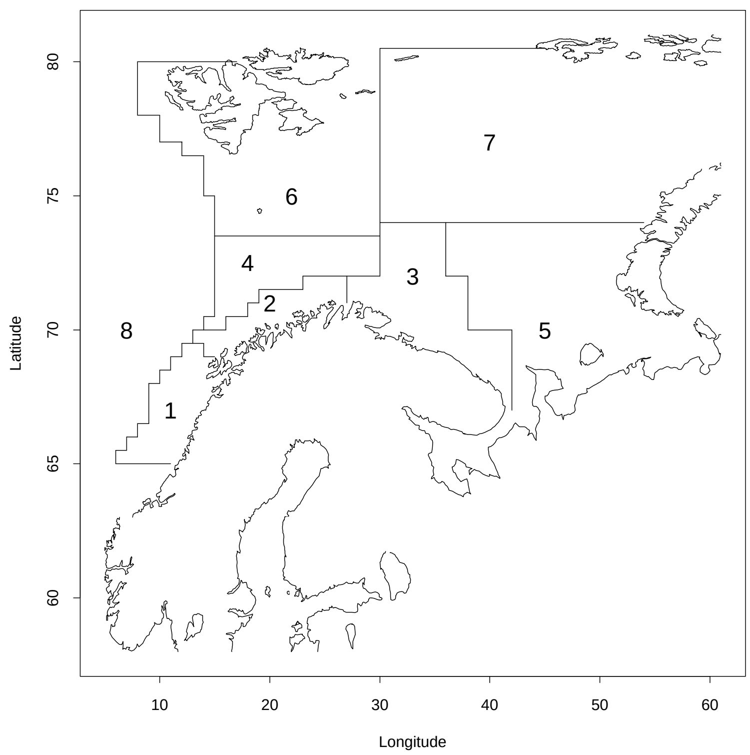
Scenario C : A program documentation

Norwegian Computing Center
APPLIED RESEARCH AND DEVELOPMENT

NOTE



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Abstract: This is the documentation of the program system `scenmod` developed during the various Scenario projects at the Norwegian Computing Center. The main emphasis is put on the default program setting, i.e. the one that is automatically chosen when the program system is initiated.

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1 Introduction

This introduction is adapted from Schweder (2005)[34].

Scenario modelling to evaluate management strategies was originally developed for whaling, but is now increasingly applied in fisheries. The basic idea is to establish a minimal but realistic model for computer simulation of the system, with removals governed by a management strategy, predation and additional natural mortality. The system is projected forward under competing strategies for a number of years and in replications to capture the statistical uncertainties surrounding the system. Strategies are compared in terms of their simulated long term performance.

The purpose of the present study is to evaluate the effect on the cod-, capelin-, and herring fisheries of managing minke whaling and harp sealing in the Barents Sea in this way. The study is funded by the Norwegian Ministry of Fisheries. In a recent White Paper (Stortingsmelding nr. 27, [37]) on the management of marine mammals in Norwegian waters, the Ministry plans "to establish a scientific basis for changing to ecosystem-based management where marine mammal stocks are managed in conjunction with the other living marine resources".

The concept of strategy is central to management. A management strategy is a feedback rule that specifies the action to be taken, given the history of the process as observed by the Agency. The actions open to the Agency are to set total allowable catches (TACs) for removals of harp seals and minke whales. The Agency also sets TACs for the fisheries. TACs are assumed in the model to be exactly filled if abundance allows. Fishermen behave also according to economic realities, and may discard or take more than the TAC. These economic realities are disregarded here.

Think of fisheries management as a game played between the Agency and Nature. The strategy of Nature is determined by the internal dynamics of the ecosystem, and its dynamic reaction to the removals caused by the fisheries. The better the Agency knows Nature's strategy, the better it can assess the quality of a given management strategy for whaling and sealing. Our Scenario C study is an attempt to assemble the available knowledge and data pertinent to the relevant dynamics of the upper trophic level of the ecosystem.

Despite more than 100 years of marine research in the area and despite the system is less complex than many other ecosystems and comparably well known, our knowledge of the Barents Sea ecosystem is rather limited. The quality of understanding varies considerably depending on the topic. For features of the ecosystem about which little is known, the model must be simple in order not to spread the available information too thinly. Other better known features might be less relevant for the interaction between the modelled species, and are therefore modelled in less detail than is possible. Our aim is not a detailed description of the ecosystem representing all available knowledge, but rather a practical and reasonably realistic model tailored to the purpose of the study. Borrowing a term from Punt and Butterworth (1995)[30], a model that balances realism and uncertainty, and that is operational and practical to use, is called a minimal realistic model.

We consider the Barents Sea, including the spawning grounds for North East Arctic cod in Lofoten, and also a residual area where Norwegian spring spawning herring and minke whales are found when they are not present in the Barents Sea. Only young herring migrates to the Barents Sea. The minke whales feed in the study area and breed elsewhere during winter. With our limited and pragmatic purpose, we will include only harp seals, minke whales, cod, capelin and herring in the model. Hamre (1994)[13] describes the main features of the Barents Sea- Norwegian Sea ecosystem.

A strategy should be evaluated in terms of its anticipated performance in the long run. The system needs more than 100 years to become stationary, due the slow dynamics of minke whales. We will therefore simulate catches and stock status over at least a hundred-year period, and study performance by statistics summarising the simulation results. It is beyond the scope of this study to give weights to the various objectives for management, and to interpret results in financial terms.

The model has yearly stochastic variation, mainly in fish recruitment and in the stock abundance estimates on the basis of which TACs are set. This last uncertainty applies also to abundance estimates for minke whales and harp seals, and translates into stochastic variation in TACs for these species as well.

The Agency is faced with uncertainties with respect to the population dynamics of the key stocks, and also to the interactions caused by predation between stocks. These uncertainties are handled by drawing parameters from statistical distributions for each run of the simulation model, but uncertainties with respect to functional forms are not addressed.

The present study (2002-2004) is a sequel to a previous Scenario Barents Sea study. The aim of that earlier study was to compare management strategies for cod, capelin and herring (Hagen, Hatlebakk and Schweder 1998 [11]). The model was previously extended to study the effects on the fisheries of retuning the Revised Management Procedure of the International Whaling Commission (the RMP of the IWC, International Whaling Commission 1994 [20]) for minke whales (Schweder, Hagen and Hatlebakk 1998; 2000[31],[32]). In addition to including harp seals in the current model, the structural forms of the predation models are changed, and they are re-estimated.

Cod, capelin, herring, harp seals and minke whales are distributed over the seven areas used in previous studies (Bogstad et al. 1997 [3]) plus a residual area (Figure 1), and over age and month. Fish are also distributed over lengths. The chosen subdivision of the study area and the time step is regarded as the coarsest possible temporal and spatial stratification respecting gradients in seasonal overlaps between predators and prey in the Barents Sea system (Tjelmeland, personal communication).

Moving from one month to the next, surviving fish of the same length are allocated to new length groups according to an individual growth schedule which depends on season and species. Individual growth in cod depends on the supply of capelin, but is independent of prey availability for capelin and herring. A fixed length-weight relationship for each fish species is used for calculating the biomass of the species at any time. This is needed because fish TACs and predation are calculated in biomass terms.

The population dynamics model for minke whale is taken from International Whaling Commission (1993) [19], and is identical to that in Schweder et al. (1998)[31]. The model for harp seal is taken from Skaug and Øien (2003)[35]. Recruitment in cod, capelin and herring is modelled by Beverton-Holt functions augmented with stochastic variability.

Minke whales and harp seals are top predators. Their population dynamics is modelled as unaffected by fish stock abundance. While this is not quite realistic, it is nevertheless considered adequate for present purposes because the modelled population dynamics broadly reflect prey abundances similar to those expected over the simulation period. The marine mammals prey on all three species of fish, and also on other organisms, as do cod which is a cannibal. Herring prey on capelin larvae. Capelin is at the base of the model.

Predation is modelled in two steps. The daily biomass consumed is calculated for each group of predators from energetic considerations and from other sources,. This consumption is then split between the groups of prey according to prey choice probabilities. The prey choice probabilities are estimated from stomach content data and estimated prey availability by time and area.

1.1 Current management.

Fish:
TACs for cod are set to target a fishing mortality of $F = 0.4$ when spawning stock biomass is estimated above B_{pa}. The stock is assessed by the VPA-method XSA, see ICES (2004) [17]. The capelin and herring fisheries are essentially managed as modelled.

Minke whaling:
Currently, Norway has a fleet of some 33 fishing vessels that harvest minke whales in the summer months in Norwegian waters. Whaling accounts for about 25% of the income for this fleet, and is economically sustainable. Minke whaling resumed in 1993 after it was stopped in 1987. The catch has increased from some 250 whales in 1993-1995 to some 600 whales in recent years. This is slightly below the TAC calculated from the management strategy. Vessel quotas are given to licensed whalers. The catch is closely controlled with skilled observers on board.

The TAC for minke whales is calculated by the RMP of the IWC. The input data to the RMP is the catch series and the series of absolute abundance estimates obtained from double platform line transect surveys (Skaug et al. 2004) [36].

The RMP can be tuned to target various population levels under cautious standard assumptions. In the early years, a target level of 72% of carrying capacity was used to set Norwegian minke whale TACs. This target level is that which would be reached after 100 years of application of the RMP to a stock, originally at its pristine level, with the lowest productivity rate considered plausible. In 2003 the tuning level was reduced to 66%, and for 2004 to 62%, resulting in higher TACs.

Harp sealing:
Norwegian sealing is currently a small heavily subsidized industry carried out with old specialized sealing vessels. In the 1990s the yearly average number of harp seals taken in the Barents Sea by Norway was 6200, and has declined in recent years.

Norway manages harp sealing in the Barents Sea together with Russia, and according to advice from ICES, which calculates TACs to keep the stock at its current level. The White Sea–Barents Sea stock is now estimated to comprise nearly two million adults, and the TAC was 53000 adult equivalents (one adult equals 2.5 pups) in 2001-2003, well above the catch. Pups become adult at age 1.

The economics of sealing has improved somewhat recently, but sealing will probably need substantial subsidies to raise the catch to what is currently regarded as sound from an economic perspective for the fishery as a whole (Stortingsmelding nr. 27)[37].

1.1.1 Management issues.

The Norwegian Government wants to develop a management strategy for sealing and whaling as part of a management regime for the ecosystem containing fish and marine mammals. For this to have scientific support, substantial research is needed, as acknowledged in the White Paper (Stortingsmelding 27)[37]. Since harp seals, cod and capelin are managed jointly by Norway and Russia, while herring is managed by five parties: Norway, Russia, the Faroes, Iceland and the EU, management of this ecosystem is far from being a national issue for Norway alone.

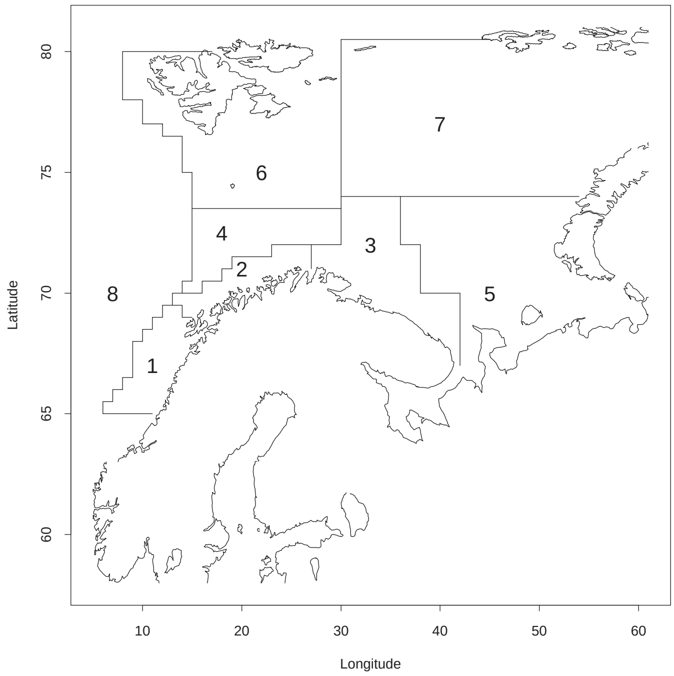

Figure 1: *The 8 regions in the ScenarioC model.*

2 Regions and migration

The Barents Sea is considered to consist of 6 subregions, and in addition the Lofoten area and the coast of Nordland is defined to make one region and the Norwegian Sea another. The resulting regions are showed in Figure 1. The fish and mammals are distributed across the Barents Sea regions according to migration patterns adopted from the MULTSPEC project at The Institute of Marine Research in Bergen (IMR) [3] and as described in the introductory section, the Norwegian Sea is included as a separate region due to the herring stock. However, the interactions between the various species are only modelled in the Barents Sea regions.

In Scenario-C the migration matrices are further developed to obtain stationary matrices for all target species in the model. We regard the monthly migrations between the regions as a random walk, following transition probabilities that are described by the migration matrices. In principle this means that stationary matrices are obtained “in the end”, i.e. by applying the transition matrices infinitely many times the stationary distributions will show up.

However, for the prey species (fish) the migrations are age dependent, which means that the transition probabilities will change every year. In addition, we have recruitment into the youngest age class. In which regions will recruitment take place, and more important: how are the recruits distributed across the regions when entering the model at age 1? The ageing is taken care of by assuring that the correct transition probabilities are chosen. The solution of the recruitment was found through discussions with Bjarte Bogstad at IMR. We did agree to distribute spawning across the regions according to IMR experience, and then let the fry follow the MULTSPEC migration for fry until the turn of the year and let them recruit according to the resulting distribution in January. In this way it was possible to let the fish stocks migrate according to the MULTSPEC migration patterns for several years, and the stationary distribution was typically obtained after one generation when the initial stock was "out of the system".

The result was a set of stationary distributions, which are stored in files and read into the scenario model as a part of the model initialization. The fish matrices have dimensionality month by age by maturity by region, because the capelin migrations are maturity dependent. The mammal matrices have only dimensionality month by region, because here the migrations are assumed to be independent of both age and maturity. Of course, this is not quite true, especially we know that female harp seals have some feeding migrations towards the Finnmark coast during the winter period, that the males do not have. Despite of this knowledge, we have chosen the simple migration model with no sex or age dependency included.

3 Recruitment

Recruitment in fish is determined by several factors:

- The recruitment curve, i.e. the expected number of recuits stemming from a mature stock of given size.
- The ordinary stochastic variation around the recruitment curve.
- The extra-ordinary variation, i.e. the odd extreme years of extra-ordinary high recruitment.
- The time of the year at which the recuitment takes place.
- At which age the recruits are explicitly taken into the model.

All these parts of the recruitment process involves a number of parameters, which can be assigned values through the various parameter files. In this section, R means the number of recruits and B means the spawning stock biomass.

The default parameter setting is that the fish recruit as 1 year olds, cod and herring in January and capelin in October. All recruits are generated in a pulse on the first day of the month.

3.1 Recruitment function

The Scenario-C model supports five different functions, of which the well known Beverton-Holt function is the default:

$$R = \alpha \cdot \frac{B}{B+\mu}. \tag{1}$$

The parameter α is a horizontal asymptote for the function, and represents the maximum value for the expected number of recruits. The parameter μ is called the "half value", and represents the spawning stock size at which the expected number of recuits will be exactly half of the maximum value.

All three species of fish have Beverton-Holt recruitment, but the parameters are species dependent.

3.2 Stochastic variation in recruitment

The recuitment function gives the expected ("mean") number of recruits, R, as a function og the mature fish stock, B. The natural variation is modeled as stochastic white noise, and the default solution is multiplicative, lognormal variation:

$$R = f(B;\theta) \cdot \exp(N(0,\sigma)) \tag{2}$$

In this formula, f represents the recruitment function (i.e. Beverton-Holt as the default case), θ represents the parameter vector included in the function and $N(0,\sigma)$ means a stochastic variable that is normally distributed with mean 0 and standard deviation σ.

Parameter	Species Capelin	Cod	Herring
α (asymptote), normal level	1800	1.33	26.52
μ (half value), normal level	0.2	0.21	1.29
α, high level	1800	2.22	280.63
μ, high level	0.2	0.21	1.29
σ (variation)	200	0.67	3.0

Table 1: *Default parameter values to the Beverton-Holt recruitment function (equation 1) and stochastic variation (equation 2). The units are 10^9 for α and σ, while it is 10^9 kg for μ. These values are obtained through personal communication with fishery researchers early in the 1990's.*

3.3 Normal and extreme recruitment

From historical data it is evident that there are years with extremely high recruitment, that can not be modeled with random variation alone. In Scenario-C the solution has been to define two recruitment levels, one "normal" level and one "high" level. The "high" level is explained by favourable survival conditions. The two levels do not need to have identical recuitment models, the default choice, however, is Beverton-Holt functions with multiplicative variation on both levels. The years of "high" recruitment appear simultanously for all three species of fish, and the level realization is a result of a stochastic process. The expected waiting time between two years of "high" recruitment is $1/p$, and p is a parameter to the simulations. The stochastic process is also constructed so that two years of "high" recruitment is at least separated with $1/(2p)$ years. This means that we have a restriction on the p-parameter: $0 < p < 0.5$.

The default value is $p = 0.10$, which means that the expected waiting time between two years of extreme recuitment is 10 years.

3.4 Other recruitment restrictions and adjustments

3.4.1 Temperature

If simulation is performed with temperature effect, the sea temperature may have influence on the recuitment. This is done by regulating the number of recruits according to the sea temperature. The default solution is no temperature dependency, however.

3.4.2 Special herring-capelin interaction

When there is herring present in Barents Sea, predation from herring on capelin larvae may reduce the capelin recruitment. When the number of herring present in Barents Sea is sufficiently large, the number of capelin recruits are reduced according to the procedure described below. Define the following quantities:

$N_{B,her}$	the number of herring in the Barents Sea
R_{cap}	the number of capelin recruits
L_{her}	lower limit of herring
U_{her}	upper limit of herring
L_{cap}	lower limit for capelin recruits

$N_{B,her}$ and R_{cap} are variables calculated in the simulation model, while the three last quantities are parameters to the simulation. The adjusted number of capelin recruits will be

$$R_{cap}(adjusted) = \begin{cases} L_{cap} & \text{if} \quad N_{B,her} > U_{her} \\ L_{cap} + \dfrac{U_{her} - N_{B,her}}{U_{her} - L_{her}} \cdot (R_{cap} - L_{cap}) & \text{if} \quad L_{her} \leq N_{B,her} \leq U_{her} \\ R_{cap} & \text{if} \quad N_{B,her} < L_{her} \end{cases} \tag{3}$$

This procedure states that the number of capelin recruits will never get below the lower limit L_{cap} due to predation from herring. When there is only a small amount of herring present in the Barents Sea ($N_{B,her} < L_{her}$), the number of capelin recruits will not be affected at all, while intermediate herring values result in a linear regulation of the number of capelin recruits. The parameter values are derived through personal communications with fishery researches early in the 1990's, and are presented in table 2.

L_{cap}	L_{her}	U_{her}
20	2	3

Table 2: *Default parameter values for herring effect on capelin recuitment. The unit is* 10^9 *and the effect is presented in equation 3. The sources for these parameter values have unfortunatey disappeared.*

3.4.3 Special fry mortality due to cannibalism

The number of recruits is also reduced when the immature stock is getting "high". The reason is that one assumes that (parts of) the immature stock will act as predators on fry from the period of spawning and till the time of recruitment. This relation is very simple:

$$R_{reduced} = \begin{cases} R & \text{if} \quad B \leq B_{\text{lim}} \\ R \cdot \exp(-\beta * (B - B_{\text{lim}})) & \text{if} \quad B > B_{\text{lim}} \end{cases} \tag{4}$$

In this equation R is the number of recruits prior to the reduction due to cannibalism and B is the biomass of the immature stock. The two parameters, B_{lim} and β are species specific. The default parameter values are found in Table 3.

	Species		
Parameter	Capelin	Cod	Herring
B_{lim}	3.0	2.0	5.5
β	4.0	0.5	1.0

Table 3: *The default parameter values in the relation which describes cannibalism on recruits. The unit of B_{lim} is 10^9 kg. The sources of these values have unfortunately disappeared.*

4 Growth

In Scenario-C growth means increase in individual length. Mean weights by length are constants that are a part of the model initialization, and these weights are not affected by growth. This entails that the model is not capable of handling emaciation due to lack of food. However, absence of suitable food will result in a slower length growth. Emaciation due to spawning is taken care of, and for the mature part of the stocks mean weights are reduced after spawning. During one year the normal mean weights are retrieved in all length groups, however.

Increase in individual length, L, is computed monthly and modeled with a difference equation [1]:

$$dL(t) = L(t + \Delta_t) - L(t) = (L_\infty - L(t)) \cdot G(t) \cdot M(t). \tag{5}$$

Here, L_∞ is the maximum length, t is the time variable, Δ_t is the time step and $M(t)$ is a discrete function, taking monthly values in the interval [0,1]. This function is used to model monthly variations in growth over the interval ["no growth", "growth potential"] according to a seasonal profile, see table 4, while $G(t)$ is the growth function defined below.

Cod	$M(t)$	$\equiv$	1, all months (i.e. no seasonal variation)
Herring	$M(t)$	$=$	(0,0,0,0,1,1,1,1,0.5,0.25,0,0)
Capelin	$M(t)$	$=$	(0,0,0,1,1,1,1,1,1,0,0,0)

Table 4: *The seasonal profiles used in the growth functions for the fish stocks. t is time variable, that means month.*

4.1 Growth function for capelin and herring

The growth function at time t, $G(t)$, generally is given by

$$G(t) = 1 - \exp(-K(t, \Delta_t)) \tag{6}$$

Here, $K(t, \Delta_t)$ is a function of biomass at time t, B_t, which indicates density dependent growth, and Δ_t is the time step (one month in Scenario-C) indicating that $G(t)$ represents the growth potential during a time step of Δ_t at time t. In the default parameterization the growth function is neither density nor temperature dependent, and the G-function is simpy defined as

$$G(t) = 1 - \exp(a). \tag{7}$$

The parameter values for capelin and herring are given in Table 5.

Parameter	Capelin	Herring
L_∞	40 cm	40 cm
a	0.14	0.55

Table 5: *Default parameter values in the growth functions for capelin and herring, se equations 5-7. The parameter values are a result of perona communication with fishery researchers in the 1990's.*

4.2 Growth function for cod

This model is described in quite detail in Hagen et.al. [10] (in Norwegian), here we will only give a short summary together with the default parameterization.

The main model for cod growth is density dependent for age groups, in the sense that it only depends on the prey stocks and not on the modeled consumption. The model for food intake in cod (se section 6.2.3) assumes each cod to be able to meet its energy need, with no room for starvation or excessive feeding impacting individual growth. Due to this, and to the fact that Scenario-C only have explicit models for a few components in the cod diet, a pure density dependent model seemed to be just as reasonable as a more sophisticated consume dependent model.

When modelling cod growth, the capelin and cod stocks are divided in three subgroups, so that the model includes seven abundance variables:

1. Immature capelin, shorter than 10 cm (CAP_1).
2. Immature capelin, longer than 10 cm (CAP_2).
3. Mature capelin (CAP_3).
4. Herring (HER).
5. 1 year old cod (COD_1).
6. 2 year old cod (COD_2).
7. Cod in age groups 3+ (COD_3).

The immature and mature capelin do separate in October, and this is the reason for the immature-mature grouping. The grouping of immatures according to length is mostly due to the suitability of being food. The young cod (1-2 year olds) is a potential prey for older cod, and according to the stomach data used to fit the models the 1 and 2 year olds do not have equal predation patterns. This is the reason for the grouping of cod. When fitting the models, the first 6 groups are prey, while the seventh group represents the competitors.

The growth model is linear:

$$
\begin{aligned}
G(t) &= \frac{L_{t+\Delta_t} - L_t}{L_\infty - L_t} \\
&= A_0 + A_1 \cdot COD_1 + A_2 \cdot COD_2 + A_3 \cdot COD_3 \\
&\quad + A_4 \cdot CAP_1 + A_5 \cdot (CAP_2 + CAP_3) + A_6 \cdot HER,
\end{aligned} \tag{8}
$$

In this model the variables are the number of individuals in each group, for cod variables the unit is 10^6, while for capelin and herring variables the unit is 10^9.

The simulation model also offers and alternative growth model, with constant yearly growth values (age-dependent). These values are also applied to put restrictions on the modelled growth, in that the growth obtained from model 8 is not allowed to depart more than a given percentage from the constant-value.These restrictions may be omitted by assigning proper parameter values to the simulation, however. The constant-values are also applied as monthly growth for age groups not covered by the coefficient matrix, in the default parameter setting this means age groups 7+.

Default parameterization

In the default parameterization the density dependent model is only applied for age groups 1 to 6, and the coefficient values (A_i's) are given in Table 7. For older age groups, the model of constant growth is applied, and the default parameter values are listed in Table 6. The modelled growth are not allowed to depart more than 30% from the corresponding values in the constant model. The maximum length for cod (L_∞ in equation 5) is set to 160 cm.

Age	1	2	3	4	5	6
Mean monthly growth (cm)	0.08975	0.07089	0.07196	0.09926	0.09856	0.09884
Age	7	8	9	10	11	12
Mean monthly growth (cm)	0.09041	0.11498	0.06092	0.09419	0.09498	0.10204
Age	13	14	15	–	–	–
Mean monthly growth (cm)	0.08551	0.06837	0	–	–	–

Table 6: *The default values for constant growth in cod stock. The sources of these values have unfortunately disappeared.*

	A_0	A_1	A_2	A_3	A_4	A_5	A_6
Age 1	0.08734	-0.01360	-0.01490	-0.01590	0.07001	0.00000	0
Age 2	0.14007	-0.00797	-0.00424	-0.05939	-0.07979	0.03693	0
Age 3	0.09676	-0.01360	0.01724	-0.03336	-0.00417	0.06256	0
Age 4	0.13136	-0.02029	-0.00161	-0.05857	0.12456	0.00000	0
Age 5	0.11909	0.00066	-0.00821	-0.04298	0.05229	0.03552	0
Age 6	0.12660	-0.01238	-0.02356	-0.03423	0.00318	0.08593	0

Table 7: *The default coefficient values for density dependent cod growth, based on equation 8. These values are found in Hagen et.al [10].*

5 Maturation

Maturation is modeled as a pulse. The time of maturing is species dependent parameters to the model, and default cod and herring mature on 1 January, while capelin matures on 1 October. The maturity ogives (fractions of mature) in each length group are logistic functions.

$$m(l) = \frac{1}{1 + e^{4P_1(P_2 - l)}}, \tag{9}$$

where l denotes mean length in the length group (midpoint in length interval). The two parameters P_1 and P_2 are species specific, P_1 represents the maturation intensity and P_2 is the "median" length at maturation. Maturation may be sex dependent in the model. The default parameter values are given in Table 8. In the default setting only the capelin are defined to have sex dependent maturity ogives.

Parameter	Capelin	Cod	Herring
P_1,male	0.6	0.1	1.0
P_1 female	0.4	0.1	1.0
P_2 male	13.75 cm	75 cm	31.25
P_2 female	14.0 cm	75 cm	31.25

Table 8: *Default parameter values for the maturity ogives defined in 9. The values are a result of poersonal communication with fishery researchers early in the 1990's.*

6 Mortality

The mortality is split according to the mortality "generating source". Predation mortality is regionally calculated over the 7 regions defined in the MULTSPEC project. The remaining types of mortality are assumed to be identical in all regions. Except for the spawning mortality, the mortalities are computed monthly.

6.1 Spawning mortality

The spawning mortality is defined to be a fraction (of the mature stock) that dies after spawning. Default the model states 100% spawning mortality for the capelin stock, while there is no spawning mortality for cod and herring.

6.2 Predation mortality

In the Scenario-C system there are three predators: minke whale, harp seal and cod. Predation from each predator is modelled separately, and it consists of two parts:

1. The model for total consume.
2. The model for preference (diet composition).

6.2.1 Minke whale predation

The computation of total consume for minke whale is based on energetics, and for each minke whale, the total energy need is weight dependent. We have adopted the parameter η_{minke} (W/kg) from Bogstad et.al. [3]. The total energy consume, E_{minke} (unit Joule), is calculated by

$$E_{minke} = \eta_{minke} \cdot B \cdot s, \tag{10}$$

with B being the total biomass of minke whales present in the current region (unit kg) and s being the number of seconds in the current time period. In Scenario-C the time step is one month, and every month is defined to have 30 days, so $s = 2,592,000$ seconds. Predation is calculated for each of the 7 regions defined in the MULTSPEC paper separately, and the consumed energy is transformed to biomass according to the energy content of the prey, see Table 10.

The energy constant, η_{minke}, is allowed to vary from month to month. The default values given in Table 9 are obtained through simulations based on information given in Folkow et.al. [7].

Preference/diet composition

The preference model of the minke whale predation is described in detail in the master thesis of Mian Zhu (2003) [38]. Here we just refer the main result that are implemented in the Scenario-C simulation program. During one month we assume that the total consume of the minke whale stock consist of capelin, cod, herring and other species. The concept

Month	March-May	June-July	August-October
η_{minke}	1.516 W/kg	1.582 W/kg	1.659 W/kg
standard dev.	0.287	0.287	0.288

Table 9: *The default energy constants for minke whales. The months November-February are not included, because in these months there are no minke whales in the Barents Sea areas, according to the migration patterns, see section 2.*

Species	Capelin	cod	Herring
Energy content	6.9 kJ/g	5.3 kJ/g	7.1 kJ/g

Table 10: *The assumed energy content in the various prey species, used to convert consumed energy to biomass. The values are a result of simuations based on the article by Folkow et.al [7].*

"diet choice" in [38] corresponds in our model to the consumed fractions of biomass of each type of prey, and these fractions (the diet choice) depend on the availability of the model species capelin, cod and herring. Let B_j be the biomass of target species j in tons, and let

$$\theta_j = \alpha_j + \beta B_j + \gamma \log(B_j), \tag{11}$$

for j =herring, capelin and cod. Then the fraction of species j, q_j, in the total consume of the whale stock is modeled, as preferred by Zhu [38], by

$$q_j = \frac{e^{\theta_j}}{1 + \sum_k e^{\theta_k}}. \tag{12}$$

Here, the sum counts the contributions from the three target species, while the 1 counts the prey category "other food". Zhu (2003) [38] found this simple model to fit the data reasonably in comparison with other models.

Parameter	$\alpha_{capelin}$	α_{cod}	$\alpha_{herring}$	β	γ
Default value	-2.516223	-3.633422	-1.820806	0.000231	0.264780
Bootstrap SE	0.238134	0.243841	0.236709	0.000209	0.046899

Table 11: *The default parameter values in the diet choice model for minke whale, see Equations 11-12.*

6.2.2 Harp seal predation

The computation of total consume for harp seal is also based on energetics, and with weight dependent needs. The model is parallel to the one for minke whale, and the corresponding energy constant is η_{harp}. This constant is allowed to vary from month to month, and the default values are given in Table 12. The values in this table are obtained through simulations, mainly based on information given in Nilssen et.al. [28]. According to Nilssen et.al, the energy constant for harp seal is in fact weight dependent, and the energy requirement will decline as the weight increases. The dependence is not very strong, however, and we have chosen to apply the constants that correspond to a body weight of 100 kg in the simulations.

Month	January	February	March	April	May
η_{harp}	1.597 W/kg	0.813 W/kg	0.813 W/kg	1.597 W/kg	0.813 W/kg
standard dev.	0.270	0.138	0.138	0.270	0.138
Month	June	July	August	Sept.	Oct.-Dec.
η_{harp}	4.792 W/kg	4.007 W/kg	4.007 W/kg	4.792 W/kg	1.597 W/kg
standard dev.	0.811	0.678	0.678	0.811	0.270

Table 12: *The default energy constants for harp seals. These vaues are a result of simulations based on the article by Nilssen et.al. [28].*

Preference/diet composition

The process of estimating a predation model for the harp seal stock is described in Hagen et.al. (2003) [12], and the model is quite parallel to the minke whale model. We model the choice probabilities, and interpret those as being fractions of total harp seal consume. The linear predictor in the harp seal predation model is given by

$$\theta_j = \begin{cases} b_j + \beta_j \cdot \log(B_j) & \text{for } j = her,\, cap,\, cod \\ b_{other} & \text{for prey category other} \end{cases} \tag{13}$$

and the corresponding fractions, q_j, are defined by

$$q_j = \frac{e^{\theta_j}}{\sum_k e^{\theta_k}},$$

with k counting all the four prey categories. The variable B_j represent the biomass of prey category j in unit tons per squared nautical mile. The parameters in equation 13 are estimated using stomach data from the period 1980-2000

	b-parameters				β-parameters		
Parameter	b_{cap}	b_{cod}	b_{her}	b_{other}	β_{cap}	β_{cod}	β_{her}
Value	1.3402	0.8226	-0.7645	2.7021	0.1831	0.3030	0.1831
std	0.1431	0.2153	0.3576	0.1364	0.0719	0.0828	0.0719

Table 13: *The default parameter values in the diet choice model for harp seal. These values are estimated under the constraints that $\beta_{cap} = \beta_{her}$ due to sparse data. The standard deviations are a result of a bootstrap process.*

Prey species	Capelin	Cod	Herring
Minimum predator (cod) length	30 cm	30 cm	35 cm

Table 14: *The minimum length values for cod to act as predator on the various prey species. The values are a result of personal communication with Bjarte Bogstad at IMR.*

6.2.3 Cod predation

Cod acts as predator on capelin, herring and smaller cod, and parallell to the whale and seal models the cod predation model consists of one model for total consume and one model for preference or diet composition. Only cod above a certain length will be predator, and the minimum predator length is species dependent. The default length values are given in Table 14.

The model for total consume (included prey category "other food") is age-dependent, and states that a cod of age a has a yearly consume of c_a kg prey biomass. We are allowed to distribute this consume unevenly over the year, using a month vector. In the default parameter setting it is assumed that the consume is constant through the year, i.e.

$$c_{m,a} = c_a/12,$$

with the c's being parameters to the model, m is a month index (1-12) and a represents the age group. The default consume values are given in Table 15. The yearly totals are estimated based on consume data from the period 1984 to 2003, that was kindly given to our disposition from the Institute of Marine Research in Bergen. The parameter values are simply the arithmetic means from the period, while the standard deviations are the corresponding sample standard deviations.

Age	1	2	3	4	5	6
Yearly consume	0.192	0.587	1.383	2.572	3.968	5.492
std	0.076	0.209	0.412	0.571	0.787	0.976
Age	7	8	9	10	11+	–
Yearly consume	8.008	9.857	11.582	12.245	12.373	–
std	1.642	1.343	1.667	1.755	1.767	–

Table 15: *The default yearly consume values for cod by age, unit is kg/year. The consume is assumed to be constant through the year, i.e.* $\kappa_m \equiv 1/12$.

	l_k			Model parameters				
Parameter	Capelin	Cod	Herring	α_{cap}	α_{cod}	α_{her}	β_1	β_4
Value	0.3	0.3	0	-2.936	-3.512	-5.125	8e-6	0.328
std	–	–	–	0.117	0.116	0.137	3e-6	0.015

Table 16: *The default parameter values in the diet composition model for cod, see equation 14. The unit of the limits, l_k, is tonnes per squared nautical miles, and the values are a result of personal communication with researchers at IMR.*

Preference/diet composition

The preference model is a slightly modified version of the conditional logit model described in Zhu et.al [39]. The model is quite similar to the corresponding models for minke whale and harp seal. Let B_k be the biomass density of prey species k at a given point of space and time, and define the linear predictors

$$\theta_k = \begin{cases} \alpha_k + \beta_1(B_k - l_k) + \beta_2 \log(B_k - l_k) & \text{if} \quad B_k > l_k \\ -\infty & \text{if} \quad B_k \leq l_k \end{cases} \tag{14}$$

Then the proportion of prey species k in the cod diet, p_k, is defined to be

$$p_k = \frac{e^{\theta_k}}{1 + \sum_j e^{\theta_j}}.$$

The parameters l_k in the linear predictor is introduced to avoid the prey species to suffer extinction due to predation from cod. This may seem to be a rather artificial variable, but it is not unreasonable to assume that whenever the biomass density becomes low the energy cost of searching for the prey will get higher and the cod will change the diet. The default values of the preference model are given in Table 16.

The model for preference is identical for all cod, but the realized consume is length dependent. Let L be the length of the predator and l be the length of the prey (or rather the mean lengths in the predator and prey length groups, respectively). Capelin and herring are defined to be prey for cod when

$$\frac{L}{l} \geq k_s, \ s = \text{capelin, herring}, \tag{15}$$

	Capelin	Herring	Cod		
Parameter	k_{cap}	k_{her}	p_1	p_2	p_3
Value	2	2.5	1.12	0.015	0.228

Table 17: *The default parameter values in the availability equations 15 and 16. The k-parameters are obtained through personal communication with researcers at IMR, while the p-parameters are found in Bogstad (2002) [2].*

and the realized consume is distributed over the prey length groups proportionally.

Small cod are defined to be suitable prey according to the assymetric bell-shaped function

$$f(l, L) = \begin{cases} e^{-\frac{\left(\log \frac{L}{l} - p_1\right)^2}{p_2}} & \text{if} \quad \log \frac{L}{l} \leq p_1 \\ e^{-\frac{\left(\log \frac{L}{l} - p_1\right)^2}{p_3}} & \text{if} \quad \log \frac{L}{l} > p_1 \end{cases} \tag{16}$$

described in Bogstad 2002 [2]. When computing the actual consume for cod with mean length L, we define the prey part of the cod stock to be

$$B_{prey}(L, l) = f(l, L) \cdot B_l, \text{ all length groups } l.$$

The realized consume is then distributed over the prey part of the stock proportionally.

6.3 Fishing mortality

Each month the simulation model computes the total biomass caught. This is done by distributing the year's total catch (section 7), by a seasonal profile over the year. The resulting biomass is then distributed over the length groups according to the selection pattern in the actual fishery. If C_i is the biomass caught from length group i, and B_i is the total biomass at the begining of the month, then the fishing mortality this month is given by

$$F_i = \frac{C_i}{B_i}. \tag{17}$$

This procedure is repeated for each species and length group.

	Capelin	Cod	Herring
Yearly mortality rate, M	0.592	–	–
M_1	–	0.108	0.153
M_2	–	0.054	0.153
$M_3 - M_{13}$	–	0.027	0.077
M_{14+}	–	0.90	0.90

Table 18: *The yearly mortality rates. For cod and herring the rates are age dependent, M_a, while for capelin the rate are independent of age, M.*

6.4 Excess mortality

The excess mortality, or natural mortality, includes predation from non-modelled species (e.g. seals and whales except harp seal and minke whale, sea birds) and mortality due to age and illness. The mortality parameter is the yearly intensity, M, which means that the probability of still being alive after one year is $\exp(-M)$. This parameter is species dependent and might also depend on age. In the default setting, cod and herring are modelled using age dependent mortality rates, see Table 18. These mortality rates are obtained through simulation based estimation, using data from the period 1974-2003, under the constraints that the proportions M_{a_1}/M_{a_2} should be kept constant. The proportion values are obtained through personal communication with researchers at IMR. The mortality rates for the oldest age groups are not estimated, however, but are defined to be 0.90 to avoid accumulation in the oldest age group.

7 Fishery and fishery management

7.1 Cod and herring

Cod and herring management is based on VPA-estimates and biological reference points, see Jakobsen [23]. After obtaining number-by-age estimates (N_a) for the stock and the reference point value, F, the quota is computed according to the formula

$$Q = \sum_a \left[\frac{F \cdot S_a}{M_a + F \cdot S_a} \cdot (1 - \exp(-M_a - F \cdot S_a)) \cdot N_a \cdot w_a \right] \tag{18}$$

The sum is over all age groups a, $\{S\}$ is the vector of selection values in the fishery (can be obtained from the VPA-analysis, or given as parameters), $\{M\}$ is the vector of age dependent natural mortality rates and $\{w\}$ is the vector of age specific mean weights. The mortalities, mean weights and selection values used in the quota computation are identical to those used in the VPA estimation.

For cod both reference points based on the yield-per-recruit curve and reference points based on the spawning stock-recruitment relation is relevant as management strategies, while for herring only the yield-per-recruit based strategies are relevant. It is possible to simulate both types of strategies in the Scenario-C system. The default strategies, however, have constant F-values, and the default values are $F = 0.45$ for cod and $F = 0.20$ for herring, respectively.

7.1.1 Fishery

The simulation model is designed for two fisheries, the legal fishery and the non-legal fishery. The legal fishery is based on the quotas, and the corresponding catches will always be reported and (if possible) the catches will equal the quota. The illegal fishery will not be reported, and it includes both general overfishing and discards. The fishery is also split according to fishing gear, to be able to reflect the varying selection patterns of the gears. The convertion of a given quota to length distributed amounts is put into an external module, which takes as input the total quota and the various fleets' selection patterns and shares of the quota, and it returns the fished amounts split into reported and non-reported catches together with corresponding total selection patterns. The fishery is then simulated according to these selection values, which roughly can be interpreted as a weighted mean pattern based on the fleets' individual patterns and quotas.

For each fleet it is possible to model a general overfishing and discards of the smallest fish. If overfishing or discards is included in the simulation, the reported catches will equal the quota while both the general overfishing and the discards will be collected as non-reported catches.

For both cod and herring we have several fleets. For cod the fleets are defined as four Norwegian fleets (trawl, gillnet, hand line and seine), one Russian fleet (trawl) and one "other" (trawl), while for herring there are two Norwegian fleets (purse seine and other) and one Russian fleet. All herring fleets are defined to have the same selection pattern.

The selection patterns for cod are defined based on selection-by-age numbers obtained through personal communication with marine researchers and fishery economists. These

Age	Selection pattern by age for cod					
	Gill net 1	Gill net 2	Gill net 3	Hand line	Seine	Trawl
3	0.00	0.00	0.00	0.12	0.11	0.11
4	0.40	0.00	0.00	0.62	0.38	0.38
5	0.80	0.25	0.00	1.00	0.66	0.74
6	0.95	0.55	0.00	0.62	0.90	0.90
7	0.90	0.85	0.22	0.12	1.00	1.00
8	0.55	1.00	0.55	0.00	1.00	1.00
9	0.35	0.75	0.75	0.00	1.00	1.00
10	0.10	0.45	1.00	0.00	1.00	1.00
11	0.00	0.25	0.85	0.00	1.00	1.00
12	0.00	0.11	0.60	0.00	1.00	1.00
13	0.00	0.00	0.35	0.00	1.00	1.00
14	0.00	0.00	0.20	0.00	1.00	1.00
15+	0.00	0.00	0.10	0.00	1.00	1.00

Table 19: *Selection pattern in cod fishery by age for various fishing gears (Norwegian fleet). These numbers are obtained through personal communication with Arne Eide (Norwegian College of Fisheries), and are based on work by Larsen (1990) [25], Løkkeborg (1988) [27] and Isaksen et.al. (1986 and 1989) [21] and [22].*

numbers are presented in Tabe 19. The values are then converted to selection by length, using information concerning the length by age distribution for cod. The resulting length dependent selection patterns are found in Table 20. Table 21 presents the selection pattern for herring, for which our sources have unfortunately disappeared.

7.2 Capelin

The capelin quotas are computed through the program CapTool (Bogstad et.al. [5]). Input data to this management procedure is an acoustic stock estimate and the assumed cod consumption. This assumed consumption is computed based on the VPA-estimates for the cod stock, using the formula (Bogstad and Gjøsæther, [4])

$$C = \sum_a \frac{N_a \cdot w_a \cdot (1 - m_a) \cdot \ln(2) \cdot \exp(0.11 \cdot T) \cdot r \cdot 24 \cdot D_a}{283 \cdot r^{0.54}}. \tag{19}$$

In this equation we have the following quantities:

a	=	age group
N	=	number of cod
w	=	mean weight of cod
m	=	proportion of matures
r	=	stomach content / body weight ratio
D	=	overlap period (in days)

In the simulation model we have assumed that the overlap period is independent of age,

Length group	Fishing gear: Trawl	Gill net	Hand line	Seine
<10 cm	0.000	0.000	0.000	0.000
10 - 15 cm	0.000	0.000	0.000	0.000
15 - 20 cm	0.120	0.000	0.120	0.110
20 - 25 cm	0.120	0.000	0.120	0.110
25 - 30 cm	0.121	0.001	0.123	0.111
30 - 35 cm	0.125	0.003	0.130	0.115
35 - 40 cm	0.147	0.014	0.172	0.138
40 - 45 cm	0.263	0.073	0.393	0.258
45 - 50 cm	0.407	0.150	0.639	0.398
50 - 55 cm	0.588	0.260	0.825	0.545
55 - 60 cm	0.759	0.374	0.892	0.702
60 - 65 cm	0.800	0.800	0.800	0.800
65 - 70 cm	0.915	0.528	0.526	0.912
70 - 75 cm	0.961	0.600	0.301	0.961
75 - 80 cm	0.993	0.657	0.116	0.993
80 - 85 cm	1.000	0.669	0.036	1.000
85 - 90 cm	1.000	0.648	0.006	1.000
90 - 95 cm	1.000	0.629	0.001	1.000
95 - 100 cm	1.000	0.598	0.000	1.000
100 - 105 cm	1.000	0.537	0.000	1.000
105 - 110 cm	1.000	0.505	0.000	1.000
110 - 115 cm	1.000	0.502	0.000	1.000
115 - 120 cm	1.000	0.492	0.000	1.000
120 - 125 cm	1.000	0.446	0.000	1.000
125 - 130 cm	1.000	0.446	0.000	1.000
>130 cm	1.000	0.446	0.000	1.000
Share of quota	67%	17%	8%	8%

Table 20: *The length specific selection patterns used when simulating the cod fishery, together with default shares of quota. The trawl quota consists of 3 sub-fleets, the Norwegian trawl fleet (12%), the Russian fleet (45%) and other (10%). The selection values are obtained using the age dependent values in Table 19 together with simple length by age distributions.*

Length group	<10 cm	10 - 25 cm	25 - 26 cm	26 - 27 cm	27 - 28 cm	28 - 29 cm
Selection value	0	0.120	0.250	0.310	0.375	0.410
Length group	29 - 30 cm	30 - 31 cm	31 - 32 cm	32 - 33 cm	33 - 34 cm	> 34 cm
Selection value	0.500	0.675	0.750	0.850	0.900	1.000

Table 21: *The length specific selection patterns used when simulating herring fishery. The sources for these selection values have unfortunatey disappeared.*

that the number of cod is the VPA-estimate and the mean weights are the mean weights used in the VPA-computations. The reference values for r and D are found in Bogstad and Gjøsæther [4], and are set to $r = 0.03$ and $D = 60$ days.

In capelin fishery there is only one fleet involved, and the fishery is conducted according to this fleets' selection pattern.

7.3 Minke whale

The minke whale stock is modeled in a separate module, and its trajectory with respect to population and yield is simulated before the fish model is simulated. The quotas are set by the RMP method of the IWC, as it is implemented in the IWC-program MANA4 (see IWC reports [19] and [20]).

7.4 Harp seal

The harp seal stock is also modeled in a separate module, using the model of Skaug and Øien [35]. The total harp seal catch, C_{harp}, is split into pup catch and adult catch, and separate quotas are given for each. The simulation model offers two alternative strategies:

1. Keep the adult stock (age 1+) constant.

2. Total quota set to a constant proportion of the adult stock.

In both alternatives an additional parameter is the ratio between pups and adults in the catches. The default strategy is the one of keeping the adult stock constant, combined with a ratio of 4, that means the number of pups caught is 4 times the number of adults caught.

8 External modules

In the Scenario-C system there are several external modules, but in this section we will only describe the three most important:

1. The minke whale module
2. The harp seal module
3. The VPA module

These modules are external for variuos reasons, and they interact differently with the Scenario-C system.

8.1 The minke whale module

This module includes both the population model and the management of the minke whale stock, and it is essentially identical to the MANA4-program of the IWC (see [19]). The original FORTRAN program is linked to the scenario system, and the only changes that has been made are a few lines to create the necessary input to the simulation.

The minke whale module is run as a part of the initialization of a simulation, and it creates an output file with yearly minke whale data for the whole simulation period. During the simulation the Scenario-C reads the necessary whale data from this file, and the minke whales act as predators on the fish stocks. This way of including the minke whale means that the state of the fish stocks will not have any effect on the condition of the whales.

8.2 The harp sea module

The harp seal module is also external, and it is based on the work by Skaug and Øien, see [35]. The Scenario-C project has adopted the population model from this work, and the harp seal module is written in the statistical package Splus.

The interaction with the Scenario-C system is somewhat different from the minke whale module, in that the harp seal trajectory must be created before the simulation is started and only the resulting output file is used as input to the main simulation. The harp seal history is simulated using the model of Skaug and Øien with historical catches in the period 1875 to 2001, and from this point of time and till the end of the simulation period the catches are obtained using the management procedure.

The harp seals act as predators on the fish stocks, but the state of the fish stocks will not have any influence on the harp seals. This implies an assumption that the harp seal will switch to prey outside the model if one or more of the model stocks are depleted, as will the minke whale.

The default parameters in the population model are the ones given as best estimates in the work of Skaug and Øien.

8.3 The VPA procedure

When computing cod and herring quotas, the fish stocks are estimated using VPA with Laurec-Shepherd tuning (Laurec and Shepherd [26]). The original programs are written in FORTRAN and are made accessibe to the Scenario project from the Institute of Marine Research in Bergen. The original program system is constructed for interactive use, asking questions that must be answered by the one who is running the program. In the context of the Scenario-C, there is no room for interactive program sessions, and so the original VPA-program has been automated. In addition some program lines have been added, to create new output for use in the quota calculation. Except for the automation and the extra output lines, the VPA program system is kept unchanged.

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