FISHRENT
Bio-economic simulation and optimisation model for fisheries

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Preface

With this publication we wish to contribute to the international research on bio-economic modelling and to preparation and analysis of fishery management options by means of bio-economic models. The structure and the specification of the model can be interpreted as an agenda for future theoretical and empirical research, in particular in areas of investment behaviour, production functions and stock-growth relations. The model shows in great detail which relations are required and which parameters must be estimated.

By the time of this publication, the model has already proven its value for practical policy preparation and evaluation. The model was developed under the EU project ‘Remuneration of spawning stock biomass’ and within this project the model generated almost one hundred scenarios analysing potential resource rents in seven major EU fisheries. The results of this project can be found on the website of the European Commission/DG Mare (Salz et al., 2010). The model was also used for additional empirical applications by the authors and is under further development for new applications.

We would like to thank the European Commission for its support under the above mentioned project. We would also like to encourage the readers to test the model and to provide feedback to the authors for further refinements. We are confident that the model contributes to a solid basis for future development in this area.

Prof.dr.ir. R.B.M. Huirne
Managing Director LEI
S.1 Key findings

The FISHRENT model is a major step forward in bio-economic modelling, combining features that have not been fully integrated in earlier models:

- Incorporation of any number of species (or stock) and/or fleets
- Integration of simulation and optimisation over a period of 25 years
- Integration of effort and TAC-driven management policies
- Three independent relations for stock growth, production and investments.

The feedbacks within the model allow for a dynamic simulation. The main application of the model is scenario analysis of policy options.
S.2 Complementary findings

The model formulates a complete set of mathematical relations, but it also contains a number of important assumptions, which remain to be tested empirically. Therefore the model presents a challenging agenda for empirical research, which should lead to further qualitative and quantitative improvements of the individual mathematical equations and parameter values.

S.3 Method

This model was developed during the EU-funded project 'Remuneration of spawning stock biomass'. Its aim was to generate consistent sets of scenarios for an assessment of potential resource rents in different EU fisheries.

The model comprises six modules, each focusing on a different aspect of the functioning of the fisheries system: biology (stocks), economy (costs, earnings and profits), policy (TACs, effort and access fees), behaviour (investments), prices (fish and fuel) and an interface linking the modules together. Input, calculation and output are clearly separated. The model produces a standard set of graphics, which provide a quick insight into the results of any model run. All output of the model runs can be exported to database software for further analysis.

The model has been built in Excel, which makes it accessible for most users. It has been used in new applications and even translated to other software. The model is continually further developed.
Samenvatting

S.1 Belangrijkste uitkomsten

Het FISHRENT-model is een grote stap voorwaarts op het gebied van bio-economische modellen. In dit model worden aspecten gecombineerd die in eerdere modellen niet op deze wijze waren geïntegreerd:
- Elk willekeurig aantal soorten (of bestanden) en/of vloten;
- Simulatie en optimalisatie over een periode van 25 jaar;
- Inspanningsbeheer en management op basis van TAC;
- Drie onafhankelijke verbanden voor groei van het visbestand, productie en investeringen.

De terugkoppelingen van het model maken een dynamische simulatie mogelijk. Het model wordt voornamelijk toegepast voor scenarioanalyses van beleidsopties.
S.2 Overige uitkomsten

Het model vormt een complete set wiskundige verbanden, maar omvat ook een aantal belangrijke aanname, die nog empirisch moeten worden getest. Daarom biedt het model een uitdagende agenda voor empirisch onderzoek, wat zou moeten leiden tot verdere kwalitatieve en kwantitatieve verbeteringen van de afzonderlijke mathematische vergelijkingen en parameters.

S.3 Methode

Dit model is ontwikkeld tijdens het door de EU gefinancierde project ‘Remuneration of spawning stock biomass’. Het doel was om een consistent set scenario’s te genereren om de potentiële ‘resource rent’ in verschillende visserijen in de EU te beoordelen.

Het model omvat zes modules die elk gericht zijn op een ander aspect van het functioneren van het visserijsysteem: biologie (visbestanden), economie (kosten, inkomsten en winst), beleid (TAC’s, inspanning en betaling voor toegang), gedrag (investeringen), prijzen (vis en brandstof) en een interface die de modules verbindt. De input, berekening en output zijn duidelijk van elkaar gescheiden. Het model genereert een aantal standaardgrafieken die snel inzicht bieden in de resultaten van elke modelberekening. Alle outputs van de modellen kunnen worden geëxporteerd naar databasesoftware voor nadere analyse.

Het model is gebouwd in Excel, waardoor het toegankelijk is voor de meeste gebruikers. Het is gebruikt in nieuwe toepassingen en vertaald in andere software. Het model wordt voortdurend verder ontwikkeld.
1 Introduction

The FISHRENT model was developed as a part of the EU funded study ‘Remuneration of spawning stock biomass’ (Salz et al., 2010) on the basis of earlier experiences of the team in bio-economic modelling, inter alia EIAA, BEMMFISH, TEMAS, AHF and other models which were evaluated within the project ‘Survey of existing bio-economic models’ (Prellezo et al., 2009). However, none of these models was appropriate to estimate resource rents under different conditions and management regimes, as required in the present project.

On the basis of the review of models and the objective of the project, it became evident that a new model had to be constructed which would meet the following requirements:

- Integrate simulation (of different management strategies) and optimisation (to determine optimum value of resource rent and other variables).
- Integrate output- and input-driven approaches, so that one model could be consistently applied to different situations in the EU, particularly the Atlantic and the Mediterranean/Black Sea areas.
- Accommodate multi-species/multi-fleet fisheries, with flexible number of species and segments.
- Close link to available economic and biological data, to allow empirical applications.
- Balanced composition between various components: biology-economics-policy.
- Dynamic behaviour over a long period, including stock-growth, investment and effort functions, to allow simulation of adjustment paths to an optimum.
- Flexibility for applications of various types of relations (e.g. different stock-growth functions, approaches to payment for access, etc.).
- Use of a well-known language (Excel) to allow a broad introduction and accessibility to different users.

The FISHRENT model contains six modules:
1. Biological module
2. Economic module
3. Interface module

1 Available at: http://ec.europa.eu/fisheries/documentation/studies/remuneration_of_the_spawning_stock_biomass_en.pdf
4. Market module  
5. Behaviour module  
6. Policy module

The main characteristics of the FISHRENT model are:
- The model accounts for eight species and eight fleet segments (4*4 version is also available), but can be extended to a larger number if required, or reduced to a smaller size. The procedures for adaptations are described in Appendix 1.
- The model is a dynamic simulation model, running for a period of 25 years. Extension to a longer period is possible.
- By using the Excel Solver tool, the model can be used as an optimisation model, which is particularly relevant in relation to the estimation of the potential optimum resource rent.
- The model combines input and output based management, as well as their combinations. This has been achieved by a two stage calculation, in which first the relevant combination of effort and catch is determined and subsequently applied in the actual simulation model.
- The model contains various options for the collection of rent (payment for access), including fixed fee per unit of capacity (vessel), payment per unit of effort (day-at sea) and tax on revenues or profits.
- The model contains a large number of features, including parameter for technological progress, discards of sized and undersized fish, various options for simulation of investments, etc. Details are presented below.
- Using Excel implies that all relations are individually specified. Consequently, the specification of any relation can be easily adapted, e.g. each stock may be characterised by a different growth function and each fleet segment by a different investment function.

In Table 1.1 the FISHRENT model is compared to several major models, which have been developed and applied recently. The comparison shows that FISHRENT contains various features that have not been integrated in a similar way before.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>FISHRENT</th>
<th>EIAA</th>
<th>BEMMFISH</th>
<th>World Bank</th>
<th>EMMFID</th>
<th>Norwegian model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model objective</td>
<td>Estimation of resource rent for specific fisheries</td>
<td>Economic evaluation of biologic advice</td>
<td>Modelling of Mediterranean fisheries</td>
<td>Estimation of resource rent on global level</td>
<td>Estimation of resource rent for the whole Danish fishery</td>
<td>Estimation of resource rent for the major part of the Norwegian fishery</td>
</tr>
<tr>
<td>Estimates resource rent</td>
<td>Per year, NPV of profits</td>
<td>Annual profit</td>
<td>Per year and NPV of profits</td>
<td>Point estimate of max. rent</td>
<td>Point estimate of max. rent</td>
<td>Point estimate of max. rent = net profit</td>
</tr>
<tr>
<td>Simulation/optimisation</td>
<td>Simulation and optimisation</td>
<td>Simulation</td>
<td>Simulation</td>
<td>Optimisation by solving the profit equation</td>
<td>Optimisation using linear programming</td>
<td>Optimisation using linear programming</td>
</tr>
<tr>
<td>Input/output driven</td>
<td>Input and output</td>
<td>Output</td>
<td>Input</td>
<td>Output</td>
<td>Input and output</td>
<td>Input and output</td>
</tr>
<tr>
<td>Policy options</td>
<td>Free access, TAC and Effort restriction</td>
<td>TAC</td>
<td>Fishing time (effort), vessels, taxes</td>
<td>None</td>
<td>Free access, TAC and Effort restriction</td>
<td>Free access, TAC and Effort restriction</td>
</tr>
<tr>
<td>Fish prices elasticity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Accounting for exogenous fuel price changes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Investment function</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Criteria</td>
<td>FISHRENT</td>
<td>EIAA</td>
<td>BEMMFISH</td>
<td>World Bank</td>
<td>EMMFID</td>
<td>Norwegian model</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>---------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>Biological input</strong></td>
<td>Biomass. Stock-growth function in a flexible format. Source: ICES and Italian institutes</td>
<td>Yield in terms of TACs and abundances of spawning stock biomasses. Source: ICES</td>
<td>Stock-growth function</td>
<td>Single species model Logistic (=2nd degree polynomial) Fox. Sources: FAO and other</td>
<td>TAC/catch restrictions</td>
<td>TAC/catch restrictions</td>
</tr>
<tr>
<td><strong>Economic input</strong></td>
<td>Multi fleet. DCF data, distinguishing 5 cost components</td>
<td>Multi fleet. DCF data, distinguishing 5 cost components</td>
<td>DCF with minor assumptions</td>
<td>Distinguishes between variable and fixed costs. Source: large variety of data</td>
<td>Detailed cost structure</td>
<td>Detailed cost structure</td>
</tr>
<tr>
<td><strong>Number of years</strong></td>
<td>25 years, expandable</td>
<td>3 point estimates Current year, next year, and long term.</td>
<td>40 years</td>
<td>Static</td>
<td>Static</td>
<td>Static</td>
</tr>
<tr>
<td><strong>HCR/management plans</strong></td>
<td>Multi-species, Six policy options: TAC min TAC max Effort min Effort max Min-Min Open access</td>
<td>Single species, management plans in terms of TAC/quotas</td>
<td>No</td>
<td>No</td>
<td>Single species, management plans in terms of TAC/quotas and effort</td>
<td>-</td>
</tr>
<tr>
<td>Criteria</td>
<td>FISHRENT</td>
<td>EIAA</td>
<td>BEMMFISH</td>
<td>World Bank</td>
<td>EMMFID</td>
<td>Norwegian model</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------</td>
<td>-----------</td>
<td>----------</td>
<td>------------</td>
<td>--------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Discards</td>
<td>Two types: undersized and over-quota</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Software</td>
<td>Excel</td>
<td>Excel</td>
<td>Java</td>
<td>None</td>
<td>GAMS/Excel</td>
<td>Matlab</td>
</tr>
<tr>
<td>Dynamic/Static</td>
<td>Dynamic</td>
<td>Static</td>
<td>Dynamic</td>
<td>Static</td>
<td>Static</td>
<td>Static</td>
</tr>
<tr>
<td>Dimensions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Fleets</td>
<td>Up to eight, expandable</td>
<td>Unlimited</td>
<td>Multi-fleet</td>
<td>Single fleet</td>
<td>26</td>
<td>25 aggregated to 11</td>
</tr>
<tr>
<td>- Species</td>
<td>Up to eight, expandable</td>
<td>25 species; 110 stocks</td>
<td>Unlimited</td>
<td>Single species</td>
<td>118</td>
<td>10</td>
</tr>
<tr>
<td>- Area unit</td>
<td>Fishery areas based on stock definitions</td>
<td>Based on stock management definition</td>
<td>None</td>
<td>Single area (Earth)</td>
<td>34 fishing areas based on stock definitions; 14 regions</td>
<td>None</td>
</tr>
<tr>
<td>- Time unit</td>
<td>Year</td>
<td>Year</td>
<td>Year</td>
<td>NA</td>
<td>Month</td>
<td>Year</td>
</tr>
</tbody>
</table>

Sources: Prellezo et al. (2009), World Bank (2009).
The FISHRENT is a full-feedback model, containing independent procedures for the development of the stock (stock-growth function), production and effort (production and investment function). Consequently, the model can shift according to the most restrictive constraint, be it the total available effort of each fleet segment or the TAC/quotas of specific species. This approach allows simulating the economic performance of individual fleet segments independently of each other over a long period of time.
2 Concepts

2.1 Modelling in general

A simulation model links a set of variables with mathematical equations in order to simulate a certain development. The solution is determined by these equations and various types of constraints to which they may be subject. In case of optimisation, the model is extended with an 'objective function' or 'objective variable'.

There are two types of variables:
- *Endogenous* (or dependent) variables - the values are determined in the model.
- *Exogenous* (or independent) variables - the values come from other sources.

Two types of exogenous variables can be distinguished:
- Equation parameters, which may have been estimated on the basis of available statistics, assumed or calibrated (i.e. determined by trial and error so that the model produces certain results, e.g. reproduces historical values);
- Baseline data, i.e. starting values of the endogenous variables - year 1 in a dynamic model, and various constants.

The model consists of two types of relations:
- *Mathematical equations*, linking the endogenous variables. Once set, the equations do not change, unless it is concluded on the basis of additional information that the form or parameter values of the equation should be adjusted.
- *Constraints and decision rules*, steering the calculations along a certain path or constraining the endogenous variables to remain with specified boundaries. Regarding constraints and decision rules, a distinction can be made again between endogenous and exogenous:
  - Endogenous constraints and decision rules are based on specific algorithms in the model.
  - Exogenous constraints and decision rules are choices which can be made before running the model.

The model needs to be based on a set of sound theoretical and empirical concepts. These concepts allow distinguishing the main modules (components) of
the model and their relations. Modular approach to model building allows at any time to develop specific modules further, without having to adapt the model as a whole. Such development does not necessarily affect the relations between the modules.

Each model is structured around three fundamental components:
- Input, i.e. the values of all exogenous variables;
- Calculation, i.e. all relations, constraints and some decision rules;
- Output, i.e. the way in which the results are presented.

These components can be further sub-divided into suitable steps.

2.2 FISHRENT modules

The FISHRENT model is a generalised multi-species multi-fleet simulation and optimisation model, built in Excel. The basic version contains eight fleets and eight species and runs for a period of 25 years. The dimensions of the model can be flexibly reduced or expanded. The model is structured in six modules: biology, economy, interface, prices, behaviour and policy. In addition, the Excel model contains a module with the totals, summing variables over fleets or species. The general structure of the model and its modules is presented in Figures 2.1 and 2.2 It can be summarised as follows:
- Biological module contains the stock-growth function.
- Economic module contains the economic performance of the fleets.
- Interface module is the core of the model containing the bio-economic production functions for each combination of segment and species. This module reflects the interaction between the fishing fleet and the fish stocks.
- Price module contains fish prices, price elasticities and the possibility to adapt the price of fuel.
- Behaviour module determines the (dis)investment behaviour of the fleet, according to the realised economic performance.
- Policy module contains six policy options based on different approaches to management by TACs and effort including an option of open access fishery.

The main characteristics of the FISHRENT model are:
- Three independent relations for stock growth, production (catch) and investment.
- Integration of TAC and effort-based policies.
- Integration of simulation and optimisation.
- Flexibility to adapt forms of all relations and the values of their parameters to suit (almost) any fishery.

Figure 2.1 shows that all variables specified in the modules are defined in any given year by segment, species or both, which is described further in Table 2.1.

The main relations within each module are in general terms presented in Figure 2.3 and described below. Figure 2.3 presents brief qualitative descriptions of the relations and the mathematical equations, which have been shortened by using only a, b, c, or d as symbol for parameters. The mathematical description, including the precise description of the parameters, the required constraints and decision rules, is presented in Chapter 3.
<table>
<thead>
<tr>
<th>Module</th>
<th>Segment</th>
<th>Species</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>ALL</td>
<td>X</td>
<td>There is a separate stock-growth and biomass relation for each species. It is assumed that each species is composed of one stock.</td>
</tr>
<tr>
<td>Interface</td>
<td>X</td>
<td>X</td>
<td>Catches are determined by a production function, specified for each relevant combination of segment and species.</td>
</tr>
<tr>
<td>Economy</td>
<td>X</td>
<td>ALL</td>
<td>Performance of each individual segment is modelled. Performance is determined by the total catch of all species, and thus revenues, and costs, which are partly fixed and partly variable, depending on effort.</td>
</tr>
<tr>
<td>Behaviour</td>
<td>X</td>
<td>ALL</td>
<td>Changes of the size of each segment are driven by a segment-specific asymmetric investment function, i.e. different constraints can be imposed to investments and disinvestments.</td>
</tr>
<tr>
<td>Prices</td>
<td>X</td>
<td>X</td>
<td>Fish prices can change with landed volumes, based on price elasticity. Furthermore price differences attributed to individual fleet segments (gears) can be accounted for.</td>
</tr>
<tr>
<td>Policy</td>
<td>X</td>
<td>X</td>
<td>Output measures (TACs) are specified by species. Input measures (effort) are specified by segment. Both are generated in the model on the basis of target harvest ratios and stock-growth relations.</td>
</tr>
<tr>
<td>Totals</td>
<td>X</td>
<td>X</td>
<td>Included at the bottom of the sheet.</td>
</tr>
</tbody>
</table>

*a) ALL means sum of all segments or species. X means that each individual segment or species is elaborated.*
Comparison of Ht and H indicates required change in effort. Ht, biomass and growth lead to sustainable advice on TAC.

**CHOICE OF EFFORT POLICY**
Based on species with highest or lowest Ht/H-ratio.

**CHOICE OF TAC POLICY**
1. Biologic TAC advice compared to management rules.
2. Choice based on most or least restrictive relative TAC change.

**COBB-DOUGLAS PRODUCTION F.**
Potential catch calculated with selected effort.

**LANDINGS AND DISCARDS**
Potential catches are compared with sustainable catch (growth) and the difference is discarded. Only sustainable catches are landed.

**CHOICE OF EFFORT**
1. Effort is selected on the basis of the policy piece.
2. Selected effort is compared to maximum feasible effort of the fleet and the lower of the two determines catches and costs.

**COSTS**
- Fuel, crew and variable costs depend on effort.
- Fixed and capital costs depend on fleet.
- Costs of acces are set by policy.

**ECONOMIC RESULTS**
- Revenues, gross cash flow, profit and break-even revenues are based on definitions.

**INVESTMENTS, FLEET, EFFORT**
- Investments depend on revenues and break-even.
- Fleet changes with (dis)investments. Maximum number of days-at-sea per vessel is assumed.
- Nominal and full-time employment.

**FUEL**
- Exogenous change of fuel price

**FISH**
- Fish prices change with price elasticity

**Pricing**

**Behavior**

**Economy**

**Biology**

**Policy**

**Interface**

Various types of payments included.
Figure 2.3  **FISHRENT model - mathematical formulation (simplified version)**  

1. **BIOLOGY**
   - **Harvest Ratio**
     - \[ H_t = \frac{[\text{Catch}_t - \text{LandT}_t]}{\text{TAC}_{t-1}} \]
   - **Biomass**
     - \[ CB = \frac{\text{Catch}_t + \text{Rec} - \left( \sum \text{Catch}_t \times (1 + \text{Disc}) \right)}{\left( \sum \text{TAC}_{sh} \right)} \]
   - **Growth**
     - \[ \text{Rec} = a_1 + a_2 \times CB^{b_1} - a_3 \times CB^{b_2} \]

2. **ECONOMIC RESULTS**
   - **Revenue**
     - \[ \text{Rev} = \sum_{t} \text{Land}_{t} \times \text{FishPr}_{t} \times \left( \frac{1}{\text{Land}_{t}} \right) \]
   - **COSTS**
     - **Fuel**
       - \[ \text{FuelPr} = \text{FuelPr}_{t-1} \times (1 + a) \]
     - **Catch**
       - \[ \text{Catch} = a_4 \times \text{CB} \times (1 + d) \]
   - **ECONOMY**
     - **PAYMENT FOR ACCESS**
       - \[ \text{PfAcc} = a_5 + b_5 \times \text{Eff} + c_5 \times \text{Rev} \]

3. **CHOICE OF EFFORT POLICY**
   - \[ E_{\text{select}} = \text{MIN} \left( \text{Eff}, \text{MIN} \left( \text{EffTAC}_t, \text{MIN} \left( \text{TAC}_{t-1}, \text{MIN} \left( \text{MaxEfC}, \text{MaxEfTAC}_t \right) \right) \right) \right) \]
   - \[ \text{Eff} = \frac{\text{E}_{\text{select}} \times \text{DAS}_{\text{max}}}{\text{Fle}} \]

4. **CHOICE OF TAC POLICY**
   - \[ \text{TAC} = \text{MIN} \left( \text{EffTAC}_t, \text{MIN} \left( \text{TAC}_{t-1}, \text{MIN} \left( \text{MaxEfC}, \text{MaxEfTAC}_t \right) \right) \right) \]

5. **BEHAVIOUR**
   - **Costs**
     - **Investments, Fleet, Effort**
       - \[ \text{Inve} = \text{MIN} \left( \text{DA} \times \text{DAS}_{\text{max}}, \text{MIN} \left( \text{Fle} \times \text{DAS}_{\text{max}} \right) \right) \]
   - **NoEmpSeg**
     - \[ \text{NoEmpSeg} = \text{MIN} \left( \text{Fle} \times \text{DAS}_{\text{max}} \right) \]

6. **PRICE**
   - Fuel
     - \[ \text{FuelPr} = \text{FuelPr}_{t-1} \times (1 + a) \]
   - Fish
     - \[ \text{FishPr} = a_6 \times \text{FishPr}_{t-1} \]

---

1. **PIF** is not presented in the formulas for simplification reasons.
2.3 Biological module

The biological module contains three relations:
- Stock-growth relation (called recruitment) - a 3rd degree polynomial function, but only 2nd degree is used in the current applications.
- Biomass function - the sum of biomass in the previous period plus recruitment minus catch. Furthermore, assumed discards of undersized fish are subtracted.
- Harvest ratio - ratio between biomass and total catch. Harvest ratio is a proxy for fishing mortality.

2.4 Policy module

The policy module determines level of landings or effort. It contains a set of decision or selection rules regarding landing and effort is determined. Running the model starts with a choice of TAC (Total Allowable Catch) or effort policy. Payment for access is also a policy option, but this is incorporated in the economic module, as its effect does not pass through the interface module.

Furthermore, the policy module contains two other features:
1. Constraints on maximum change of TAC from one year to another, the +/- 15% applied in various EU recovery and management plans (harvest control rules)
2. The 'policy intensity factor' reflects the extent to which policy decisions follow the biologic advice. Value below 1 implies that the policy is more restrictive than the biologic advice. On the other hand, value above 1 means that policy concludes on higher TACs than the biologic advice proposes. This factor allows simulating the consequences of taking into account 'socio-economic dimensions' of taking restrictive management measures.

The policy choice is made within a multi-species context and therefore the policy must decide whether the most or the least restrictive biologic advice (in relation to harvest ratio of a given set of species) should be taken as a starting point. For example, species 'A' may be relatively abundant, but effort which could be allowed on this species may lead to overfishing of a species 'B'. On the other hand, if species 'B' is taken as a reference point of the policy, this will lead to underutilisation of species 'A'. The policy module contains six policy choices, which precisely highlight these policy dilemmas:
- \( \text{TAC}_{\text{min}} \) - The most restrictive TAC is used to determine the level effort which the fleet can exert. This may lead to underutilisation of other species.
- Effort_{min} - Most restrictive effort level is allowed, which leads to relatively low catches.
- TAC_{max} - The least restrictive TAC is used to determine the level effort which the fleet can exert. This may lead to overfishing of other species.
- Effort_{max} - Least restrictive effort level is allowed, which leads to relatively high catches.
- Open access - Fishery is driven by economic incentives. Neither TAC nor effort constraints are imposed.
- Min min - This is the most restrictive policy. In this option, Effort_{min} is compared to effort level, which follows from TAC_{min} and the lower of the two is selected. This choice is made in each year separately, which means that throughout the simulation period, different species and different types of policies determine the outcomes.

Effort which follows from an 'Effort policy option' is inserted in the production function and generates catch. When a 'TAC police option' is selected, then a corresponding level of effort is calculated from an 'inverse production function', where effort is the endogenous variable.

Both effort and TACs are derived from the present and target harvest ratio in combination with other variables in the model.

Policy formulas contain a PIF-ratio (Policy Intensity Factor). PIF is included in the Drivers sheet. PIF allows the policy to be more or less restrictive than the simulated biologic advice. Distinction is made between PIF for effort or PIF for TAC based policy.

### 2.5 Interface module

The interface module determines the level of catch and effort, which are subsequently input to the economic module and catches form feedback to the biologic module. It contains conditional choices of effort, which are described in detail in Chapter 3.

The interface module contains seven functions for each combination of fleet segments and species:
1. Catch - based on a standard Cobb-Douglas production function. Power of 'effort'-variable contains an additional parameter which represents the technological progress.
2. Effort - inverse production function, using catch as input to determine required effort.
3. Discards - over-quota catch is discarded. Catch is confronted with 'Target landings' (segment share of TAC, see policy module) and if catch exceed Target landings, part of the excessive catch can be discarded. An assumed value of a discard parameter determines which percentage is discarded and consequently also how much is landed, albeit illegally. Discards of undersized fish are accounted for in the catchable biomass equation, as a fixed percentage of catch. These discards occur only in case of output (TAC) driven policy.

4. Landings - difference between catch and discards.

5. Target landings - share of segment in the total sustainable catch (TAC).

6. Choice of effort in relation to policy - level of effort depends on policy choice and maximum effort which the fleet can exert. When the policy is TAC driven, then the model calculates the required effort with the inverse Cobb-Douglas production function. If the policy is effort driven, then effort is adapted proportionately with the required adaptation of the harvest ratio to the target harvest ratio.

7. Comparison of effort allowed by policy and maximum effort feasible for the fleet. After determination of the level of effort from one of the two policies, it is checked against the maximum level of effort feasible for the fleet and the lower value is selected.

The selected production function in the interface is a Cobb-Douglas production function in which fishing effort in terms of days-at-sea and catchable biomass determines the catches. Technical progress is included in the production function. Through these selection procedures it is possible to integrate input and output driven policy into one model.

2.6 Economic module

The economic module contains the following relations:
- Revenues - sum of landings times prices. Prices can be adapted to qualities attained by different segments.
- Fuel costs - depend proportionately on fishing effort. Can be adapted by changing the fuel price, either once (instantaneously) or trend-wise (annual change).
- Variable costs - depend proportionately on fishing effort.
- Crew costs - based on a share of revenues and if appropriate taking account of fuel and/or variable costs.
- Fixed costs - are a fixed value per vessel. Change with the size of the fleet.
- Capital costs - as fixed costs, constant per vessel, changing with size of the fleet.
- Gross cash flow - according to definition.
- Profit - according to definition revenues minus all costs.
- Payment for access - allows for different kinds of payments:
  - Lump-sum
  - Share of profit
  - Payment per unit of effort
  - Share of revenues per species
  - Profit after payment for access
- Gross value added - according to definition.
- Fuel use - fuel costs divided by fuel price.
- Break-even revenues - according to definition. Break-even revenues drive the investment function. Therefore crew costs are considered as fixed costs, on the basis of the expectation that fishing may not be an attractive profession at a level of income lower than the level realised in a given year.

The economic module also generates net present values of profit and gross value added over 15 and 25 years. This distinction between two periods was introduced in particular in relation to the optimisation runs of the model. When a model is run for 15 years and profit or gross value added are maximised over that period, the model will tend to fish out all the stocks at the end of the period as it does not take into account what happens beyond that time horizon. This is evidently not desirable. This problem has been resolved by 'optimising' over a period of 25 years, but using the net present value of the first 15 years only. In this way destruction of stocks is avoided within the first 15 years.

2.7 Behaviour module

The behaviour module simulates the level of fishing effort through changes of the number of vessels and/or the number of days-at-sea per vessel. It contains the following relations:
- Fleet (number of vessels) - the fleet of the preceding year plus or minus investments (fleet change).
- Days-at-sea/vessel - operational - total effort (see policy module) divided by the number of vessels.
- Days-at-sea/vessel - maximum - assumed value. This can be annually adapted by an assumed parameter. Together with the number of vessels it determines the maximum effort of a segment.
- Maximum effort (Fleet * days) - follows from fleet and maximum days-at-sea per vessel.
- Investment (number of vessels) - it is assumed that the fleet changes, i.e. (dis)investments take place, proportionately to the ratio between the break-even revenues and the realised revenues, which is adapted by the share of profits dedicated to investments. However, maximum limits to annual increase or decrease of the fleet can be imposed in terms of the percentage change of the fleet. The two limits can be different, which creates asymmetric (dis)investment behaviour. Furthermore, size of the fleet is reduced when the capacity utilisation falls below an assumed level. This means that it is assumed that investments take place only when the capacity utilisation is above this level.
- Nominal employment - number of vessels times average crew.
- Full time employment - nominal employment, corrected with the ratio of operational/maximum days-at-sea.

2.8 Price module

Price module contains two equations:
1. Prices of fish, which include price elasticity for each species. Furthermore, price differentials for specific segment-species combinations can be accounted for using specific parameters.
2. Fuel price can be adapted with one-time rise or continuous annual trend.

1 The maximum increase of the fleet from one year to next has been set at 10% and the maximum decrease at -20% of the number of vessels. These percentages are based on the EU DCF data 2002-2008, which show that 75-85% of annual changes of the size of the fleet fall in this range.
2.9 Structure of the workbook

The workbook contains six worksheets:
- Two Input sheets: Drivers and Model parameters
- Calculation sheet: Multi-year model
- Output sheet: Drivers and DB2 (DB = database)
- Two Intermediate sheets: Model input and DB1

The model contains several macros, so Excel must be run in macro-enabled mode. The different modules of the model are coloured differently for easier navigation in a worksheet with more than 800 rows.

**Drivers sheet**

 drivers sheet contains the following components (Figure 2.4):
- Choice of the six policy options;
- Policy intensity factor (PIF) i.e. to which extent the manager will follow the biologic advice or enforce the policy restrictions (harvest control rules);
- Input area for ‘scenario number’, to distinguish the results of each model run in subsequent analysis (see DB2);
- Input areas for the names of the relevant species and segments;
- Input area for setting the discount rate per segment, which may serve as a proxy for shadow valuation. For example, using a lower discount rate for small-scale fleets means that in the long run their existence gets a relative preference for ‘socio-economic reasons’;
- Output area with the main results regarding net present value of gross value added, profit and payment for access over 15 and 25 years;
- Output area with selected graphics showing the development of the main indicators over the simulated period of 25 years:
  - Biological: biomass, sustainable catch, stock growth;
  - Economic: Landings, revenues, gross value added and profit;
  - Technical: fleet and effort (days-at-sea).

Inclusion of main outputs allows running the model and seeing the results immediately in the same worksheet. The user inserts the main information in the light yellow cells.
Figure 2.4  Drivers sheet (example of North Sea flatfish fishery)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Name/No.</th>
<th>Net present value (NPV) of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAC MIN</td>
<td></td>
<td>Revenue value added 15 years</td>
</tr>
<tr>
<td>Hif MIN</td>
<td>1</td>
<td>Revenue value added 25 years</td>
</tr>
<tr>
<td>TAC MAX</td>
<td>2</td>
<td>Model 10 years</td>
</tr>
<tr>
<td>Hif MAX</td>
<td>3</td>
<td>Profit 10 years</td>
</tr>
<tr>
<td>Opt set</td>
<td>4</td>
<td>Revenue for excess 15 years</td>
</tr>
<tr>
<td>MIN MIN</td>
<td>5</td>
<td>Revenue for excess 25 years</td>
</tr>
<tr>
<td>Policy uncertainty factor</td>
<td>PPF</td>
<td></td>
</tr>
</tbody>
</table>

We optimize NPV against the willingness to implement a recovery
i.e. to invest and/or effort, PPF is more realistic the worse it is.

### Sustainable Catch
- **Plaice**

![Sustainable Catch Graph](image)

### Landings
- **Sole**
- **Plaice**

![Landings Graph](image)

### Vessels
- **BEL TBB 24-40**
- **DEN POP 12-24**
- **DEN POP 12-24**
- **GER TBB 24-40**
- **NL TBB 24-40**

![Vessels Graph](image)

### Revenue
- **BEL TBB 24-40**
- **DEN POP 12-24**
- **DEN POP 12-24**
- **GER TBB 24-40**
- **NL TBB 24-40**

![Revenue Graph](image)
**Model parameters**

The Model parameter sheet contains the following information in the various columns (Figure 2.5):

A. Full description of the variable
B. Specification whether the variable is an endogenous (result of a formula), constraint or start value, which must be filled in.
C. Dimension of the variable, clarifying the value to be entered.
D. Variable name, used in the model (see also Chapter 3). Each name is composed of 'Variable name_xy', where x is index for fleet segment and y stand for species.
E. The cells in column E the initial values of all variables, either calculated with a formula in the cell or entered by hand.
F. Columns F-L contain names and values of parameters required to calculate specific formulas.
G. Column Z explains the meaning of each row in greater detail.

Areas where values have to or can be inserted are white, while all other areas are coloured.

**Model input**

*Model input* (MI) sheet contains all equations for one year (Figure 2.6). It is constructed parallel to the following Multi-year model sheet. It presents information entered in the preceding three sheets. It serves as a guideline to the use of the model and an intermediate sheet for input in the Multi-year model sheet. An important aspect is that the cells in columns I, K, M, etc. bear names indicated in the columns H, J and L. The formulas in the MYM-sheet refer to these names. No data needs to be entered on this sheet.
**Figure 2.5** Model parameters sheet

<table>
<thead>
<tr>
<th>Text</th>
<th>Formula / Initial value</th>
<th>Parameter name</th>
<th>Parameter value</th>
<th>Explanation</th>
</tr>
</thead>
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<tr>
<td>Sustainable catch landing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SNCatch</td>
<td></td>
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<tr>
<td>Sustainable catch landing</td>
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<td>SNCatch</td>
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<tr>
<td>Profit for access</td>
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<tr>
<td>Profit cont</td>
<td>1,000</td>
<td>FProfit_cont</td>
<td>0</td>
<td>FProfit_cont</td>
</tr>
<tr>
<td>Profit for access</td>
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<td>Profit cont</td>
<td>1,000</td>
<td>FProfit_cont</td>
<td>0</td>
<td>FProfit_cont</td>
</tr>
<tr>
<td>Fleet (number of vessels)</td>
<td>Start value</td>
<td>FVesss</td>
<td>55</td>
<td>FVesss, The number of vessels in the baseline for the segments</td>
</tr>
<tr>
<td>Days at sea/vessel - operational</td>
<td>Start value</td>
<td>DAopts</td>
<td>230</td>
<td>DAopts, The operating average number of days per vessel per year in the baseline for the segments</td>
</tr>
<tr>
<td>Days at sea/vessel - maximum</td>
<td>Start value</td>
<td>DAlmax</td>
<td>230</td>
<td>DAlmax, The maximum number of days per vessel per year in the baseline for the segments</td>
</tr>
<tr>
<td>Investment per vessel</td>
<td>Start value</td>
<td>Inv</td>
<td>1</td>
<td>Inv, The total investments divided by the number of vessels in the baseline for the segments</td>
</tr>
<tr>
<td>Investment (number of vessels)</td>
<td>Formulas</td>
<td>FVesss</td>
<td>55</td>
<td>FVesss, The number of vessels in the baseline for the segments</td>
</tr>
<tr>
<td>Target landing</td>
<td>Count</td>
<td>LandT</td>
<td>72.8</td>
<td>LandT, The share of TNC of each species per segment</td>
</tr>
<tr>
<td>Target landing</td>
<td>Count</td>
<td>LandT</td>
<td>3,060</td>
<td>LandT, The share of TNC of each species per segment</td>
</tr>
</tbody>
</table>
Figure 2.6
Model Input Sheet
Multi-year model sheet

Multi-year model (MYM) contains the calculation for a 25-year period (Figure 2.7). It also contains the calculation of the net present values of gross value added and profit over 15 years, 25 years and infinity. Inclusion of the calculation of net present values is necessary on this sheet in order to allow the use of the Excel Solver. The Solver can be run on one sheet only and cannot refer to objectives or constraints on other sheets.

Database 1 sheet (DB1)

This sheet copies the MYM sheet for database use (Figure 2.8). It contains a macro ‘Convert’ which converts a 2-dimensional table (variables * years) to a 1-dimensional table and writes it in sheet Database 2 (DB2), generating a database format. The sheet contains precise description how the macro should be run.

The column E merges all dimensions of each variable into one composite name, in order to create a simple 2 dimensional table.

Database 2 sheet (DB2)

DB2 contains the complete MYM sheet in a database format, which then can be analysed using Pivot table(s), MS Access or another database software (Figure 2.9). The results of each scenario (model run) can be copied from DB2 into a new database or workbook and compared, as each run bears a different number.

Columns A-D rewrite the dimensions of each variable in their original form, on the basis of column E. Columns I-L rewrite the information entered on the Drivers sheet. This is useful so that later dataset output can contain the actual names of segments and species, instead of only Sg1 etc. Inclusion of scenario number allows to run different scenarios of one policy, e.g. if it is desirable to use different equation parameters.
**Figure 2.7 Multi-year model sheet**

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<th>Policy type</th>
<th>Segments</th>
<th>Species</th>
<th>Test</th>
<th>Formula, constraint, start vals</th>
<th>Dimension</th>
<th>Variable names</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>Multi-year model</td>
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**Time/Year 1**

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<th>Policy type</th>
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</tbody>
</table>

**Note:** The table and diagram represent the multi-year model sheet with specific policies, constraints, and variable names. The values for each cell in the table are not shown here but would typically include mathematical expressions, boundary conditions, or initial values for the simulation.
<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<th>J</th>
<th>K</th>
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<tbody>
<tr>
<td>1</td>
<td><strong>1. Place cursor in E6</strong></td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td><strong>2. Select all data by CTRL-Shift+</strong></td>
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</tr>
<tr>
<td>3</td>
<td><strong>3. Click on ‘Convert’</strong></td>
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**Figure 2.9** DB2 sheet

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*For new scenarios delete only cells for E6-G6 and below*
3 Model definition

The Model parameters sheet contains all input, including the values of year 1, as the baseline for the Multi-year model sheet. The following sections present the mathematical formulation and discuss their meaning, justification and assumptions.

Variable names are composed as follows:

\[ \text{Name}_{xy}, \quad x = \text{segment index}, \ y = \text{species index}; \]

when index = a this means, sum of all species and/or segments

Parameter names are composed as:

\[ \text{Name}_{xyz}, \quad x = \text{segment index}, \ y = \text{species index and} \]
\[ z = \text{sequential number of the parameter in a relation}; \]

This notation and the names of the variables and parameters is used throughout the model. In the following text, parameters are written in italics, variables in normal. In most equations, only variables of the same year are related, so that time denomination is not required. When referring to the preceding year, time denomination (t-1) is stated.

The model makes a distinction between 'target' and 'non-target' species. Target species are species included explicitly in the model with their biological functions. Non-target species are all other species caught/landed by the segment. Non-target species must be included to obtain the total revenues of the segment.

The model distinguishes segments specified in the Drivers sheet and one segment called 'Other'. Segments are explicitly included in the model with their economic functions. Segment 'Other' represents all remaining fleets which also catch (some of) the target species. 'Other' segment must be included to obtain the correct catches and harvest ratio of each target species.

Catches of 'non-target species' by the segment 'Other' are not included in the model. This may require a significant amount of additional data and it would increase the size of the model even further, while it generates little relevant additional information for later analysis.
3.1 Biological module

Growth function

The biological module simulates the growth for each species using 3rd degree polynomial stock-growth function.

\[ \text{Rec-ay} = \text{Rec-ay}_0 + \text{Rec-ay}_1 \cdot \text{CB} \cdot a_1^{\text{Expo-ay}_1} - \text{Rec-ay}_2 \cdot \text{CB} \cdot a_1^{\text{Expo-ay}_2} + \text{Rec-ay}_3 \cdot \text{CB} \cdot a_1^{\text{Expo-ay}_3} \]

Where:  
\( \text{CB} \) = catchable biomass
\( \text{Rec} \) = parameters
\( \text{Expo} \) = exponents/parameters

The advantage of the 3rd degree polynomial is that it is easy to estimate using Excel standard functions.

It is well known that stock-growth and stock-recruitment functions are statistically weak. The function selected in the model is just one of many possibilities and may be replaced by functions like Ricker or hockey-stick. By using the RANDBETWEEN function in Excel, it is also possible to run the model stochastically, with random growth (only limited by the known minimum and maximum values). This would require running the model many times and subsequently analysing the boundaries of such 'chaotic' system.

Biomass function

The biomass function contains the following elements:
- Biomass of the preceding year;
- Growth;
- Catch of the individual segments, upgraded for discards of undersized fish (not part of TAC);
- Upgrade of the catch of specified segments for catch by segments 'other', expressed as \((1/\text{sum of TAC shares})\);
- The production function (15) may lead to a catch which is greater than the biomass, which is evidently not possible. Furthermore, reducing the biomass to zero implies that complete extinction, making later recovery impossible.

---

1 SSB has been used as a proxy.
In order to avoid fishing out a species completely (or even negative values) a minimum size of the catchable biomass must be set. The CB is set at a very low value of 0.000001. In this way the catches are also reduced to a very low value, having little or no impact on the final result. The problem that Catch may exceed CB could be also resolved by introducing a CBproxy, which would first check whether Catch<CBproxy and, if this condition would not be met, adapt the Catch with another theorem. However, this would further complicate the model and the numerical results would not significantly improve.

\[
\text{(2) } \text{CB-ay} = \text{IF } \left\{ \frac{(\text{CB-ay}_{t-1} + \text{Rec-ay}_{t-1} - \left[ \sum_x \text{Catch-xy}_{t-1} \cdot (1+\text{Disc}_{xy0}) \right])}{\left( \sum_x \text{TACsh}_{xy0} \right)} < 1, 0.000001, \right\} \frac{(\text{CB-ay}_{t-1} + \text{Rec-ay}_{t-1} - \left[ \sum_x \text{Catch-xy}_{t-1} \cdot (1+\text{Disc}_{xy0}) \right])}{\left( \sum_x \text{TACsh}_{xy0} \right)}
\]

Where
\[
\text{CB}_{t-1} = \text{catchable biomass in year } t-1 \\
\text{Rec}_{t-1} = \text{growth in year } t-1 \\
\text{Catch} = \text{catch in year } t-1 \\
\text{Disc} = \text{discards of undersized fish} \\
\text{TACsh} = \text{TAC share of the segment}
\]

**Harvest ratio**

The harvest ratio is calculated as catch divided by biomass. However, as the segments in the model do not necessarily catch the whole TAC, their catch is extrapolated to total catch by dividing by their aggregate TAC share.

\[
\text{(3) } \text{H-ay} = \frac{\text{Catch-ay}}{\left( \sum_x \text{TACsh-xa} \right)} / \text{CB-ay}
\]

Where
\[
\text{CB}_{t-1} = \text{catchable biomass in year } t-1 \\
\text{TACsh} = \text{TAC share of the segment} \\
\text{Catch} = \text{catch}
\]

### 3.2 Policy module

**Policy choice**

The fisheries management pursues the achievement of long-term sustainable exploitation of fish stocks at MSY level. There are in principle two approaches:
the output (TAC) driven approach and the effort-driven approach. Although in some fisheries constraints in both areas exist, one of them is always more binding. However, in a multi-species multi-fleet situation, it is usually impossible to achieve the MSY level for all species concurrently. This gives rise to two situations:

- One species is fished at MSY level, while other species are overfished. Policy focusing on this species will be least restrictive, using the TAC or effort related to that species as benchmark for the overall activity of the fleet.
- One species is fished at MSY level, while other species remain underutilised. Policy focusing on this species will be most restrictive, using the TAC or effort related to that species as benchmark for the overall activity of the fleet.

These two options have been included in the model. A third option, which would take some 'average' value as a starting point has not been modelled, as it is not clear how such 'average' should be determined and because the two 'extreme' options provide information about the 'limits of the system' within which all other options fall.

The model requires determining a unique and consistent composition of three elements:
- catches, which affect biomass,
- landings, which together with prices determine revenues, and
- effort, which determines part of the costs.

This is achieved in the policy module as follows:
1. The MSY level of biomass and growth (sustainable harvest) of each species is calculated from the 2nd degree polynomial stock-growth function, by setting the first derivative equal to zero.
2. The resulting harvest ratio \((\text{Catch/Biomass})_{\text{msy}}\) is interpreted as \(H_{\text{msy}}\) or \(H_{\text{target}}\).
3. Current harvest ratio \((H)\) realised in each year is compared to \(H_{\text{msy}}\) and the ratio \((H_{\text{msy}}/H)\) determines the biologic advice: either effort or TAC is adjusted proportionately by that ratio. Evidently, the ratios are different for each species, which creates the need to select from the most or the least restrictive approach.
4. The level of \(H_{\text{target}}\) may be adapted by the policy maker with the Policy intensity factor (PIF). Setting PIF>1 will lead to higher TAC or effort than advised by science. This allows to account for 'socio-economic considerations'. Setting
PIF<1 implies that more severe restrictions are imposed, e.g. to protect other parts of environment, net reflected in the TAC or effort proposals.

5. It is then a policy choice whether output or input driven policy should be implemented and whether the most or the least restrictive approach should be followed. This leads to four possible choices, which have been supplemented by further two choices: open access (free fishing) and pursuit of most restrictive policy possible. Consequently the model contains six policy choices:

a. $\text{TAC}_{\text{min}}$: leads to effort required to catch the most binding TAC/quota;
b. $\text{Effort}_{\text{min}}$: choose the lowest effort determined by comparing the ratio $H_{\text{target}}/H$ for all species;
c. $\text{TAC}_{\text{max}}$: choose the effort required to catch the least binding TAC/quota
d. $\text{Effort}_{\text{max}}$: choose the highest effort determined by the ratio $H_{\text{target}}/H$ for all the species;
e. Open access: no restrictions imposed;
f. Min-min: choose the lower of the effort levels defined by $\text{TAC}_{\text{min}}$ and $\text{Effort}_{\text{min}}$.

The selected policy is applied every year of the model separately. This means that in different years different species may be used as a min or max restriction. In the min-min policy, it is possible that effort constraint is used in one year and TAC constraint in another.

**Sustainable catch and selected TAC**

Sustainable catch is calculated as the growth of the biomass, including natural mortality and adapted to the ratio harvest ratio divided by total harvest. The model uses the Baranov function (Lassen, 2000). In some EU fisheries it has been agreed that the TACs would change at most by X% from one year to another (e.g. 15% in the flatfish recovery plan). Therefore, this constraint has been also incorporated. The constraint can be lifted by setting $\text{TAC}_{\text{ay}0}=0$.

(4) $\text{TAC}_{\text{ay}} = \begin{cases} \text{IF}(\text{CB}_{\text{ay}} \times (1 - \exp(\frac{\text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}})) \times \text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}} < (1 - \text{TAC}_{\text{ay}0}) \times \text{TAC}_{\text{ay}t-1}, & \\
\text{IF}(\text{CB}_{\text{ay}} \times (1 - \exp(\frac{\text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}})) \times \text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}} > (1 + \text{TAC}_{\text{ay}0}) \times \text{TAC}_{\text{ay}t-1}, & \\
\text{CB}_{\text{ay}} \times (1 - \exp(\frac{\text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}})) \times \text{PIF}_{\text{TAC}} \times H_{\text{target}_{\text{ay}0}}}{\text{PIF}_{\text{TAC}} + M_{\text{ay}0}})
\end{cases}$
Where  

\[
\begin{align*}
\text{CB-ay} & \quad = \text{catchable biomass} \\
H_{\text{target-ay0}} & \quad = \text{target (msy) harvest ratio} \\
M_{\text{ay0}} & \quad = \text{natural fishing mortality} \\
TAC_{\text{ay0}} & \quad = \text{maximum change of TAC from one year to another} \\
TAC_{\text{ayt-1}} & \quad = \text{TAC preceding year} \\
\text{PIF-TAC} & \quad = \text{Policy intensity factor applied to TAC policy}
\end{align*}
\]

Equation (4) simulates biological advice (i.e. proposed TAC):  

\[
\text{CB-ay} \times (1 - \exp(-(H_{\text{target-ay0}} + M_{\text{ay0}})) \times H_{\text{target-ay0}}/(H_{\text{target-ay0}} + M_{\text{ay0}})
\]

and compares it to the TAC of the preceding year, checking whether the change does not exceed the maximum change agreed in the management plan. After the comparison the appropriate value of the new TAC is selected. PIF-TAC factor allows the policy maker to increase or decrease the biologically proposed target harvest ratio, based on other political considerations.

**Minimum and maximum effort computed from TAC**

As elaborated above, when TAC policy is selected, the TAC resulting from equation (4) is inserted in the inverse production function to determine the effort required to catch each species. The effort levels are compared and the lowest or highest effort level is selected to be used in the model for the calculation of catch of other species and costs.

\[
\begin{align*}
\text{MinEfTAC-xa} & = \min\left(\frac{\text{LandT-xy}}{\text{Catch-xy0} \times \text{CB-ay} \times (\text{Catch-xy2} \times (1 + \text{Catch-xy3}))^{\frac{1}{\text{Catch-xy1}}}}\right) \\
\text{MaxEfTAC-xa} & = \max\left(\frac{\text{LandT-xy}}{\text{Catch-xy0} \times \text{CB-ay} \times (\text{Catch-xy2} \times (1 + \text{Catch-xy3}))^{\frac{1}{\text{Catch-xy1}}}}\right)
\end{align*}
\]

Where  

\[
\begin{align*}
\text{LandT-xy} & \quad = \text{target landings} \\
\text{CB-ay} & \quad = \text{catchable biomass} \\
\text{Catch-xy0, Catch-xy1, Catch-xy2, Catch-xy3} & \quad = \text{parameters of the production function}
\end{align*}
\]

**Minimum and maximum effort from Htarget**

When effort policy is selected, allowable effort for each species is adjusted by the ratio between target harvest ratio and partial harvest ratio caused by the
segment. The ratios regarding all species are compared and minimum or maximum is selected according to the policy choice. Adjustment from one year to the next is not constrained by an X% limit, as in case of TACs. PIF-Eff allows the policy maker to deviate from biological advice.

\[
\text{MinEfC} = \text{MIN}(\text{Eff-}x_{a_t-1} \times \text{PIF-Eff} \times \text{Htarget-}a_{0} / (\text{H-}a_{t-1}))
\]

\[
\text{MaxEfC} = \text{MAX}(\text{Eff-}x_{a_t-1} \times \text{PIF-Eff} \times \text{Htarget-}a_{0} / (\text{H-}a_{t-1}))
\]

Where  
\( \text{Eff-}x_{a_t-1} \) = effort preceding year  
\( \text{Htarget-}a_{0} \) = target harvest ratio  
\( \text{H-}a_{t-1} \) = harvest ratio in preceding year  
\( \text{PIF-Eff} \) = Policy intensity factor applied to effort policy

**Payment for access**

The formula for payment for access contains four different types of payments, all being segment specific so that in principle different segments could be 'taxed' differently:
- Lump sum;
- Payment per unit of effort;
- Profit tax;
- Payment as percentage of value of landed fish.

By setting the parameters at 0 or a non-0 value, various combinations of payments can be simulated.

\[
\text{PfAcc-}x_{a} = \text{PfAcc-}x_{a0} + \text{PfEff-}x_{a0} \times \text{Eff-}x_{a} + \text{ProTax-}x_{a0} \times \text{Prf-}a_{1} + \sum_{a}(\text{PfFish-}a_{0} \times \text{Land-}a_{-} \times \text{FishPr-}a_{})
\]

Where  
\( \text{PfAcc-}x_{a0} \) = lump sum payment  
\( \text{PfEff-}x_{a0} \) = payment per unit of effort  
\( \text{Eff} \) = effort  
\( \text{ProTax-}x_{a0} \) = profit tax  
\( \text{Prf} \) = profit  
\( \text{PfFish-}a_{0} \) = payment for landed value  
\( \text{Land} \) = landings  
\( \text{FishPr} \) = fish price
3.3 Interface module

The purpose of the Interface module is to generate a consistent set of landings and effort, taking into account the policy choice and the maximum effort which can be exerted by the fleet. The possible combinations are presented in Table 3.1. The first two columns determine the policy choice: TAC of Effort and Min or Max. Third and fourth column shows which effort level is selected for the model. The last column shows how the catch is calculated.

<table>
<thead>
<tr>
<th>Policy</th>
<th>Max/Min</th>
<th>Relation between required effort and maximum effort</th>
<th>Effort used in the model</th>
<th>Model catch</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAC</td>
<td>Min</td>
<td>Required eff &lt; Max. eff</td>
<td>Required eff</td>
<td>TAC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required eff &gt; Max. eff</td>
<td>Max. eff</td>
<td>Catch=f(Max. eff)</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>Required eff &lt; Max. eff</td>
<td>Required eff</td>
<td>TAC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required eff &gt; Max. eff</td>
<td>Max. eff</td>
<td>Catch=f(Max. eff)</td>
</tr>
<tr>
<td>Effort</td>
<td>Min</td>
<td>Required eff &lt; Max. eff</td>
<td>Required eff</td>
<td>Catch=f(Required eff)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required eff &gt; Max. eff</td>
<td>Max. eff</td>
<td>Catch=f(Max. eff)</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>Required eff &lt; Max. eff</td>
<td>Required eff</td>
<td>Catch=f(Required eff)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Required eff &gt; Max. eff</td>
<td>Max. eff</td>
<td>Catch=f(Max. eff)</td>
</tr>
</tbody>
</table>

Catch - production function

The core equation of the model is the Cobb-Douglas production function and its inverse. Two situations are distinguished:
- Equation 10: The catch (excluding undersized discards) is a function of effort, stock abundance and technological progress. In this case effort is the exogenous variable, which means that the policy determines how much effort is allowed and subsequently catch can be determined. In this case the normal form of the Cobb-Douglas production function is used. This could be called effort driven production function.
- Equation 11: When the policy is determined by TACs, then the required effort level can be calculated using an inverse Cobb-Douglas production function.

(10) \( \text{Catch}_{xy} = \text{Catch}_{xy0} \times \text{Eff}^{\text{Catch}_{x}1} \times \text{CB}^{\text{Catch}_{y}2} \times (1+\text{Catch}_{xy3}) \)
\[ \text{Eff-xy} = \frac{\text{LandT-xy}}{(\text{Catch-xy}^0 \cdot \text{CB-ay}^\text{Catch-xy}2 \cdot (1+\text{Catch-xy}3))^{1/\text{Catch-xy}1}} \]

Where
- \(\text{Eff} = \) Effort
- \(\text{CB} = \) Catchable biomass
- \(\text{LandT} = \) Target landings based on segment share in TAC
- \(\text{Catch-xy}3 = \) Rate of technological progress
- \(\text{Catch-xy}0, \text{Catch-xy}1, \text{Catch-xy}2 = \) estimated parameters
- \(\text{Catch-xy}1 + \text{Catch-xy}2 = 1\)

The total catch of a species includes the catch by 'other' segments, which has been accounted for in the biomass function (2) using the sum of TAC shares of the specified segments.

The parameters of the function are estimated based on theory and few empirical studies. The technological progress is hardly above 1.5% per year (Frost et al., 2009). For trawlers that are less impacted by stock abundance than by technology the exponent for effort is between 0.6-0.9 while the exponent for the stock is between 0.1-0.4. For gillnetters the opposite is to be expected. For pelagic and demersal species with schooling behaviour the exponent for the stock is low while it is higher for dispersed demersal species. Setting the values of these parameters makes it possible to estimate the \(\text{Catch-xy}0\) parameter.

The importance of the exponents is significant, as shown in Figure 3.1 in which the catch and the fishing costs (being a function of the effort) are shown for different harvest ratios. For further explanation see Frost et al. (2009). It is seen that the optimal fishing mortality rate may not differ in the two examples but the size of the resource rent, and what could be gained by optimal adaptation differs significantly.
Figure 3.1  Catches and costs under different assumptions about the relationship between harvest ratio and effort

<table>
<thead>
<tr>
<th>2.1 Cobb-Douglas production function</th>
<th>2.2 Cobb-Douglas production function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha=0.4$</td>
<td>$\alpha=0.9$</td>
</tr>
<tr>
<td>$\beta=0.6$</td>
<td>$\beta=0.1$</td>
</tr>
<tr>
<td>Low catch-effort flexibility</td>
<td>High catch-effort flexibility</td>
</tr>
<tr>
<td>High stock-catch flexibility</td>
<td>Low stock-catch flexibility</td>
</tr>
</tbody>
</table>

Source: Frost et al. (2009), Figure 7.

Costs (E) = assumes linear relation between costs, effort and mortality.
Costs (F) = assumes non-linear relation between costs, effort and mortality.

**Target landings**

Target landings are equal to the historical segment share in the TAC. Target landings allow calculation of the effort level required to exploit the set TACs and the over-quota catches.
(12) \( \text{LandT-xy} = \text{TAC-ay} \times \text{TACsh}_xy \times 0 \)

Where

- \( \text{TAC} \) = total allowable catch
- \( \text{TACsh} \) = historical segment share in the EU TAC

**Over-quota discards**

The landings are derived from the catches after subtraction of over-quota catches, which must be discarded.

(13) \( \text{Disc-xy} = \text{IF} (\text{Catch-xy} > \text{LandT-xy}, \text{Disc}_xy \times 1 \times (\text{Catch-xy} - \text{LandT-xy}), 0) \)

Where

- \( \text{Catch} \) = catch
- \( \text{LandT} \) = target landings, based on segment share in TAC (see policy module)
- \( \text{Disc} \) = share of over-quota catch which is discarded

**Landings**

Landings of a segment are catches minus over-quota discards.

(14) \( \text{Land-xy} = \text{Catch-xy} - \text{Disc-xy} \)

Where

- \( \text{Catch} \) = catch
- \( \text{Disc} \) = over-quota discards

**Effort selection**

Appropriate level of effort is selected on the basis of the policy choice. The last term 'Policy type?' is included as a warning should an invalid number of policy type be inserted.

(15) \( \text{Eselect} = \text{IF} (\text{PolT}=1, \text{MinEfTAC-xa}, \text{IF} (\text{PolT}=2, \text{MinEffC-xa}, \text{IF} (\text{PolT}=3, \text{MaxEfTAC-xa}, \text{IF} (\text{PolT}=4, \text{MaxEffC-xa}, \text{IF} (\text{PolT}=5, \text{FreeE-xa}, \text{IF} (\text{PolT}=6, \text{MIN} (\text{MinEfTAC-xa}, \text{MinEfC-xa}), \text{Policy type?}))))) \)

Where

- \( \text{PolT} = \text{Policy type} \)
**Effort choice - policy versus fleet**

Effort is measured as the total number days-at-sea for each fleet segment. This is the product of the number of vessels and the operational number of days-at-sea per vessel per year. Total effort which a segment can exert depends on the selected policy option (see policy module). However, the effort level allowed by the policy may be higher than the maximum effort which the segment can generate. Therefore, the appropriate effort level has to be selected.

\[
\text{Eff}_{xa} = \text{IF}(\text{Eselect}_{xa} > \text{Fle}_{xa} \times \text{DASmax}_{xa}, \text{Fle}_{xa} \times \text{DASmax}_{xa}, \text{Eselect}_{xa})
\]

Where
- \( \text{Eselect} \) = effort selected in the policy module
- \( \text{Fle} \) = fleet
- \( \text{DASmax} \) = maximum number of days-at-sea per vessel

The model also operates with the maximum number of days-at-sea per vessels per year.

### 3.4 Economic module

**Revenues**

Gross revenue is estimated for each fleet segment taking the landings net of discards and multiplied with fish prices. Specific price differential of the segment from the average is included. Revenues from target species are upgraded by revenues from other species, either by a lump sum or a percentage. This choice can be made in the model parameter sheet with appropriate values of the parameters.

\[
\text{Rev}_{xa} = \left( \sum \text{Land}_{xy} \times \text{FishPr}_{ay} \times \text{PrSeg}_{xy0} \right) \times (1 + \text{OtSpR}_{xa0}) + \text{OtSpF}_{xa0} \times \text{Eff}_{xa}
\]

Where
- \( \text{Land} \) = landings
- \( \text{FishPr} \) = fish price
- \( \text{PrSeg} \) = price differential for the segment from the average price
- \( \text{Eff} \) = effort
- \( \text{OtSpR} \) = revenues from non-target species as a percentage of target
species

$OtSpF = \text{revenues from non-target species per unit of effort}$

**Fuel costs**

The fuel costs depend on fuel use per unit of fishing effort, effort and fuel price. Fuel price may be differentiated between segments.

(18) $FuC_{xa} = FuU_{xa0} \cdot Eff_{xa} \cdot FuelPr_{1a0}$

Where

- $FuU$ = fuel use per unit of fishing effort
- $Eff$ = effort
- $FuelPr$ = fuel price (may be segment specific)

**Crew costs**

Crew costs are often calculated as a share of the gross revenues after deduction of fuel costs and/or variable costs.

(19) $CrC_{xa} = (Rev_{xa} - CrC_{xa1} \cdot FuC_{xa} - CrC_{1a2} \cdot VaC_{xa}) \cdot CrC_{xa0}$

Where

- $Rev$ = revenues
- $FuC$ = fuel costs
- $VaC$ = variable costs
- $CrC_{xa0}$ = crew share
- $CrC_{xa1}$ and $CrC_{xa2}$ are either 0 or 1 to take the fuel costs or variable costs into account.

**Variable costs**

Variable costs, being e.g. costs of landings, auction and harbour fees, depend on gross revenues.

(20) $VaC_{xa} = Rev_{xa} \cdot VaC_{xa0}$

Where

- $Rev$ = revenues
- $VaC_{xa0}$ = variable costs as percentage of gross revenues
**Fixed costs**

The fixed costs, also named vessel costs or semi-fixed costs are administration, insurance, maintenance, etc. It is assumed that these costs depend implicitly on the value of the vessel and are constant per vessel. The value of the segment is separated in a value index per vessel and the number of vessels. In this way fixed costs will change with the changing number of the vessels in the segment. If the value index is set at a different value than 1, then changes in construction costs can be accounted for.

\[ F_{xC} = F_{xC,0} \times F_{e} \times InvPrice \]

Where
- \( F_{e} \) = number of vessels
- \( F_{xC,0} \) = fixed costs per vessel
- \( InvPrice \) = value index

The fixed costs per vessels (\( F_{xC,0} \)) are determined taking the total fixed costs for a segment in the base year divided by the number of vessels. Using the value index (\( InvPrice \)) may be appropriate when the size of the fleet would be significantly expanded and construction costs of new vessels would be expected to be above the value of the existing vessels.

**Capital costs**

Capital costs are calculated in the same way as fixed costs.

\[ C_{aC} = C_{aC,0} \times F_{e} \times InvPrice \]

Where
- \( F_{e} \) = number of vessels
- \( C_{aC,0} \) = capital costs per vessel
- \( InvPrice \) = value index
**Gross cash flow**

The gross cash flow is the difference between revenues and all operational costs.

\[ \text{GCF-}xa = \text{Rev-}xa - \text{FuC-}xa - \text{CrC-}xa - \text{VaC-}xa - \text{FxC-}xa \]

Where
- \(\text{Rev}\) = revenues
- \(\text{FuC}\) = fuel costs
- \(\text{CrC}\) = crew costs
- \(\text{VaC}\) = variable costs
- \(\text{FxC}\) = fixed costs

**Profit**

Profit is calculated before and after payment for access.

\[ \text{Prf-}xa = \text{GCF-}xa - \text{CaC-}xa \]

Where
- \(\text{GCF}\) = gross cash flow
- \(\text{CaC}\) = capital costs

\[ \text{PrfaTax-}xa = \text{Prf-}xa - \text{FpfAcc-}xa \]

Where
- \(\text{Prf}\) = profit
- \(\text{FpfAcc}\) = full payment for access

Payment for access is a policy (control) variable and the function form is included under the policy module (equation 9).

**Net present value of profit and gross value added**

The discounted net profit and gross value added have meaning only in the dynamic model working for a number of years. Different discount rates are allowed for the different segments to reflect different time preferences although it seems most meaningful to use the same discount rate for all segments as default.

The net present values are computed for a 15 and 25-year period and for infinity. As already explained earlier, this distinction between the two periods of 15 and 25 years was introduced in particular in relation to the optimisation runs...
of the model. When a model is run for 15 years and profit or gross value added are maximised over that period, the model will tend to fish out all the stocks at the end of the period as it does not take into account what happens beyond the set time horizon. This is evidently not desirable. This problem has been resolved by 'optimising' over a period of 25 years, but using the net present value of the first 15 years only. In this way destruction of stocks is avoided within the first 15 years.

The net present value of net profit for infinity (equation 28) may be also used to estimate the maximum resource rent from a fully adjusted fishery. As a 15-year period normally is long enough to expect full adjustment it is assumed that the profit in year 15 will continue infinitely.

\[
\text{(26)} \quad \text{NpvPrf}_{15,\text{xa}} = \sum_{t} \text{Prf}_{-15,\text{xa}} \times [1 - (1 + \text{Dis}_{\text{xa0}})^{(\text{DisPeriod}_{\text{xa1}}/\text{Dis}_{\text{xa0}})}] \\
\text{(27)} \quad \text{NpvGVA}_{\text{xa}} = \sum_{t} \text{GVA}_{-15,\text{xa}} \times [1 - (1 + \text{Dis}_{\text{xa0}})^{(\text{DisPeriod}_{\text{xa1}}/\text{Dis}_{\text{xa0}})}] \\
\text{(28)} \quad \text{NPV}_{\text{xa}} = \text{Npv15}_{\text{xa}} + \text{Prf}_{-15}/\text{Dis}_{\text{xa0}} \times (1 + \text{Dis}_{\text{xa0}})^{\text{year} \text{t}}
\]

Where
- \text{Prf} = \text{profit}
- \text{GVA} = \text{gross value added}
- \text{Dis}_{\text{xa0}} = \text{discount rate}
- \text{DisPeriod}_{\text{xa1}} = \text{year t}

\textit{Break-even revenues}

The break-even revenue shows the gross revenue with given capital costs that yields a zero profit. Break-even can be used for different analytical purposes. It is an indicator of profit and it provides an indication of economic overcapacity.

The break-even revenue is used in the model as a driver of investments (equation 29). Ratio of break-even revenues to realised revenues determines the level of investments in the following period. Therefore the break-even revenues consider crew costs as fixed costs. This is justified on the basis of three mutually related arguments:

- Skipper ownership is commonplace in the EU fisheries. This implies that there is no clear distinction between remuneration of labour and capital.
- Crews are remunerated on share basis. Break-even revenues may imply an unacceptably low crew share, making fishing an unattractive occupation. Then it would be unrealistic to expect that operation at break-even level could be continued indefinitely, while that is precisely the principle of break-even.
- Inclusion of crew costs among 'fixed costs' reduces the fluctuations of investments throughout the simulated period.

\[
(29) \quad \text{BER}_{xa} = \frac{(\text{CrC}_{xa} + \text{FxC}_{xa} + \text{CaC}_{xa})}{(1 - \frac{\text{FuC}_{xa}}{\text{Rev}_{xa}} - \frac{\text{VaC}_{xa}}{\text{Rev}_{xa}} - \frac{\text{FPfAcc}_{xa}}{\text{Rev}_{xa}})}
\]

Where

- \( \text{CrC} \) = crew costs
- \( \text{FxC} \) = fixed costs
- \( \text{CaC} \) = capital costs
- \( \text{FuC} \) = fuel costs
- \( \text{Rev} \) = revenues
- \( \text{VaC} \) = variable costs
- \( \text{FPfAcc} \) = full payment for access

**Fuel use**

Fuel use is for some fisheries an important indicator. Therefore a fuel use relation has been included in the model.

\[
(30) \quad \text{FuU}_{xa} = \text{Eff}_{xa} \times \text{FuU}_{xa0}
\]

Where

- \( \text{Eff} \) = Effort
- \( \text{FuU}_{xa0} \) = Fuel use per unit of effort

### 3.5 Behaviour module

The behaviour module determines the (dis)investment and changes in effort level (days-at-sea per vessel).

**Investment function**

Theoretically the investments are determined by expectations of future profit, but there is no empirical data, which could be used to support such theorem in the model. Instead, perceived profitability in the preceding year, expressed as ratio between break-even revenues minus realised revenues divided by realised revenues is used to determine the (dis)investments in each year. When break-even revenues exceed realised revenues, the ratio is positive and the fleet will expand and vice versa.
This leads in some years to quite substantial changes in the number of vessels in a fleet segment, which could occur as vessels from other segments may enter the given fishery. At the same time, it was recognised that the inertia of the system (licensing, knowledge of skippers, etc.) does not allow such full flexibility. Consequently, parameters have been introduced to limit the maximum annual (dis)investments. As different parameters have been applied to investments and disinvestments, asymmetric investment and disinvestment behaviour can be simulated.

Furthermore, it has been assumed that the active fleet will first achieve a certain minimum number of days-at-sea per vessel before the number of vessels will be expanded. This assumption was introduced to avoid continuous growth of the fleet, while at same time the number of days-at-sea per vessel could be proportionately falling\(^1\), as long as break-even revenues exceed realised revenues.

\[ \text{Inv}_xa = \text{IF}(\text{DASope}_xa < \text{InvDays}_xa3 \times \text{DASmax}_xa, \text{IF}(\text{BER}_xa < 0, \text{IF}(\text{PrfShare}_xa0^* (\text{REV}_xa - \text{BER}_xa)_t/\text{REV}_xa_t > \text{InvLimu}_xa1, \text{InvLimu}_xa1 \times \text{FLE}_xa, \text{IF}(\text{PrfShare}_xa0^* (\text{REV}_xa - \text{BER}_xa)_t/\text{REV}_xa_t < -\text{InvLimd}_xa2, \text{InvLimd}_xa2 \times \text{FLE}_xa, \text{PrfShare}_xa0^* (\text{REV}_xa - \text{BER}_xa)_t/\text{REV}_xa_t \times \text{FLE}_xa))) \]

Where

- \( \text{Rev} \) = revenues
- \( \text{BER} \) = break-even revenues
- \( \text{FLE} \) = fleet, number of vessels
- \( \text{DASope} \) = operational (actual) number of days-at-sea per vessel
- \( \text{DASmax} \) = maximum number of days-at-sea per vessel
- \( \text{PrfShare}_xa0 \) = share of profit dedicated to investments,
- \( \text{InvLimu}_xa1 \) = upper limit for investments, as a relative change of the fleet
- \( \text{InvLimd}_xa2 \) = lower limit for investments, as a relative change of the fleet
- \( \text{InvDays}_xa3 \) = minimum level of capacity utilisation, under which no investments take place

\(^1\) Such situation has occurred in practice in the past, e.g. the king crab fishery in Alaska.
The behaviour module assumes that only segments which historically participated in the fishery will be able to do so also in the future. While the size of these segments may be reduced almost to zero, there is no provision to allow new types of vessels (technologies) to enter into the fishery.

**Fleet (number of vessels)**

Number of vessels in a segment is equal to the fleet of the preceding year (t-1) plus the (dis)investments in the preceding year (t).

\[ \text{Fle}_x = \text{Fle}_{x-1} + \text{Inv}_{x-1} \]

Where \( \text{Fle} \) = fleet
\( \text{Inv} \) = (dis)investments

The number of vessels is constant if the investment function is turned off e.g. by setting the profit investment share, PrfShare-xa0, at zero. Changes in the number of vessels affect the number of days-at-sea, fixed and capital costs and ultimately the profit.

In case of free fishery it can be expected that the fleet will exert the maximum number of days-at-sea per vessel.

\[ \text{FreeE}_{xy} = \text{Fle}_x \times \text{DASmax}_x \]

Where \( \text{Fle} \) = fleet (number of vessels)
\( \text{DASmax} \) = maximum number of days-at-sea per vessel

**Employment**

Distinction is made between nominal and full time employment. Nominal employment is based on average crew per vessel.

\[ \text{NoEmp}_x = \text{Fle}_{xy} \times \text{Crew}_x \]

Where \( \text{Fle} \) = fleet (number of vessels)
\( \text{Crew} = \text{average crew per vessel} \)
Full time employment is based on the notion that a full time crewman would be also continuously on board when a vessel would be operating the maximum number of days-at-sea.

\[ \text{FTE}_\text{Seg} = \text{Fle} \times \text{NoEmp} \times \text{DASope} / \text{FTE}_{-\text{norm}} \times \text{xa} \]

Where
- \( \text{Fle} \) = fleet (number of vessels)
- \( \text{NoEmp} \) = average crew per vessel
- \( \text{DASope} \) = operational number of days-at-sea
- \( \text{FTE}_{-\text{norm}} \) = assumed FTE standard of number of days-at-sea

The FTE-norm is set for each segment, according to the national definition of FTE and interpretation of FTE in the specific fishery. The approach should be consistent with the definition of FTE under DCF.

### 3.6 Price module

**Fish prices**

Fish prices are based on the prices of the baseline year, possibly adapted by price elasticity. However, this is only relevant if the fishery lands a significant share of the total supply of a species. Setting price elasticity at zero leads to constant prices. If required, the formula could be easily adapted to include a price trend.

\[ \text{FishPr}_{-\text{ay}} = \text{FishPr}_{-\text{ay}0} \times (\text{Land}_{-\text{a1}} / \text{Land}_{-\text{a1,1,1}})^{(-\text{PrEl}_{-\text{a11}})} \]

Where
- \( \text{FishPr} \) = fish price
- \( \text{Land} \) = landings
- \( \text{PrEl} \) = price elasticity

**Fuel price**

The fuel price can be adjusted by an annual percentage change (\( \text{FuelPr}_{-\text{xa0}} \)), which can be also differentiated between fleet segments. Fleet performance at a generally higher level of fuel price can be simulated by setting the FuelPr at a desired initial level.
(37) \( \text{FuelPr}_xa = \text{FuelPr}_xa_{a-1} \times (1 + \text{FuelPr}_xa_0) \)

Where \( \text{FuelPr}_xa_0 \) is annual percentage change of fuel price

### 3.7 Totals

At the bottom of the worksheet, totals of all relevant variables are calculated as sums of segments.

(38) \( \text{Catch} \)

(39) \( \text{Discards} \)

(40) \( \text{Landings} \)

(41) \( \text{Target landing} \)

(42) \( \text{Revenues} \)

(43) \( \text{Fuel costs} \)

(44) \( \text{Crew costs} \)

(45) \( \text{Variable costs} \)

(46) \( \text{Fixed costs} \)

(47) \( \text{Capital costs} \)

(48) \( \text{Gross cash flow} \)

(49) \( \text{Profit} \)

(50) \( \text{Full payment for access} \)

(51) \( \text{Profit after access payment} \)

(52) \( \text{Profit discounted} \)

(53) \( \text{NPV 25 years} \)

(54) \( \text{NPV infinity} \)

(55) \( \text{Break-even revenues} \)

(56) \( \text{Gross value added} \)

(57) \( \text{Fuel use} \)

(58) \( \text{Fleet (number of vessels)} \)

(59) \( \text{Days-at-sea/vessel - operational} \)

(60) \( \text{Effort - segment} \)

(61) \( \text{Total investment} \)

(62) \( \text{Investment (number of vessels)} \)

(63) \( \text{Nominal employment} \)

(64) \( \text{Full-time employment} \)
### 3.8 Other indicators

Three other indicators are calculated as well, although they are not used in the model.

\[
(65) \text{Partial harvest ratio} \quad H_{\text{par-xy}} = \frac{\text{Catch-xy}}{\text{CB-ay}} \\
(66) \text{Catchability} \quad \text{Catchability} = \frac{F_{\text{par-xy}}}{\text{Eff-xy}} \\
(67) \text{Catch per unit effort} \quad \text{CPUE-xy} = \frac{\text{Catch-xy}}{\text{Eff-xy}}
\]
4 Adaptation of the model to fewer fleet segments and species

The model is constructed for eight fleets segments and eight species (8x8 version) but it is also available in smaller versions (4x4 and 2x2). These versions can be used for fewer fleet segments and species.

When an 'oversized' model is used, i.e. specified number of segments or species is smaller than the model size, then two types of error will arise:
- Division by zero.
- Choosing effort according to the policy choice of effort determined by the most restrictive TACs or effort.

Division by zero

Number of vessels set at zero for a segment implies zero revenue, but as revenue is used as denominator in the break-even and hence in the investments calculations this leads to an error. Therefore, the number of vessels for segments that are not used must be set close to zero e.g. 0.0001.

Species in terms of fish stocks set at zero imply an error in the number of days-at-sea as stocks are used as denominator in some of the effort equations depending on H and Htarget. Therefore the stocks that are not used must be set close to zero, e.g. 0.0001.

In the model the stocks are not allowed to go below 1 (or another small number close to zero) to make sure that the model does not work with negative stocks and that a stock can grow again after having been depleted. Therefore the stocks will always be 1 even if set close to zero in the Parameter sheet. This will cause a very small error (over estimation) in the in the results (profit, GVA) of the fleet segments. This error is well within the margins of error which can be expected in such a model.
Choosing effort according to minimum TAC or effort

This adjustment is related to the choice of policy and is only needed if fewer species are used than the dimension of the model. If species are omitted by setting the initial stocks at zero the model still takes these species into account in the choice of TAC or effort in the policy equations. As the model in the MIN case chooses effort according to the most restrictive quota of the species or the most restrictive effort, the effort will be determined by the 'empty' species and hence the effort will be zero.

Therefore it is necessary to delete the species not used from the policy equations in the model. This is done in the Policy module of the model, which comprises four sub-sections - choice of the most restrictive or the least restrictive TAC and choice of the most restricted or the least restrictive effort. There is one equation for each fleet segment i.e. 32 equations must be adapted when 8 segments are specified. However, only the equations for the most restrictive TACs or effort constraints (the MIN cases) need to be adjusted and only for the equations including the active fleets segments.

For example, if the 8x8 version is used for six fleet segments and eight species no adjustment is necessary as all species are used. But if the model is used for 6 species 12 equations need adjustment in order to delete the two species 'positions' not used in the equations for the six fleet segments.
When using the FISHRENT model for optimisation it must be born in mind that the Solver may not produce optimum results in its first run (Figure 5.1). The default settings of the Options are set at maximum time of 100 seconds and maximum 100 iterations, which may not be sufficient. Increasing the default settings does not provide a guarantee that the optimum values will be found. Therefore it is recommended to run the Solver in several consecutive steps until the results do not change any more. After each run the Excel file must be stored under a new name and the Solver must be run again in this new file.

The Solver must be set according to the desired values, on the sheet 'Multi-year model', example being presented in the following figure:
- Target set points to required value in column I or K
- Changing cells are the rows containing the number of vessels
- Constraints reflect values which cannot be exceeded, i.e. minimum or maximum effort.
Figure 5.1  Example of setting values to run the Excel Solver
References


### Appendix 1

List of parameters and their initial settings

<table>
<thead>
<tr>
<th>Name</th>
<th>Acronym</th>
<th>Units</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target harvest ratio</td>
<td>Htarget-ay0</td>
<td>Coefficient</td>
<td>Calculated</td>
<td>From the relevant advisory body (ICES)</td>
</tr>
<tr>
<td>Mortality - natural</td>
<td>M-ay0</td>
<td>Coefficient</td>
<td>Species specific</td>
<td>From the relevant advisory body (ICES)</td>
</tr>
<tr>
<td>TAC constraint</td>
<td>Tac-ay0</td>
<td>Coefficient</td>
<td>Species specific</td>
<td>From the relevant advisory body (ICES)</td>
</tr>
<tr>
<td>Payment - lump sum</td>
<td>PfAcc-xa0</td>
<td>1000 euro</td>
<td>0</td>
<td>Is the payment for the license</td>
</tr>
<tr>
<td>Payment per unit of effort</td>
<td>PfEff-xa0</td>
<td>Coefficient</td>
<td>0</td>
<td>Related to the effort</td>
</tr>
<tr>
<td>Payment - profit tax</td>
<td>ProTax-xa0</td>
<td>Coefficient</td>
<td>0</td>
<td>Related to the effort</td>
</tr>
<tr>
<td>Payment - fish value</td>
<td>PfFish-ay0</td>
<td>Coefficient</td>
<td>0</td>
<td>Related to the landings</td>
</tr>
<tr>
<td>Fleet (no. of vessels)</td>
<td>Fle-xa</td>
<td>Number</td>
<td>Segment specific</td>
<td>Number of vessels of the segment</td>
</tr>
<tr>
<td>Days-at-sea/vessel - operational</td>
<td>DASope-xa</td>
<td>Number</td>
<td>Calculated</td>
<td>Operational days-at-sea per vessel</td>
</tr>
<tr>
<td>Days-at-sea/vessel - maximum</td>
<td>DASmax-xa</td>
<td>Number</td>
<td>Assumed</td>
<td>Maximum number of operational days-at-sea per vessel</td>
</tr>
<tr>
<td>Days-at-sea/vessel - maximum</td>
<td>DASmax-xa1</td>
<td>Percentage</td>
<td>0</td>
<td>Potential percentage increase of the maximum number of fishing days. Not used</td>
</tr>
<tr>
<td>Nominal employment</td>
<td>NoEmp</td>
<td>Number</td>
<td>Calculated ex-ante</td>
<td>Based on historical data</td>
</tr>
<tr>
<td>Name</td>
<td>Acronym</td>
<td>Units</td>
<td>Value</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Investment price vessel</td>
<td>InvPrice-xa</td>
<td>1000 €</td>
<td>1</td>
<td>Total investment of the total segment divided by the number of vessels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>in 1000 €. Not used</td>
</tr>
<tr>
<td>Investment (no. of vessels)</td>
<td>InvPrice-xa0</td>
<td>Percentage</td>
<td>0</td>
<td>Not used</td>
</tr>
<tr>
<td>Investment (no. of vessels)</td>
<td>PrfShare-xa0</td>
<td>Coefficient</td>
<td>0.2</td>
<td>It is a Boundary coefficient. The share between the (Rev-BER)/Rev.</td>
</tr>
<tr>
<td>TAC share</td>
<td>TACsh-110</td>
<td>Coefficient</td>
<td>Calculated</td>
<td>It is the share of the landings made by the segment to the total</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>landings of the stock</td>
</tr>
<tr>
<td>Catchable biomass</td>
<td>CB-ay</td>
<td>Tonnes</td>
<td>Species specific</td>
<td>Spawning stock biomass used as a proxy.</td>
</tr>
<tr>
<td>Growth</td>
<td>Rec-ay</td>
<td>Tonnes</td>
<td>Species specific</td>
<td>Growth is estimated by recruitment (number of fish) multiplied by</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>yield per recruit. The function include M and r</td>
</tr>
<tr>
<td>Growth</td>
<td>Rec-ay0</td>
<td>Coefficient</td>
<td></td>
<td>Estimated (intercept)</td>
</tr>
<tr>
<td>Growth</td>
<td>Rec-ay1</td>
<td>Coefficient</td>
<td></td>
<td>Estimated (order 1)</td>
</tr>
<tr>
<td>Growth</td>
<td>Rec-ay2</td>
<td>Coefficient</td>
<td></td>
<td>Estimated (order 2)</td>
</tr>
<tr>
<td>Growth</td>
<td>Rec-ay3</td>
<td>Coefficient</td>
<td></td>
<td>Estimated (order 3)</td>
</tr>
<tr>
<td>Growth</td>
<td>Expo-ay1</td>
<td>Coefficient</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Growth</td>
<td>Expo-ay2</td>
<td>Coefficient</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Growth</td>
<td>Expo-ay3</td>
<td>Coefficient</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Catch</td>
<td>Catch-110</td>
<td>Coefficient</td>
<td></td>
<td>Estimated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Constant in the production function</td>
</tr>
<tr>
<td>Catch</td>
<td>Catch-111</td>
<td>Coefficient</td>
<td>0.2 or 0.6</td>
<td>Exponent of effort</td>
</tr>
<tr>
<td>Catch</td>
<td>Catch-112</td>
<td>Coefficient</td>
<td>0.8 or 0.4</td>
<td>Exponent of biomass</td>
</tr>
<tr>
<td>Name</td>
<td>Acronym</td>
<td>Units</td>
<td>Value</td>
<td>Comment</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Catch</td>
<td>Catch-113</td>
<td>Percentage</td>
<td>0</td>
<td>The annual technical progress, (note that the function is not linear)</td>
</tr>
<tr>
<td>Discards - undersized fish</td>
<td>Disc-110</td>
<td>Percentage</td>
<td>0</td>
<td>Percentage of the discards</td>
</tr>
<tr>
<td>Discards - quota fish</td>
<td>Disc-111</td>
<td>0 to 1</td>
<td>0</td>
<td>1: can land all caches 0: cannot land over-quota catch</td>
</tr>
<tr>
<td>Fuel price</td>
<td>FuelPr-xa</td>
<td>Coefficient</td>
<td>1</td>
<td>It is the nominal increased of the fuel cost relative to base case year: =1: Fuel cost as in the base case &gt;1 Fuel cost higher than in the base case &lt;1 Fuel cost lower than in the base case. Not used</td>
</tr>
<tr>
<td>Fuel price</td>
<td>FuelPr-xa0</td>
<td>Percentage</td>
<td>0</td>
<td>Annual growth of the fuel cost relative to the previous year</td>
</tr>
<tr>
<td>Fish prices</td>
<td>FishPray</td>
<td>€/kg</td>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>Fish prices</td>
<td>PrElay1</td>
<td>Coefficient</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Fish prices</td>
<td>PrSeg-110</td>
<td>Coefficient</td>
<td>1</td>
<td>If &gt;1 the price of this segment/species is increased</td>
</tr>
<tr>
<td>Revenues</td>
<td>OtSpR-xa0</td>
<td>Percentage</td>
<td></td>
<td>Calculated Percentage of the revenue obtained by the other species.</td>
</tr>
<tr>
<td>Revenues</td>
<td>OtSpF-xa0</td>
<td>1000€</td>
<td></td>
<td>Calculated Fixed amount of the other species by vessel</td>
</tr>
<tr>
<td>Revenues</td>
<td>Related to the effort</td>
<td>1000€/fishing day</td>
<td></td>
<td>Calculated Not done yet Not used</td>
</tr>
<tr>
<td>Fuel costs</td>
<td>FuC-xa0</td>
<td>Coefficient</td>
<td></td>
<td>Total fuel cost in 1000 € divided by total fishing days</td>
</tr>
<tr>
<td>Crew costs</td>
<td>CrC-xa0</td>
<td>Coefficient</td>
<td></td>
<td>Depends on the drivers (CrC-1a1 and CrC-1a2)</td>
</tr>
<tr>
<td>Name</td>
<td>Acronym</td>
<td>Units</td>
<td>Value</td>
<td>Comment</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Crew costs                  | CrC-xa1 and CrC-xa2 | 0 or 1   | Calculated | If (0,0) total crew cost divided by total revenues
(1,0) total crew cost divided by (total revenues - fuel cost)
(0,1) total crew cost divided by (total revenues - variable costs)
(1,1) total crew cost divided by (total revenues - variable costs - fuel costs) |
| Variable costs              | VaC-xa0 | Coefficient | Calculated | Total variable costs divided by total revenues                           |
| Fixed costs                 | FxC-xa0 | 1000€/vessel | Calculated | Fixed costs divided by number of vessels                                 |
| Capital costs               | CaC-xa0 | 1000€/vessel | Calculated | Capital costs divided by number of vessels                                |
| Discount rate               | Dis-xa0 | Coefficient | 3.5%     | At a first stage. Common for all the fleets but with a sensitive analysis of it |
| Fuel use                    | FuU-xa0 | 1000 liters /sea day | Calculated | Not a role in the model but the result is calculated. Not used            |
| Policy intensity factor     | PIF     | 0 to 1   | 1        | =1: strictly follows biologic advice
>1: less strict than biologic advice
<1: more strict than biologic advice |
## Appendix 2

List of variables and symbols

### Biological module
- Catchable stock biomass: CB
- Yield per recruit: $Y_{pR}$
- Recruitment: Recr (3rd degree polynomial or Ricker)
- Parameters: Rec (4 coefficients) and Expo (3 exponents)

### Policy module
- TAC constraint: TAC
- Effort constraint: EfC
- Payment for access: PfAcc
- Payment for fish: PfFish
- Target harvest ratio: $H_{target}$
- Natural fishing mortality: $M$
- Tac band: Tac

### Economic module
- Revenues: Rev
- Fuel costs: FuC
- Crew costs: CrC
- Variable costs: VaC
- Fixed costs: FxC
- Capital costs: CaC
- Gross cash flow: GCF
- Profit: Prf
- Payment for access: FPfAcc
- Profit after tax: PrfaTax
- Profit discounted: PrfDiS
- NPV 15 years: Npv15
- NPV infinity: Npv
- Break-even revenues: BER
- Fuel use: FuU
- Discount factor: Dis
Discount period

\textit{Interface}
- Target landings (TACs) \hspace{1cm} \text{LandT}
- Catch including under- and oversized discard \hspace{1cm} \text{CatchT}
- Catch excl. undersized discards \hspace{1cm} \text{Catch}
- Discards oversized fish \hspace{1cm} \text{Disc}
- Landings \hspace{1cm} \text{Land}
- Catch-xy0 \hspace{1cm} \text{catch coefficient}
- Catch-xy1 \hspace{1cm} \text{exponent for effort (days-at-sea)}
- Catch-xy2 \hspace{1cm} \text{exponent for stock size}
- Catch-xy3 \hspace{1cm} \text{coefficient for technical progress (\%)}

\textit{Prices}
- Fuel price \hspace{1cm} \text{FuelPr}
- Fish prices \hspace{1cm} \text{FishPr}
- Price elasticity \hspace{1cm} \text{PrEl}

\textit{Behaviour}
- Effort (Fleet * days) \hspace{1cm} \text{Eff}
- Investment (number of vessels) \hspace{1cm} \text{Inv}
- Fleet (number of vessels) \hspace{1cm} \text{Fle}
- Days-at-sea/vessel - operational \hspace{1cm} \text{DASope}
- Days-at-sea/vessel - maximum \hspace{1cm} \text{DASmax}
- Investment price vessel \hspace{1cm} \text{InvPrice}
- Investment share of profit \hspace{1cm} \text{PrfShare}
- Interest rate \hspace{1cm} \text{Int}
- Time horizon for investment \hspace{1cm} \text{Period}
- Average crew per vessels \hspace{1cm} \text{Crew}
- Nominal employment \hspace{1cm} \text{NoEmp}
- Full time employment in segment \hspace{1cm} \text{FTESeg}
- Norm for FTE \hspace{1cm} \text{FTE-norm}
Appendix 3

Enquiries

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