SMS-OP, SMS USED FOR "OPERATING MODEL"

The SMS-OP program is made to work as "Operating model" for use in Management Strategy Evaluation (MSE). SMS-OP projects the stock one or more years ahead, using an initial N at age and a model for predation mortality (M2) together with data for the fishery outtakes within the period. The model operates by annual or seasonal time steps, e.g. quarters of the year.

The model includes three area explicit options:

1. One area model: Both F and M2 are calculated for the entire stock area
2. M2 by area: M2 is calculated by sub-areas, but F is assumed global
3. M2 and F by area: Both M2 and F are calculated by area

For option 2 and 3, it is assumed that the stock is redistributed between each season according to an input stock distribution key, that provide the proportion of the stock numbers at age within in a particular area by season and year. It is assumed that there is no exchange of fish between areas within a season.

Based on the initial stock size (1st January) the stock is projected forward using one of two options for fishery outtake:

i. F at age and season
   a. No area information, for option 1) and 2) above
   b. With area information, for option 3) above
ii. Catch number at age and season
   a. No area information, for option 1) and 2) above
   b. With area information, for option 3) above

1 Model specification

1.1 Survival of the stocks

The survival of the stock s is described by the standard exponential decay equation of stock numbers (N)

$$N_{s,a,y,q+1} = N_{s,a,y,q} \exp(-Z_{s,a,y,q}) \qquad \textbf{Eq. 1}$$

or

$$N_{s,a+1,y+1,q=1} = N_{s,a,y,q=\text{last season}} \ \exp(-Z_{s,a,y,q=\text{last season}}) \qquad \textbf{Eq. 2}$$

The instantaneous rate of total mortality, $Z(s,a,y,q)$ by species *s*, age-group *a*, year y and season *q*, is divided into three components; predation mortality (*M2*), fixed residual natural mortality (*M1*) and fishing mortality (*F*):

$$Z_{s,a,y,q} = M1_{s,a,q} + M2_{s,a,y,q} + F_{s,a,y,q} \qquad \textbf{Eq. 3}$$

The area index has not been included in the equations above, but is used where relevant.

For non-assessment species which act as predators (e.g. grey seal or horse mackerel) stock numbers must be given as input by season and size group (and area if relevant).

1.1.1 Recruitment

Recruitment is estimated from a specified stock recruitment relationship (f(SSB)) and a log normal distributed noise term with standard deviation std.

$$R = f(SSB) * e^{(std * NORM(0,1))} \qquad \textbf{Eq. 4}$$

NORM(0,1) is a number drawn from a normal distribution with mean=0 and standard deviation 1. At present the stock recruitment relationship f(SSB) includes, Ricker, Beverton&Holt, “Hockey stick” and geometric mean.

Eq. 4 gives a median recruitment as specified by f(SSB). Optionally, recruitment can be adjusted with half of the variance, to obtain a mean recruitment given by f(SSB).

$$R = f(SSB) * e^{(std * NORM(0,1))} * e^{(-(std^2/2))} \qquad \textbf{Eq. 5}$$

1.2 Stock distribution

For area based models the stock is assumed redistributed between areas between each season of the model

$$N_{s,a,y,q}^{area} = N_{s,a,y,q} * DIST_{s,a,y,q,area} \qquad \textbf{Eq. 6}$$

Where DIST is a stock distribution key that sums up to 1

$$\sum_{area} DIST_{s,a,y,q,area} = 1$$

1.3 Fishing mortality

The actual way of estimating Fishing mortality, F depends on the chosen option. If F is given as input, F values are simply used as specified. When catch at age numbers are provided, F at age are derived from a Newton iteration, such that F= C/Nbar

1.4 Natural Mortality

Natural mortality is divided into two components, predation mortality (*M2*) caused by the predators included in the model and a residual natural mortality (*M1*), which is assumed to be known and is given as input.

M2 of a prey with size group l_{prey} due to a predator with size group l_{pred} is calculated as suggested by Andersen and Ursin (1977) and Gislason and Helgason (1985).:

$$M2_{prey,l_{prey},y,q} = \sum_{pred} \sum_{l_{pred}} \frac{\overline{N}_{pred,l_{pred},y,q} \, RA_{pred,l_{pred},y,q} \, S_{prey,pred,q}(l_{prey}, l_{pred})}{AB_{pred,l_{pred},y,q}} \qquad \textbf{Eq. 7}$$

where *RA* denotes the food ration (weight) of the individual predator per time unit, where *S* denotes the food suitability coefficient defined below and where *AB* is the total available biomass. *AB* is defined as the sum of the biomass of preys weighted by their suitability. This prey biomass includes also the socalled "other food" (*OF*), which includes all prey items not explicitly modelled, e.g. species of invertebrates and non-commercial fish species. Other food species is combined into one group, such that the total available prey biomass becomes:

$$AB_{pred,l_{pred},y,q} = \sum_{prey}\sum_{l_{prey}} \overline{N}_{prey,l_{prey},y,q} \; w_{prey,l_{prey},y,q} \; S_{prey,pred,q}(l_{prey}, l_{pred}) + OF_{pred,l_{pred}} \; S_{OF,pred,l_{pred},q} \quad \textbf{Eq. 8}$$

The biomass of other food is assumed known and the suitability of other food is set to 1.

M2 cannot directly be calculated from Eq. 7 because *M2* also is included in the right hand term in Eq. 9 to calculate N-bar.

$$\overline{N} = \frac{1-\exp^{-(M1+M2+F)}}{M1+M2+F} N \qquad \textbf{Eq. 9}$$

As no analytical solution for *M2* exists, *M2* has to be found numerically (se section XX)

1.4.1 Use of size distribution by age

The equations outlined in the section above provides M2 at size groups, however, predation mortality by age is needed as well because F and catches are age-structured.

If just one size group per age group of predators and preys is assumed Eq. 7 can be used directly where the age index substitute the size group index.

Given more size groups per age, the calculation of M2 at age requires age-length-keys to split Na t age to N at size group.

$$N_{prey,l_{prey},y,q} = \sum_{a} N_{prey,a,l_{prey},y,q} ALK_{prey,l_{prey},a,y,q} \qquad \textbf{Eq. 10}$$

where $ALK_{s,l_s,a,y,q}$ denote the observed proportion of size group l_s for a given species and age group, i.e. $\sum_{l_s} ALK_{s,l_s,a,y,q} = 1$

Assuming that *F* and *M1* depends only of the age and that *M2* only depends of the length, *M2* at age is estimated by: (leaving out the species, year and quarter indices)

$$M2_a = Z_a * \frac{\sum_l \overline{N}_{a,l} * M2_{a.l}}{D_a} = \log(\frac{N_a}{N_a - D_a}) * \frac{\sum_l \overline{N}_{a,l} * M2_l}{D_a} \qquad \textbf{Eq. 11}$$

where

$$\overline{N}_{a,l} = N_{a,l} * \frac{(1-\exp(-(F_{a,l} + M1_{a,l} + M2_{a,l}))}{F_{a,l} + M1_{a,l} + M2_{a,l}} = N_{a,l} * \frac{(1-\exp(-(F_a + M1_a + M2_l))}{F_a + M1_a + M2_l} \quad \textbf{Eq. 12}$$

and where

$$D_a = \sum_l \overline{N}_{a,l} * (F_a + M1_a + M2_l) \qquad \textbf{Eq. 13}$$

denotes the number of individuals died within a season.

1.4.2 Area based SMS

As stated in the introduction, the model includes three area explicit options:

1. One area model. Both F and M2 are calculated for the entire stock area
2. M2 by area. M2 is calculated by sub-areas, but F is assumed global
3. M2 and F by area. Both M2 and F are calculated by area

The calculation of M2 for Option 1) is provided above.

The method for option 3) is very similar, but the calculations must be done by each sub-area separately.

$$Z_a^{area} = F_a^{area} + M1_a + M2_a^{area} \qquad \textbf{Eq. 14 (vi kan lade M1 være area bestemt???)}$$

Option 2) is the hybrid, where F is global but M is calculated by area.

$$Z_a^{area} = F_a + M1_a + M2_a^{area} \qquad \textbf{Eq. 15}$$

Nbar in an area is calculate in the usual way

$$\overline{N}_a^{area} = N_a^{area} \frac{1-\exp(-(Z_a^{area})}{Z_a^{area}} \qquad \textbf{Eq. 16}$$

The total number of individuals died due to predation mortality (DM2) then becomes

$$DM2_a = \sum_{area} M2_a^{area} \ \overline{N}_a^{area} \qquad \textbf{Eq. 17}$$

M2 for the whole stock can be estimated from

$$M2_a = \log(\frac{N_a}{N_a - D_a}) * \frac{DM2_a}{D_a} \qquad \textbf{Eq. 18}$$

Where

$$D_a = \sum_{area} DF_a^{area} + DM1_a^{area} + DM2_a^{area} \qquad \textbf{Eq. 19}$$

And DF and DM1 are the number died due to fishery and residual mortality (M1).

1.4.3 Food suitability

As suggested by Andersen and Ursin (1977) and Gislason and Helgason (1985) the size dependent food suitability is defined as the product of a species dependent vulnerability coefficient $\rho_{i,j}$, a size preference coefficient $g_{i,j}(l_i, l_j)$ and an overlap index, $o_{i,j,q}$ to describe the seasonal variability of predator prey habitat overlap such that suitability is defined as:

$$S_{prey,pred,q}(l_{prey}, l_{pred}) = \rho_{prey,pred}\ g_{prey,pred}(l_{prey}, l_{pred})\, o_{prey,pred,q} \qquad \textbf{Eq. 20}$$

For the "other food" part suitability is defined as

$$S_{OF,pred}(l_{pred}) = \rho_{OF,pred}\ o_{OF,pred,q}$$

where *pred* and *prey* denote predator and prey species, and where l_{prey} denote the prey and l_{pred} the predator size classes.

The overlap index may change between seasons, but is assumed independent of year and sizes.

1.4.3.1 Log-normal distributed size selection

Several functions can be used for size preference. Andersen and Ursin (1977) assumed that a predator has a preferred prey size ratio and that a prey twice as big as the preferred size is as attractive as another half the prey size. This was formulated as a log-normal distribution:

$$g_{prey,pred}(l_{prey}, l_{pred}) = \exp\left(-\frac{\left(\log\left(\frac{w(l_{pred})}{w(l_{prey})}\right) - \eta_{PREF\,pred}\right)^2}{2\sigma^2_{PREF\,pred}} \right); \qquad 0 < g \le 1 \qquad \textbf{Eq. 21}$$

where η_{PREF} is the logarithm of the preferred size ratio, σ^2_{PREF} is the "variance" of relative preferred size ration, expressing how selective a predator is with respect to the size of a prey and where $w(l_s) = a_s l_s^{b_s}$ *is* the mean weight of species *s* with length *ls.*

1.4.3.2 Uniform size selection

Alternatively, a uniform size preference can be assumed within the range of the observed size ratio and zero selection outside that ratio:

$$g_{prey,pred}(l_{prey}, l_{pred}) = \begin{cases} 1 & \eta_{MIN_{pred,prey}} \le \dfrac{w(l_{pred})}{w(l_{prey})} \le \eta_{MAX_{pred,prey}} \\ 0 & \text{outside observed range} \end{cases} \qquad \textbf{Eq. 22}$$

where η_{MIN} and η_{MAX} are the observed minimum and maximum size ratios.

1.4.3.2.1 Constraint uniform size selection

The uniform size preference does takes not into account that the preferred predator/prey size ratio might change by size, such that larger individuals select relatively smaller preys (Floeter and Temming, 2005; Sharft et al., 2000). A way to account for that is to assume that the fixed minimum and maximum constants, η_{MIN} and η_{MAX} , depend on the predator size:

$$g_{prey,pred}(l_{prey}, l_{pred}) = \begin{cases} 1 & c_{pred,prey} + d_{pred,prey} \log(w(l_{pred})) \leq \log\left(\frac{w(l_{pred})}{w(l_{prey})}\right) \leq e_{pred,prey} + f_{pred,prey} \log(w(l_{pred})) \\ 0 & \text{outside regression range} \end{cases}$$

Eq. 23

The regression parameters are estimated by quantile regression (Koenker and Bassett 1978) using the 2.5% and 97.5% percentiles of stomach content data..

1.4.4 Area based suitability parameters

For the "one area" SMS suitability is defined by Eq. 20

The area based version uses an area specific vulnerability and overlap index, while the size preference is assumed independent of area.

$$S^{area}_{prey,pred,q}(l_{prey}, l_{pred}) = \rho^{area}_{prey,pred} \; g_{prey,pred}(l_{prey}, l_{pred}) \; o^{area}_{prey,pred,q}$$ **Eq. 24**

1.5 Growth

TO DO: Density dependent growth (herring and sprat)

Other growth (cod)

1.6 Food ration

Food ration pr. time step is estimated assuming an exponential relationship between ration and body weight w (ICES, 2005):

$$RA_{pred,l_{pred},q} = \gamma_{pred,q} \; w^{\delta_{pred}}(l_{pred})$$ **Eq. 25**

where the coefficients γ and δ are assumed to be known. (CHECK size dependency for parameters)

2 Implementation

The SMS-OP has been implemented using the AD Model Builder. There is a such no use of the automatic differentiation in SMS-OP used for operating model, but the software choice allows a use of SMS-OP for optimization purposes (e.g. find the “right” combination of F-multipliers to be applied on specified exploitation pattern to provide MSY for all species simultaneously).

Input and output file are simple ASCII files.

Input:

1. OP.dat: Option file (see section 2.1)
2. OP_config.in: Specification of “environment” and parameters (see sec 2.2)
3. OP_N.in: Initial stock numbers in year y
4. OP_C.in: catch numbers or OP_F.in: fishing mortality
5. Additional input data files

Output:

- OP_N.out: stock numbers in year y+1
- Additional data files, annual mortalities (M1, M2, Z, and F) in year y
- Additional data files, detailed output by quarter, area, species and age (C, N, F, M2, and Z)

2.1 Options

Options to SMS-OP are provided by the OP.dat file. An example for the Baltic Sea is shown below:

```
# OP.dat option file
# the character "#" is used as comment character, such that all text after # are skipped
#
########################################
# Produce output (option test.output)
#  0 no test output
#  1 output file OP.dat  as read in
#  2 output OP_parameters.in as read in
#  3 output all data files as read in
#  4 output file OP_trigger.in as read in
0
########################################
# Produce output (option output)
# Operating model options
# 10 output for operating model (stock N by year and age)
# 11 as 10 plus output by year and age ( C, M2, F, and Z)
# 12 as 10 plus output by quarter, areas and age (C, M2, F, Z)
# 15 10 + 11 + 12
#
# Optimization output
# 20 detailed output
# 21 condensed output
# 29 20+21
10
########################################
## first year of input data (option first.year)
2012
########################################
## last year of input data (option last.year)
2012
########################################
```

```
# Species names, for information only. See file species_names.in
#  Cod Herring Sprat
########################################
# truncation of standardised normal distribution used to produce noise on recruitment
# lower and upper   (values -15.0 and 15.0 give no truncation, -2 and 2 give approximately 95%
of the distribution)
#         Cod     Herring       Sprat
         -2         -2          -2
          2          2           2
########################################
# factor to adjust expected recruits (option adjust.recruits)
#         Cod     Herring       Sprat
          1          1           1
########################################
# adjust recruitment with half of the variance (factor exp(-(CV^2)/2) option adjust.recruit.CV
# 0=no adjustment, 1=do adjustment
#         Cod     Herring       Sprat
          0          0           0
########################################
# Update N by 1= F at age or 2=Catch at age (option F.or.C)
#         Cod     Herring       Sprat
          1          1           1
########################################
#### %%%%%%%%%%%%%  'observation and implementation errors'  %%%%%%%%%%%%%%%%%%% ###
# options obs.noise.lower and obs.noise.upper
#      truncation of standardised normal distribution used to produce noise on observations
#      lower and upper   (values -15.0 and 15.0 give no truncation, -2 and 2 give approximately
95% of the distribution
#         Cod     Herring       Sprat
         -2         -2          -2
          2          2           2
########################################
# options asess.error.dist and assess.bias and assess.std
#    assessment observation uncertainties (on stock numbers) - model, mean and std deviation
#        distribution model (-1=not used, 0=normal, 1=log normal,
#        mean (mean is mean bias factor, mean=1 produces no bias)
#        std dev for log normal dist, or CV for normal dist
#      same noise. Use same noise for all ages (same noise=1) or independent noise per age(same
noise=0)
#         Cod     Herring       Sprat
          1          1           1
          1          1           1
       0.17        0.15        0.25
          1          1           1
########################################
## Maximum M2 iterations (option M2.iterations)
5
########################################
## convergence criteria (option max.M2.sum2)
#  use max.M2.sum2=0.0 and M2.iterations=7 (or another high number) to make Hessian
0
########################################
#### %%%%%%%%%%%%% various for other predators %%%%%%%%%%%%%%%%%%% ###
# annual change factor for population number
# first year (relative to first prediction year) year of change  (-1 is no change)
# last year (relative to first prediction year) of change (-1 is no change)
# other predator stock numbers
#         No other predator
         -1
         -1
         -1
########################################
```

2.2 Configuration

The OP_config.dat files describes the “environment” (number of species, ages ranges, predator prey etc.) and parameters for calculating predation mortality etc. The file is produced automatically by the SMS program, and user should not normally change the contents. An example for the Baltic Sea “environment” is shown below:

```
########################################
```

```
# Single/Multispecies mode (option VPA.mode)
# 0=single species mode
# 2=multi species mode, Z=F+M1+M2
2
########################################
# Area explicit options for M2 and F (option area.FM)
# 1=Both F and M2 are calculated for the entire stock area
# 2=M2 is calculated by area, but F (or C) is assumed global
# 3=Both M2 and F (or C) are assumed by area
3
######
4  # Number of areas
######
3  # number of species
######
0  # first age, all species
######
8  # max age, all species
######
4  # no of seasons
######
3  # recruitment seasons
########################################
## various information by species
# 1. last age
# 2. first age where catch data are used (else F=0 assumed)
# 3. plus group, 0=no plus group, 1=plus group
# 4. predator species, 0=no, 1=VPA predator, 2=Other predator
# 5. prey species, 0=no, 1=yes
##
8 2 1 1 1 # Cod
8 1 1 0 1 # Herring
7 1 0 0 1 # Sprat
################################################
# Stock recruitment parameters
#model alfa  beta std
100 1.633539e+000 9.000000e+004  5.477213e-001 # Cod
1 6.434938e+001 1.451900e-006  5.476208e-001 # Herring
3 1.829677e+001 0.000000e+000  5.477221e-001 # Sprat
##
############### Multi species ##################
0  # Usage of age-length-keys for calc of M2 (option simple.ALK))
0   # Usage of food-rations from input values or from size and regression parameters
## Variance of size selection (option size.selection) by predator
 11
## Max prey size/ pred size factor for inclusion in M2 calc by predator
 0.300
################################################
# Predator prey vulnerability
# Area 1
 24.80473 2.92819 3.35567
# Area 2
 10.97636 1.97994 3.42278
# Area 3
 16.54544 1.69615 1.78253
# Area 4
 0.00000 0.00000 0.00000
################################################
# Seasonal overlap
# Area 1
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
# Area 2
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
# Area 3
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
# Area 4
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
```

```
 1.00000 1.00000 1.00000 1.00000
 1.00000 1.00000 1.00000 1.00000
################################################
# Size selection parameters
# size model
 11
# prefered size
 5.76690
# variance of prefered size
 2.66439
# adjustment of prefered size
 0.50091
# prey_size_adjustment
 1.00000 1.00000 1.00000
################################################
# Other food size dependency
 0.00000
################################################
# minimum predator prey size ratio
 5.64497 3.33333 6.37769
# maximum predator prey size ratio
 565.36663 1004.22533 1465.32685
################################################
# Constraint uniform size selection
# Intercept, minimum
 0.00000 0.00000 0.00000
# Slope, minimum
 0.00000 0.00000 0.00000
# Intercept, maximum
 0.00000 0.00000 0.00000
# Slope, maximum
 0.00000 0.00000 0.00000
################################################
# Predator presence (0=absent, 1=present) in an area
 1 1 1 0 # Cod
################################################
# Predator eaten by prey (0=no, >=1 means yes) in an area
# Area 1
 1 2 3
# Area 2
 4 5 6
# Area 3
 7 8 9
# Area 4
 0 0 0
################################################
# Other food by area and predator
 1000000
 1000000
 1000000
 1000000
################################################
# Size of predator for constant available other food
 0.056891
```

2.3 Specification of Input

2.4 Specification of output

2.5 How to run OP_SMS

Operating model: op –maxfn 0 -nohess

Optimization: op -nox