THE CAPELIN ASSESSMENT MODEL - A DOCUMENTATION

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ABSTRACT

The mathematical model used for management of the Barents Sea is documented. The model is used for predicting the evolution of the stock to evaluate the consequences of various catch quotas.

1. INTRODUCTION

Giving advice on harvesting the capelin stock involves measuring the actual stock abundance and evaluating the impact of a possible catch quota. This is done each year in September during a joint Soviet/Norwegian cruise, which is followed by recommendations for the total allowable catch (TAC) in the coming regulation period. The present regulation strategy aims at maintaining the spawning stock at 0.5 mill. tonnes, although other strategies are conceivable, for instance, keeping the autumn stock as measured in September at a certain level.

At the Marine Research Institute a mathematical model of the Barents Sea capelin stock is used in conjunction with management. This model is used in three different ways:

Based on the acoustic estimate of the stock obtained during the September cruise, the future state of the stock is predicted as a function of future catches. These calculations then serve as a basis for giving TAC advice.

Based on historical data, acoustic estimates as well as catches, the stock size and stock structure is calculated from September to September. The outcome is then compared to the measurement to determine optional values for the various parameters in the model. Such parameters govern the effect on the stock of natural mortality, growth etc. To use the model this way, a program compares model outcome and stock measurement.

The model can also make long-range predictions based on arbitrary historical measurements of the stock as starting point. Runs for over 50 years show that after a transient period of 5-10 years, the model autumn stock and spawning stock stabilizes. By making a series of runs, each with different levels of catch, the maximum sustainable yield (MSY) can be found. By observing which level of the spawning stock (or, alternatively, the standing stock in the autumn) corresponds to MSY, one obtains a guideline for regulation.

In order to build a model package capable of handling the three-step management task outlined above, two models are necessary:

Basic model: This model describes the evolution of the capelin stock over one year beginning with measuremnts taken in September. The basic model is a collection of the maturation, mortality and growth models.

Recruitment model: In order to describe the evolution of the capelin stock for more than one year, the basic model must be augmented with a recruitment model. The recruitment model is fully endogenous, i.e. the recruitment is calculated on the basis of outputs from the basic model only, and consists of the submodels of recruitment in total numbers and the length distribution of recruiting yearclass.

In a management situation, values other than those actually estimated may be used, such as when long-term changes in the population cannot be accounted for by the model. Then the time period used for estimation may not be representative for the actual situation. This is the case with capelin growth, which is dependent on geographical distribution. Therefore, the model accommodates interactive changes of parameter values.

In section 2 the submodels of the basic model are described. Section 3 deals with the recruitment model. Section 4 deals with parameter estimation and data communication and (hopefully) gives the reader a feeling of the model's accuracy and applicability. Sections 5 and 6 deal with the use of the model in management. For detailed documentation of the computer implementation of the model a special manual is provided.

2. THE BASIC MODEL

2.1 Population layout

How detailed the population should be described is dependent on both the quality of the available data base and how broad the aspects of population dynamics which are considered vital for the management.

In accordance with these considerations the number of capelin is divided into age groups 2-5 and length groups ranging from 7.5 cm to 20.0 cm in .5 cm intervals.

The division on length groups is necessary in order to build a maturation model, which must be length-dependent.

Age groups enable the calculation of the spawning biomass each year, and the establishment of a recruitment model. The 2-year-olds are the youngest to be accurately measured, while the upper age limit of 5 years is chosen bacause the measurement of older fish becomes uncertain due to insufficience of data caused by a high mortality of 5-6 year old fish.

The population is further divided into mature and immature in October-March. The implementation of the model could also keep track of the mean weights within each length group, which are at present calculated from the lengths and the total biomass of the population.

2.2 Submodels

2.2.1 Maturity

As it is assumed that maturation is more dependent on length than on age, the simplest model is then to use length at maturity, above which all fish are maturing. Thus, if the maturation length is, for instance, 13.8 cm, then 60% of the fish in the 13.5-14.0 cm group is allocated to the immature part of the population and 40% to the maturing part of the population.

2.2.2 Mortality

2.2.2.1 Spawning mortality

A constant fraction of the spawning population is assumed to survive and remain part of the total population the following autumn. For the time being, this fraction is set to zero.

2.2.2.2 Non-spawning natural mortality

The part of the population lost due to natural (i. e. not fishing) causes apart from death by spawning, is assumed at each instant to be proportional to the population. That is, the equation

$$\frac{dN}{dt} = -M \cdot N$$

familiar from the traditional VPA technique is used. Here, N is the population in numbers, t is the time, M is a parameter later to be estimated from the data. The equation above is applied to each cell in the length-age space.

2.2.2.3 Fishing mortality

The equation used is similar to the one used for natural mortality:

$$\frac{dN}{dt} = - F \cdot N$$

Here F is a constant, the so-called fishing mortality. However, this equation is used in different ways according to whether the model is run for a time period for which there are catch records or whether it is used to predict the future. If the model is run into the future, the above equation is used as it is and the program asks the operator for a value of the parameter F. If the model is used for a past period with catch data, the program calculates the value of F from the familiar catch equation used with VPA-analysis:

$$C= \frac{N \cdot F}{F+M} \cdot (1-\exp(-(F+M))$$

Here, N is the number of fish at the start of the time step, usually one month, and C is the catch in numbers. The same F applies to all length groups although the equations above are used for each age group separately.

2.2.3 Growth

The growth of the immature population from September to September and the growth of the mature population from September to April must be handled separately.

2.2.3.1 Growth of the immature population

The choice of model is the simplest possible. The length increment per time unit is assumed constant for all length groups and all age groups. In addition a possibility for density-dependent growth reduction is provided. The data available give no room for sophistication concerning the actual form of the density-dependence, so any mathematical function reducing the growth monotonically with increasing population might suffice. To calculate the growth we have chosen the mathematical function:

$$\frac{dl}{dt} = A_l \cdot (1-(B/B_l)^2) \cdot (1-(N/N_l)^2)$$

Here, l is the length, A_l, B_l and N_l are constants to be estimated from the data and B is the total biomass of the population. The other parameters are:

A_l	Maximum growth
B_l	Density-dependence (biomass)
N_l	Density-dependence (total number of fish)

As the length of the fish is not a modelled entity , the implementation of the above equation assumes that fish are moved upwards through the length groups so that the validity of the equation above is retained.

The model provides no independent equation for growth in weight. Growth in length and growth in weight are linked together through the equation

$$w = A_w \cdot l^{C_w} \cdot (1-(B/B_w)^2) \cdot (1-(N/N_w)^2)$$

Here, w is the mean weight in each length group. Density dependence enters through the dependence on l as well as directly.

2.2.3.2 Growth of the mature population

There are no equations similar to the ones above for the growth of the mature population. However, it is possible to increase the mean weight per age group by some fraction, using data on mean weight in the spawning population together with calculated mean weights of the mature population in the autumn. This is no trivial task, however, since these weight increase functions will be dependent on the length at maturity used.

The model program provides an opportunity for calculating these weight correction factors interactively for a given range of years.

2.2.3.3 The actions of the basic model

When the basic program starts to run a one year cycle, all parameters are assumed to have their correct values. When the program is used as a stand-alone model, a special communication module enables the operator to check the parameter values and make necessary changes. When the program is used by other programs, these programs furnish the correct parameter values.

The simulation is performed according to the following scheme:

The population data are read in from the data file. This includes the number of fish per age and length group and the mean weight in each length group.

The catch data in numbers by month and age group is read in from data file.

The population at December 31. is calculated by reducing the initial population by the natural mortality and catch.

The population is split into a mature and an immature part.

The catch data for the next year is read in from the catch data file.

The spawning population by March 31. is calculated by reducing the mature population by the catch and natural mortality for the months January-March. The spawning biomass is calculated. If the basic model is used with programs where the recruitment model is used, the recruiting population is calculated.

The immature part of the population is calculated from January 1. to September 31. by reducing by the natural mortality for the whole period and by the fishing mortality for the autumn season. The growth is calculated for the part of the time that falls within the growth period.

3. THE RECRUITMENT MODEL

The recruitment model is composed of two parts: recruitment in total number and the length distribution of the recruiting yearclass.

3.1 Recruitment in total number

The traditional Beverton-Holt function is used:

$$R = N_r \frac{B}{B_r + B}$$

Here, N_r is the maximum recruitment and B is the spawning stock biomass. B_r is the value of the spawning stock biomass producing a recruitment of half the maximum value. This function leads to a recruitment proportional to the spawning stock at small values and to an asymptotical recruitment of N_r at high values of the spawning stock.

3.2 The length distribution of the recruiting yearclass

The data show that, as a general rule, the mean length of the recruits is smaller in years of abundant recruitment than in years of a weak recruitment. This density-dependent growth of the recruiting yearclass is correlated more to the abundance of the recruiting yearclass than to the abundance of the total stock.

The length distribution of the recruiting yearclass may be of great significance when using the model for management. It directly influences the contribution of 3 year old fish to the spawning stock of the next year. Being the initial length for the bulk of the forthcoming spawning population the next year, it influences the TAC for the autumn fishery. The manager using this model should take particular care for how this part of the program works.

The length distribution of the recruiting yearclass is built up by pooling together historical length distributions of 2-year-old capelin. For details of this procedure see section 4.5.

The formula for the total number of the recruiting yearclass has been constructed by using the observed strengths of 2-year-old fish. No provision has been made for adjusting the fishery on this yearclass prior to the time of measurement, since the relative impact in August and September has been very small, compared to other sources of uncertainty. However, in periods when the mean age of the stock is low, as is the present situation, this may well not be true. So when the model is being re-parameterized using data also after 1980 effort should be directed into removing this source of error.

4. PARAMETERIZATIONS AND DATA DOCUMENTATIONS

So far, the description of the management model for Barents Sea capelin has only dealt with the basic modelling of the stock over a one year period. However, the model may give different results, depending on the values of the parameters. We will find the values of the parameters controlling the model output, which is a function of the measurement of the stock one year earlier as well as of the model itself, resemble the actual measurement of the stock most closely. To this end, two problems must be solved:

The deviation between model output and measurement must be quantified.

A method must be found for varying the parameters and selecting the set of parameter values giving the smallest deviation between model and measurement.

The latter problem is easily solved by using a standard program called MINUIT, developed at the high-energy research center at CERN, Geneva. Although developed for solving problems of high-energy physics, this program is of general use, and well suited to the kind of parameter estimation described in this paper.

The expression for the deviation between model and measurement (the so-called goal function) depends on an understanding of the probability laws applicable to the model outputs. We will here take a pragmatic approach and use goal functions that give good estimates of the parameters, but where it is not possible to estimate the range of uncertainty.

4.1 <u>Length at maturity and natural mortality</u>

Understanding maturation is the most essential process in managing the Barents Sea capelin fishery effectively. The length at maturity affects both the total number and the mean length of the immature and mature part of any yearclass. Therefore, both these two quantities might be used to determine the most accurate value of the maturation length. However, the mean length is also affected by the growth.

In order to estimate the maturation length as independently of other processes as possible, we will compare the age distributions of the model output to the measurements. This age distribution is strongly affected by the length at maturity, the widely different initial length distributions of different age groups, and by the natural mortality. It is not possible to escape inter-parameter correlation totally. We will estimate the length at maturity and natural mortality simultaneously with the goal function, which has the advantage that these two properties are not too closely coupled. The length at maturity has a strong influence on both the absolute level of the stock and the age distribution of the stock, whereas the natural mortality affects the absolute level strongly and the age distribution only slightly. We use:

$$F(l,M) = SUM((S_3/N_3 - 1)^2 + (S_4/N_4 - 1)^2)$$

Here:

$F(l,M)$ is the goal function to be minimized

S_3, S_4 the model output of 3- and 4-year-old capelin (no. ind.)

N_3, N_4 the measurements of 3- and 4-year-old capelin (no. ind.)

S_3 and S_4 are dependent on l (length at maturity) and M (natural mortality). The values are summed for the years 1973-1980. This period of time is also used for estimating the other parameters of the model.

The numbers of 3- and 4-year-old capelin measured and predicted by the model using the estimated parameters are given in the table below:

3-year-old fish (10^7)

	1974	1975	1976	1977	1978	1979	1980
Predicted	17498	26595	15651	8184	6548	16833	14342
Measured	17925	30407	16733	10171	7585	11249	15413

4-year-old fish (10^7)

	1974	1975	1976	1977	1978	1979	1980
Predicted	167	6287	8938	2852	895	721	1923
Measured	356	8790	7844	4159	886	478	3262

It is seen that, as a rule, there is good correspondence between model predictions and measured values. However, there are anomalies of which the year 1979 is the most pronounced. The deviations between predicted and measured values fluctuate more for 4-year-old fish than for 3-year-old fish.

4.2 Growth

Growth in length is more important to management than growth in weight, since the spawning stock in numbers is directly dependent on the length distribution through the use of the length at maturity. Once the length at maturity has been estimated, the model's mean lengths are dependent on the growth only. Both thr growth in length and in weight are estimated by constructing a least squares function similar to the one used for estimating length at maturity. The predicted and measured values for the mean length are given in the table below:

3-year-old fish (cm)

	1974	1975	1976	1977	1978	1979	1980
Predicted	14.0	13.7	14.5	15.3	14.9	14.3	14.9
Measured	12.7	13.4	14.1	15.0	14.8	14.2	15.3

4 year old fish (cm)

	1974	1975	1976	1977	1978	1979	1980
Predicted	16.1	14.3	15.3	15.8	15.9	15.8	15.9
Measured	16.0	15.1	15.3	15.9	16.0	16.0	16.6

The deviation of prediction from measurement is largest in 1980, a year of substantial growth. The low mean length of 3-year-old fish measured in 1974 gives rise to large deviations for the predicted mean lengths of those fish in 1974 and in 1975.

4.3 Fishing mortality pattern

As mentioned earlier, when the basic model is being used for a past period, the catches are transformed into numbers of fish by age-group and month. When the model is being used for prediction, the operator selects the F-value to be used. However, a fishing mortality pattern has to be defined. The mortality is calculated by dividing the historical catches per age group by the estimated numbers of the same age group and averaging over a range of years. The fishing pattern will thus be slightly dependent on the maturation length and natural mortality. With the values of length at maturity and natural mortality currently being used for management the fishing pattern presently in use is 0.045, 0.081, 0.116 and 0.158 for 2-, 3-, 4- and 5-year-old fish. These values are then scaled up or down by the F-value given by the operator. It should be noted that when running the model into the future, the entity of interest is the "F-output biomass". The F-value merely is a control variable.

The model program allows for an interactive calculation of the fishing mortality pattern for a given range of years.

4.4 Recruitment

The parameters of recruitment are estimated in two steps: Firstly, the spawning stock biomass is calculated throughout the time period of interest, using the model and the estimated value of the maturing length. Then the parameters are estimated by comparing the recruitment calculated by using the recruitment function to the observed numbers of 2 year old fish for the corresponding yearclass. The result is shown in figure 1.

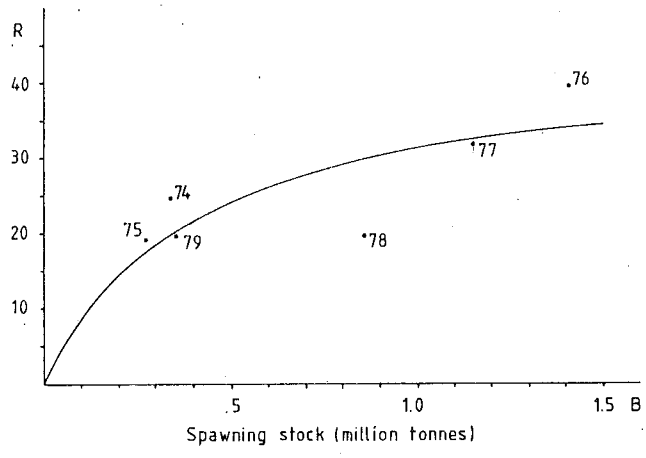

Figure 1. Stock-recruitment relation of Barents Sea capelin. The solid line shows the function $R=\frac{44.5 \cdot B}{0.43 + B} \cdot 10^{10}$ where R is the number of recruited individuals and B is the spawning stock in million tonnes. (Hamre and Tjelmeland, 1982).

It must be noted that the parameters of the recruitment relation are dependent on the length at maturity and weight correction factors applied for the spawning stock.

4.5 Length distribution of recruiting yearclass

As noted in section 2, the length distribution of the recruited 2 year olds has a tendency to shift towards higher lengths when the strength of the yearclass is low. For an example, consider figure 2.

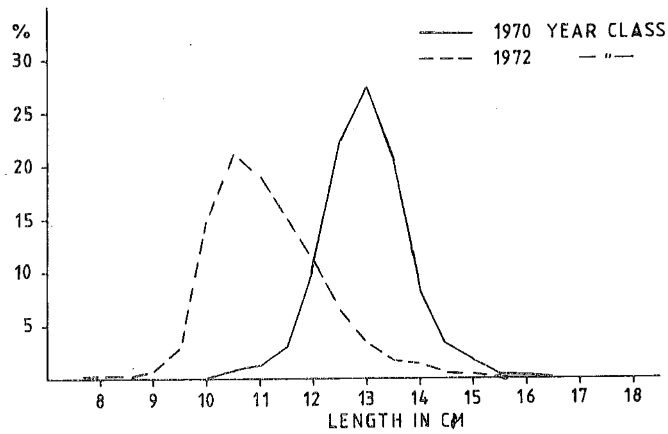

Figure 2. Length distribution of 2-year-olds in the 1970 and 1972 yearclasses of Barents Sea capelin.

Figure 3 shows the mean length of 2 year old fish and corresponding strength measured in total number of fish. The years pooled when constructing the length distribution of the recruiting yearclass are also shown.

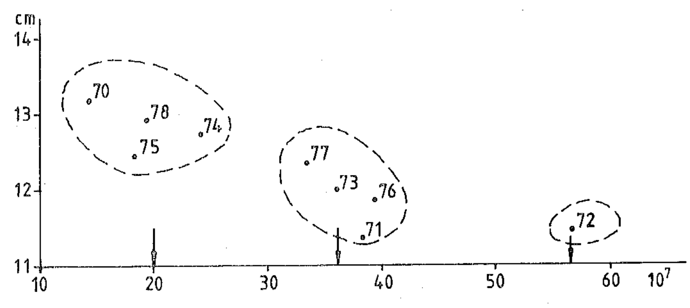

Figure 3. Mean length vs. stock strength of 2-year-olds in the yearclasses 1970-1978 for Barents Sea capelin. (Hamre and Tjelmeland, 1982).

The strength of the recruiting yearclass is used when constructing the length distribution of the recruiting yearclass. If the strength is equal to 20,36 or 56 x 10^{10} individuals, the length distribution from the yearclass clusters pointed to by arrows are pooled to form a length distribution for the recruits. If the strength is between these values an interpolation is performed, i. e. two neighbouring length distributions are added, with weights proportional to the difference between the strength of recruitment and the strength of the clusters.

5. MAXIMUM SUSTAINABLE YIELD

The basic model is augmented with the recruitment model. The result is a fully endogenous model. The model may then be run with different values of autumn and winter F-values and the corresponding values of mean spawning stock and mean F-output biomass may be found. The result is the yield curve for Barents Sea capelin shown in figure 4.

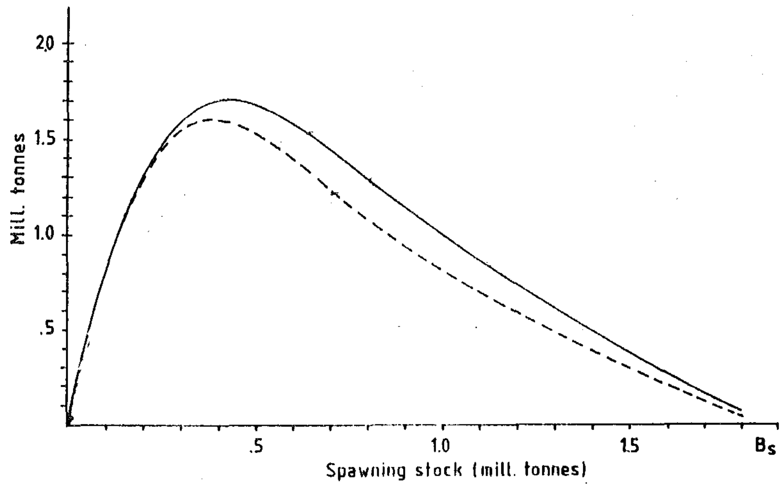

Figure 4. Sustainable yield for Barents Sea capelin at different levels of spawning stock (B_s). Broken lines apply to winter fishing only, solid lines to autumn fishing only.

It is seen that for winter fishing only the MSY is 1.6 mill. tonnes while for autumn fishing only the MSY is 1.7 mill. tonnes. In the first case the spawning stock is somewhat lower than 0.4 mill. tonnes, in the latter case somewhat higher.

6. PRACTICAL USE OF THE PROGRAMS WITH MANAGEMENT

In constructing this model, some very crude assumptions have been made. Vital aspects of the Barents Sea capelin dynamics have been omitted, including:

Sex-dependent growth

Sex-dependent maturing lengths

Age-dependent maturing lengths

Age- and sex-dependent spawning survival

Area-dependent growth in connection with observed change of distribution area

Time- and area variations of spawning migration, giving rise to strong fluctuations of larval growth and survival having in turn impact on recruitment function

Time change of predator species giving rise to time change of natural mortality

These are areas of current research, and eventually the model may take several or all of these effects into account. At the present level of development, the model must be used with caution and is therefore very flexible. There is provision for interactive change of

Maturing length
Natural mortality
Recruiting yearclass of a particular year
   This is specially useful when one wants to use the larval index as a guide to recruitment
Growth
Fishing mortality pattern
Weight correction of mature population

7. REFERENCES

Hamre, J. and S. Tjelmeland 1982. Sustainable yield estimates of the Barents Sea capelin stock. In. Coun. Explor. Sea C.M. 1982 H:45 17pp + 7 pp tables and figures. [Mimeo.]