.
${}^{k}D^{y}$	Days at sea per vessel in fleet segment *k* in year *y*.
${}^{k}D_{MAX}^{y}$	Maximum allowed number of sea days for each vessel in fleet segment *k* in year *y*.
${}^{k}\Pi^{0}$	Revenue of fleet segment *k* in the start year *y=0*.
${}^{k}\Pi^{y}$	Revenue of fleet segment *k* in year *y*.
${}^{k}\Psi^{0}$	Gross margin profit for fleet segment *k* in the start year, *y=0*.
${}^{k}\Psi^{y}$	Gross margin profit for fleet segment *k* in year *y*.
$p_{a}^{0,j}$	Price of species *j* at age *a* in the start year *y=0*.
$p_{a}^{y,j}$	Price of species *j* at age *a* in year *y*.
α_{j}	Price flexibility for species *j*.
${}^{k}TTC_{V}^{0}$	Total variable costs for fleet segment *k* in the start year *y=0*.
${}^{k}TTC_{F}^{0}$	Total fixed costs for fleet segment *k* in the start year *y=0*.
$\mathbf{I}^{\mathbf{k}}$	The investment/disinvestment function for fleet segment *k*.
${}^{k}LAG$	The investment lag for segment *k*, i.e. the number of years it takes for a decision about investment/disinvestment to be put into force.
${}^{k}LGT$	The number of years (minus one) on which the investment decision for fleet segment *k* is based.
R	Interest rate
${}^{k}LT$	Expected lifetime of a vessel in fleet segment *k.*
${}^{k}G^{y}$	Total decommissioning grant for fleet segment *k* in year *y*.
${}^{k}\Phi^{y}$	Decommissioning rate for fleet segment *k* in year *y*.
${}^{k}\overline{R}^{y}$	Projected average revenue through ${}^{k}LGT+1$ year for fleet segment *k* in year *y*.
${}^{k}\Delta$	Discounting of future revenues for fleet segment *k*.
${}^{k}I^{+}$	Investment share for fleet segment *k*, i.e. how big a fraction of average (positive) revenues is used for investing.
${}^{k}I^{-}$	Disinvestment share for fleet segment *k*, i.e. how big a fraction of average (negative) revenue is compensated for by disinvesting.
${}^{k}V_{IN}$	Investment price for fleet segment *k*.
${}^{k}V_{OUT}$	Disinvestment price for fleet segment *k*.
${}^{k}O$	Decommissioning rate for fleet segment *k*.
${}^{k}NV^{MAX}$	Maximum allowed number of vessels in fleet segment *k*.

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