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1.1 Model experiments and other parallels to scenario modelling and experiments

The science of fisheries management is a pragmatic science with many parallels to engineering. The core in fisheries management is a management regime (or strategy) for a particular fishery (group of fisheries). The aim is to regulate the fisheries so as to obtain a good continuing yield. The management strategy is composed of methods for estimating abundance and other parameters in the management model for the ecological system at hand, and a control law for calculating quotas or other regulating quantities when the management model has been estimated on the incoming data. The management strategy is parallel to a design for physical constructions (say ship hulls) in engineering. Engineering designs are supposed to perform satisfactory according to more or less formalized performance criteria. As in fisheries, knowledge of the system in which the engineering construct is to operate will be imperfect. It will be required that the performance is reasonably robust with respect to uncertainty attached to system behaviour. It is also required that the design/management strategy should be able to handle the better understood statistical variability (natural variation) of the system.

Model experiments is an important tool in engineering. In ship building, small scale models of hull designs are tested in a basin where waves, wind and current are manipulated according to a research plan. The scenarios for the real ocean system simulated in the model basin will typically span the range of plausible states of nature. Repeated simulations will be needed to obtain statistical information on performance under natural variability inherent in each scenario. A rigid observational regime is imposed to register the performance of the model ship under the various scenarios in replicated trials. To draw the parallel, the simulation model corresponds to the test basin and the management strategy corresponds to the ship hull to be tested.

1.2 Scenario modelling in fisheries science

Physical experiments are not feasible for testing out management regimes for fisheries regulation. For large systems like marine ecosystems, computerbased simulation modelling is the only practical technology for model experiments of management regimes. This will in fact also be the case in various fields of engineering and other pragmatic sciences, and it is indeed the case for policy experimentation in economics. We will use the terms *scenario modelling* for the process of establishing a computerbased test bench for management regimes for fisheries, and *scenario experimentation* for carrying out simulation experiments to evaluate a given *management procedure*. A *scenario model* has three main ingredients: a simulation model, a *management procedure* and a set of performance measures.

The simulation model is a parametric model capable of representing the main dynamics of the ecological system in the Barents Sea and its interaction with human activity like fishing and resource surveying. The simulation model should provide a conceptually simple computerbased framework which allows the competent researchers to specify the various plausible states of nature (including human activity) which they wish to consider. The set of such scenarios should ideally span the uncertainty with respect to knowledge of the system. Uncertainty in the form of natural variation is incorporated in each scenario as stochastic variation.

The *management procedure* is a feedback mechanism representing a management regime for the system. The present regime is a single species VPA analysis of cod and herring, calculating capelin quotas to target the spawning stock at a given level, allowing the cod to have its estimated demand for capelin met. As other management regimes, this is a mixture of abundance estimation of the relevant stocks, based on data from the fisheries and the surveys, and of a control law for calculating quotas on basis of the abundance estimates. To represent this regime in a *management procedure*, the methods behind the various informal judgements involved must be clearly specified. A *management procedure* is thus a computerized formalization of a management regime which interacts with the simulation model to constitute a fully specified dynamic model for the system. The *scenario model* will be made capable of handling various management regimes to be evaluated.

The evaluation of a management regime will be based on appropriate performance statistics. These statistics represents features of the simulated development of the system for a given scenario and for the management procedure under study. Summary statistics based on the joint distribution of performance statistics like mean yearly catch of cod, value of total catch, spawning stock of cod at end of period etc. over replicated runs of the same scenario, will be used to characterize the management regime.

Scenario modelling and experimentation may be used for various purposes. One purpose is simply to investigate the performance of a given management regime, say that presently in use for the Barents Sea fisheries. Because of the uncertainty attached to our understanding of the ecological system and its interaction with fishing and research, several scenarios must be considered to reasonably span the plausible range. To delineate this plausible range of scenarios will be a valuable exercise in itself. Features common to the various scenarios will represent knowledge of the system, and variability in features across scenarios will represent the uncertainty attached to the knowledge. Ideally, it should be the knowledge and uncertainty as agreed by the scientific community of researchers in relevant fields of oceanography, marine biology, fisheries science etc. which should be represented by the set of scenarios. When disagreement and uncertainty is great, many and diverse scenarios will be needed. The process of establishing a set of scenarios will usually have to be a co-operative process of a group of scientists from the various relevant fields and laboratories.

In addition to the simulation model and its agreed set of scenarios, the management regime will need to be formalized into a *management procedure*. To make explicit how fisheries actually are managed makes this field of policy more open for insight and debate than is the case when judgements and estimation are done more informally. This increased openness will enhance improvement in the management strategy.

The third component of the *scenario model* for testing out a current management regime, the set of performance statistics and their internal weighting, will bring to the open a debate over the aims and goals of fisheries management. The various fractions of the fisheries industry, as well as fisheries economists, planning bureaucrats and politicians will all have ideas of performance criteria by which to judge a management regime. These ideas are not necessarily in agreement. To get a reasonable set of performance measures, co-operation between various interest groups will be required. The task of hammering out a minimal set of explicit performance statistics on which to base the evaluation of a management regime, will hopefully stimulate debate and co-operation between interested parties, and even possibly result in an agreed over-all criterion based on balancing the often mutually competing sub-criteria.

In summary, the process of scenario modelling and experimentation to investigate the current management regime will hopefully represent a challenge and provide a research environment which will crystallize the scientific knowledge and uncertainty of the ecological and fisheries system at hand, open up the actual management regime for scrutiny and improvement, and enhance the understanding of the aims and goals for management of the given fishery. Further use of *scenario modelling* will then be to identify important research problems, improving the management regime, and in helping interest groups, industry and politicians better to understand possibilities and limitations in fisheries management. The perspectives for scenario modelling for fishery management seems to us to be great.

1.3 Pioneering scenario modelling in IWC

Scenario modelling has not previously been done in fisheries science to any extent. A pioneering case of scenario modelling was, however, carried out by the Scientific Committee of the International Whaling Commission (IWC). When IWC in 1982 decided to impose a world-wide moratorium on commercial whaling, it was also decided to carry out a comprehensive assessment of potentially exploitable whale stocks. An important component of the comprehensive assessment was to develop a management procedure for whaling which should be robust against the great uncertainty attached to our understanding of the population dynamics of whale stocks and to the great imperfections in abundance estimates and other data on the status of the whale stocks. In IWC, a management subcommittee was established within the Scientific Committee. Five different groups of scientists were engaged in designing candidate management procedures. Together with a few additional scientists, they met for workshops once every half year in a 5 year period. At the workshops, results were compared and discussed. The atmosphere was competitive, with two "green" research groups, two research groups from whaling countries (Iceland and Japan) and one neutral group (South Africa). The comparison and discussion of simulation results provided an exchanging of ideas. In addition to discussing the results of the preceding half years development and simulation, the workshop discussed and decided upon further scenarios to be implemented and simulated, and also further development of the performance measures. This forward looking provided a plan for the work of the next half year, and it provided explicit challenges for the management strategy.

An interesting feature of the IWC work is that the procedure developers to little extent used theory of optimal control to deduce a strategy. They rather developed their candidate strategies by a process of creative construction based on simulation results and exchange of ideas between the research groups. This was partly due to the fact that emphasis was on robustness versus imperfection in knowledge and data, and not on optimization.

The candidate procedures did not converge in structure or method. To a considerable degree, however, they did converge in performance. It was therefore not self evident that it should be possible to select one of the procedures as the preferred one at the meeting in Reykjavik in 1991. However, by tuning the candidate procedures to common targets in a reference scenario, it was possible on the basis of simple descriptive statistics computed from the performance measures to conclude that one of the procedures was to be preferred and that its robustness properties were acceptable for real implementation. The revised management procedure is described in [11].

1.4 Different types of fisheries models

It is helpful to distinguish between three basic types of models: assessment models, management models and scenario models.

The purpose of an assessment model is to organize the information concerning one stock, or an ecosystem consisting of several stocks, so as to obtain the best possible assessment of the status of the stock or the system. Assessment models are often complex, and the issues of parameter estimation are central when building and using an assessment model. The various VPA models and methods are cases of assessment models. Hilborn ([8]) reviews the state of the art in stock assessment for the purpose of management. He makes the point that these various methods generally rely on one set of data each, ignoring other relevant sets of data. In fisheries, various models of the multispecies type have been developed for the purpose of assessment. The MULTSPEC model by Bogstad and Tjelmeland (1993) [3] has been developed for assessing capelin and cod in the Barents Sea. In the Scenario Barents Sea project, we will draw on the experience and competence of the MULTSPEC group, and in due time, management strategies based on MULTSPEC might be tested out in the Scenario Barents Sea model.

A management model is a feedback model aimed at explicating the management strategy. The management model will often be a rather simple assessment model coupled with a control law. This is at least the case for the management model, called the Catch Limit Algorithm of the revised management procedure of IWC.

As explained above, scenario models are, so to speak, model laboratories for testing out assessment models and management models (or rather, assessment methods and management schemes).

1.5 Probing and uncertainty scenarios

In the Scenario Barents Sea project, scenarios are organized in two groups. The *probing scenarios* are chosen to investigate specific questions, often one at the time. They are selected to probe current management issues, but also to improve our understanding of the model. *Uncertainty scenarios*, on the other hand, are systems of scenarios designed to span a plausible region in state space. A reference group of experts in fishery biology, economy and management is instrumental in setting plausible limits to parameters and structures in the simulation model. Hypothesis generated by the probing scenarios might be tested in uncertainty scenarios. Issues of robustness and efficiency are central to the analysis of simulation results for uncertainty scenarios.

2 A scenario model for the Barents Sea

As already mentioned, the scenario model has three main ingredients, the simulation model, the management procedure and the performance measures. This section presents these three ingredients briefly, as they are currently implemented.

2.1 The simulation model

Our model is supposed to be a rather simple simulation model of the ecosystem in the Barents Sea, containing the main biological and environmental factors. The intention is not to build a "true" model, but to establish a framework for operational specification of various plausible hypothesis concerning the fisheries system. As such, it must be capable of producing variability at the same level as observed in nature. The main factors in the simulation model will depend on a few essential parameters. Ideally, it should be possible to imitate plausible states of nature (ecosystem and fishermen's behaviour) by varying these parameters.

In order to make the simulation model practical and understandable for others than the project workers, the concepts must be simple in structure and nature. The more it is based on biological and economic theory, the better. For a simulation model to be practical it must be executable in the usual sense. In addition, because the model is supposed to be run for a great number of times, runtime must be kept down.

Only the main factors in the system will be explicitly modeled. At present, these are:

- Three species of fish: cod, capelin and herring. All three species are modeled as age- and length distributed. Recruitment, maturation, growth, predation and natural mortality for all three species are modeled as parameter dependent. Both the parameters and the functions describing these mechanisms can be changed.
- Human activities in the Barents Sea: fishery and research surveys. In the simulation model, fishery is carried out on the simulated stocks according to quotas given by the management procedure. There is room for overfishing and discards of small fish. Data from the research surveys are modeled when they are needed as input to the management procedure. At present we have implemented only acoustic stock estimates for herring and capelin, and tuning indices for the cod stock. As for catch based input data to the management procedure, plausible levels of bias and variability are imposed on the survey data.

- Some environmental factors, like sea temperature and primary production. At present, these environmental factors are subsumed in a few proxy variables which generates a random environment for the interacting fish stocks.

The management procedure itself is not a part of the simulation model, and may be replaced by other management procedures. The model does communicate with the management procedure by giving necessary data input to it, and by letting the data fisheries be regulated by the quotas set by the management procedure.

The main elements in the model system are the fish stocks and human activity related to these. The purpose of the scenario model is to follow the stock abundances and the catches over a period of time under specified environmental conditions and a given management regime. During a year the stocks are exposed to reducing factors (natural mortality, predation, fishery) and to increasing factors (growth, recruitment), and the simulation model is supposed to be capable of imitating all these factors in various plausible ways. Natural variations in the system are mainly modeled by probability distributions.

Before turning to more details, let us shortly describe the dynamics in the simulation system. The system starts at 1 January after being initialized. Then recruitment is computed and added to the stocks, and the age distributions are updated. The appropriate components of the cod and herring stocks are maturing. The next step in the process is to compute quotas for each stock, by calling the management procedure(s). For each month following, mortality and growth are executed (in that order). When arriving at 1 October, capelin is maturing and so divided in two separate stocks. All three species are aging at the turn of the year.

2.1.1 Growth

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

$$\begin{aligned} dL(t) &= L(t+\Delta_t) - L(t) \\ &= (L_\infty - L(t)) \cdot G(t) \cdot M(t) \end{aligned} \tag{1}$$

The function $M(t)$ is a discrete function to indicate seasonal variations in growth (seasonal profile). In the simulations presented, the following profiles are used (monthly values):

$$\begin{array}{lccl} \text{Cod:} & M(t) & \equiv & 1, \text{ all months (no seasonal variation)} \\ \text{Herring:} & M(t) & = & (0, 0, 0, 0, 1, 1, 1, 1, 0.5, 0.25, 0, 0) \\ \text{Capelin:} & M(t) & = & (0, 0, 0, 1, 1, 1, 1, 1, 1, 0, 0, 0) \end{array}$$

The G-function for cod is dependent on the predation, and is explained in detail in [7] and more briefly in appendix A. For capelin and herring the model is

$$G(t) = 1 - exp(-K(t)\Delta_t) \tag{2}$$

The parameters are explained in table 1. Increase in length is computed monthly.

Weight
Mean weight in each length group is preliminary given as parameters to the simulation

t	=	time variable
Δ_t	=	time interval of fixed length (one month in the simulation model)
L_∞	=	maximum length
$K(t)$	=	$\left(a + b\, e^{-B(t)}\right) g(\Delta T, f)$
a, b	=	parameters
$B(t)$	=	stock abundance at time t, (indicating density dependent growth)
ΔT	=	temperature deviation from a defined "normal" value
f	=	food variable
g	=	function to regulate growth according to sea temperature. Linear in ΔT

Table 1: *The parameters involved in the functions (1) and (2) for length growth of herring and capelin. All parameters, except the sea temperature are specific for each species of fish.*

model, and these weights are not affected by growth. This entails that the model is not capable of handling emaciation due to lack of food at this stage. However, absence of suitable food results in a slower length growth. Emaciation due to spawning is taken care of, and for the mature part of the stocks mean weight is reduced after spawning. During one year the normal mean weights are gained in all length groups, however.

2.1.2 Recruitment

In the simulation model, juveniles are recruited into the stocks between age 1 and 2 (age is incremented at the turn of the year), capelin as one year olds on 1 October, cod and herring as 2 year olds on 1 January. To describe the relation between the mature stocks in the spring and the number of recruits more than a year later, we use the Beverton-Holt function. In historical data one can observe some years with extreme high recruitment, especially for the herring stock. In the simulation model there are two levels of recruitment for each species, both modeled according to a Beverton-Holt function but with different parameter values for maximum level and half value. Approximately every 10th year recruitment is performed according to the extreme function, and this is done simultaneously for all three species. When simulating, the first 5 years after a year of extreme recruitment the recruitment is on normal level. Thereafter the level is drawn randomly each year, with probability $\frac{1}{5}$ of getting the extreme one, until a year of extreme recruitment is drawn. The approximate period of 10 years is a model parameter, and can easily be changed. If so is done, half a period passes with normal recruitment, before extreme recruitment can occur with probability $\frac{1}{\text{half period}}$.

Also the temperature may have an influence on the recruitment. This is modeled by regulating the maximum number of recruits according to temperature, so high temperature is favourable and more juveniles will survive until the age of recruitment. Similarly, low temperature will lower the maximum number of recruits. The regulating function is linear in ΔT (temperature deviation from the defined "normal" temperature), and is identical for all three species. If high recruitment coincides with high abundance of (young) herring in the Barents Sea, the direct effect is increased capelin recruitment. Increased predation from herring might however counterweight this effect, and the result might be reduced capelin recruitment. This is modeled similarly to the temperature influence, by a linear function lowering the maximum number of capelin recruits. Both these effects can be "turned off" by setting the regulating function $\equiv 1$. In the simulations presented in this note, there is no temperature influence included.

2.1.3 Maturation

Maturation is modeled as a pulse. Cod and herring matures at the turn of the year, while capelin matures at 1 October. These dates are parameters to the simulation model, and might be changed. The maturity ogives (fractions of mature) in each length group is computed from a logistic function:

$$m(l) = \frac{1}{1 + e^{4P_1(P_2 - l)}} \tag{3}$$

where l denotes mean length in the length group (midpoint in length interval). The two parameters P_1 and P_2 are specific to each species of fish, P_2 being the "median" length at maturation. Maturation is not sex-dependent.

2.1.4 Mortality

The model differs between three types of mortality:

- Predation mortality due to species included in the model, mainly cod.
- Fishing mortality.
- "Natural" mortality, including predation mortality from species not explicitly represented in the simulation model.

Natural mortality is simply modeled by way of the yearly (or monthly) mortality rate. For capelin, spawning mortality is explicitly modeled.

Predation

Predation is a major component of the dynamics of the simulation model, and a quite detailed description of the predation model is given in appendix A. In the simulation model all (species, length)-groups can in principle be both predator and prey. However, in practice cod is the main predator and capelin is prey. When present in the Barents Sea, herring is prey for cod, and also possibly predator on small capelin. In addition, cod is some times cannibal, and so the smallest cod is both predator (on capelin and younger herring) and prey (for older/larger cod). The model does not allow stocks to suffer extinction due to predation. When the predator stock is large compared to the prey, this will entail reduced individual growth.

Fishing mortality
Each month the simulation model computes the total biomass caught according to the year's total and a seasonal profile dividing the fishery over the year. Then this biomass is "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 was the total biomass at the beginning of the month, then the fishing mortality this month is given by

$$F_i = \frac{C_i}{B_i}$$

This procedure is followed for each species and length group.

Spawning mortality
Spawning mortality is modeled for the capelin stock. It is possible to parameterize the model so that a given fraction of mature capelin dies after spawning.

Total mortality
If G is the monthly rate of spawning mortality, P the rate of (modeled) predation mortality, F the rate of fishing mortality and M the rate of mortality due to other reasons, the monthly survival of the stock is:

$$N_{i,t+1} = N_{i,t} \cdot (1 - G) \cdot (1 - P) \cdot (1 - F) \cdot (1 - M) \tag{4}$$

where $N_{i,t}$ is the number of individuals in length group i at the beginning of month t.

2.1.5 Environmental factors

At this stage only temperature is taken explicitly into account. The "normal" (yearly) mean temperature (T_0) is a system parameter. Variations in mean temperature is modeled with $\Delta T = T - T_0$ following a sine curve with period p_1 and amplitude p_2:

$$\Delta T(t) \;=\; p_2 \cdot \sin\left(\frac{2\pi t}{p_1}\right), \quad t \text{ is time variable}$$

p_1 and p_2 are constant parameters in the simulation model, and normal values will be a period of approximately 10 years, and an amplitude of approximately 2^oC. Seasonal variations is modeled according to historic data. The temperature variations might be turned off, and the simulations presented later are performed without temperature effects.

2.1.6 Fishery and research surveys

Fishery
Inside the simulation model there are only two fleets for each species of fish, One which represents the legal fishery and the other representing the non-legal. The last one includes both general overfishing and discards, and at present it is not possible to differ between

those two. This is of course a considerable drawback, because discards are lost resources, while the general overfishing most often is landed. If the scenario specification includes discards, then the terms “legal” and “non-legal” fishery is a little misleading, since the large fish caught are defined “legal” until the quota is filled, while the small fish all are defined “non-legal”. Without discards, the non-legal fishery equals the general over-fishing of quotas.

However, at the turn of the year the simulation model calls for the management procedure, and the management procedure computes a total quota. In the simulations one can decide that the total quota is not allowed to change considerably from one year to the next. If such a flag is set, the simulation program controls whether or not the quota is “legal” (too small quotas are increased to a minimum value = a percentage of last years's quota, and too large quotas are reduced to a maximum value the same way). Then the simulation program calls for a “distribution system”, which distributes the total quota to several fisheries (or fleets) according to the scenario specification. The scenario specification also includes the amount of overfishing and discards, and the total catch as a consequence of this is computed. At least weighted selection patterns in the legal and the non-legal fishery are computed. The total biomass to be taken “legally” and “non-legally” are returned to the simulation system together with the respective selection patterns. The simulation model then conducts fishery according to those data. This procedure is followed for the cod and the herring fishery, while for the capelin we have only modelled one fleet of “legal” fishery.

Research surveys (cod)
Cod assessment is dependent on data input from research surveys together with age-distributed catch- and weight- data. Each year 5 research surveys are simulated. The objective of the research surveys is to give indices for assessment of the cod stock. The surveys are modeled with basis in the model stock at different points of time: the two first at 15 February, the two next at 1 October and the last one at 1 November. For each survey a total index I is computed from the total stock:

$$I = f(B) + \text{random noise}$$

where the function f at present is either linear in B or in $\sqrt{B}$. The random noise is modeled as a normally distributed variable, with zero expectation. All parameters (included noise variance) are specific to each survey, and the parameter values are estimated by linear regression on historical survey data and VPA-estimated stock data([10]). At present, the random noise has constant variance. The total index is then distributed over age classes according to the age distribution of the model stock.

By comparing the historical survey indices with VPA-estimates (suitably forward calculated according to estimated fishing mortalities and a natural mortality 0.2), age distributions in survey data do show some trends. Surveys during winter (early spring) tend to have an over-representation of the youngest age groups, while surveys during autumn tend to have an over-representation of the oldest age groups. At present, such trends are not built into the survey simulation, and the age distribution of the survey indices are correct.

2.2 Performance measures

The purpose of building a simulation model for the Barents Sea is not the model itself, but rather to construct an instrument for evaluating regimes of fishery management. In such a model, old and new management procedures can be tested, analyzed and compared in scenarios defined by qualified researchers.

To evaluate a management procedure one needs statistical performance measures. In the simulations conducted so far, we have used rather simple performance measures. Since cod is defined the most important species commercially, the response variables have been mainly "cod responses". In a simulation study performed in 1994 (described in [6]), the responses were:

1. Mean yearly catch of cod during the simulation period.
2. Mean yearly biomass of cod.
3. Minimum biomass of cod.
4. Mean yearly catch of capelin.

In that version of the simulation model, the herring was not fully integrated with the other species, and so "herring responses" were of no particular interest. To judge a management strategy, we look at the responses on all performance measures included. It is not obvious how to weight the four response variables against each other, and it is far from obvious that the chosen measures are the most appropriate for evaluating management procedures. Economic considerations are, for example, not included.

In the planned simulation experiment, described in section 4.1, economic aspects will be considered when defining the performance measures.

2.3 Management procedures

Management regimes usually consist of more or less informal expert judgment in conjunction with statistical analysis of catch and survey data. The data analysis is often flavoured by informal human input. This creates a problem when the management regime shall be integrated in a scenario model. It is not practicable to include this human element for at least two reasons:

- The procedure will be called many times during a simulation run. A quota is to be set (at least) once a year in the simulation period, and there typically will be many years (> 40), with replications, and also many scenarios to be simulated. It is important that all decisions made during the runs are consistent. Also the time spent on making decisions ought to be minimized. Both these concerns exclude the human element.
- It is desirable that the scenario model and its management procedure is explicitly and precisely defined. This opens up for scrutiny, evaluation and improvement. Common sense and expert judgement should, however, have its place when the improved management procedure is to be used for real fisheries.

For each management regime to be evaluated in the scenario model, we therefore need to specify precise instructions for every decision that will be taken. We then impose the required consistency. Even though some knowledge and experience are lost when formalizing the management regime into a management procedure, we hope to minimize the loss by relying on advice from the experts. We will now shortly describe the implemented procedures, and then take a closer look at the management strategies used for cod and herring.

2.3.1 The implemented procedures

Cod.
The cod assessment is based on VPA-analysis with Laurec-Shepherd tuning[13, 15]. The management strategies implemented are either based on constant fishing mortality rate, or on biological reference points such as F_{med} or F_{max}[12]. The cod procedure can be summarized as follows:

1. The simulation program creates the necessary data for the VPA, based on the simulated fishery and research surveys.
2. The VPA program system is called, and an estimate for the cod stock is computed using a tuning criterion that all age groups 7-15+ shall have identical estimated fishing mortality (tuning data covers age-groups 3-7).
3. A special quota routine is then called, to compute an advised quota according to the actual management strategy in use, and based on the VPA-estimate for the total stock.
4. The resulting quota is given as input to the simulation model, and the model fishery the next year in the simulation period is conducted according to this quota. The quota is distributed to several fleets and the actual catch might be adjusted according to overfishing and discards, as described in section 2.1.6.

Fishery is modeled according to a length selection, while the quota is calculated according to an age dependent selection. The age selection might be determined from the catches using separable VPA[14], or could be a constant selection pattern computed from the fleets' individual length dependent selection patterns.

Capelin.
The capelin procedure is based on the CapTool-strategy[2], In the simulations, fishing is only effected on the mature stock (winter fisheries), and the regulation condition is to maintain a spawning stock of a given size. Predation from cod is taken into account, when the quota is set. Input data to this management procedure is an acoustic estimate of the stock abundance and the assumed cod consumption. This assumed consumption is computed using the VPA estimates for the cod stock.

Herring.
The herring procedure is also based on VPA-analysis, but does not involve the tuning

procedure. Inputs to the procedure are acoustic stock estimate and reported catches, and quotas are set using biological reference points or constant normative fishing mortality. Only reference points based on the yield-per-recruit function are implemented for herring.

2.4 Management strategies for cod and herring

The scenario model requires explicit and operational formulation of the management strategies to be studied. Although management strategies in terms of reference points based on VPA are broadly known, the precise description of the implementation of such strategies in the scenario model is presented below.

The different management strategies are represented by normative fishing mortalities (F-values) computed on the basis of such parameters as natural mortality, weight, age at maturation and recruitment. The level of fishing mortality is also called a biological reference point.

We consider two types of VPA management. In the first the reference points are in terms of F_{high}, F_{med} and F_{low}, which are based on the ratio between the number of recruits and the spawning stock biomass. The other type of strategies refer to F_{max} and F_p which both are based on the yield per recruit function.

2.4.1 The strategies F_{high}, F_{med} and F_{low}

F_{high}, F_{med} and F_{low} are estimated from the VPA-calculated ratio (R) between the spawning stock biomass and the number of recruits. The ratio values are chosen from the ordered values for R. The median is used for F_{med}. For F_{low} the value of R is chosen where exactly 10 % of the observed values are lower, while for F_{high} 90 % of the values are lower. Quotas are then computed, based on the ratio number, the natural mortality, individual age, weights and the selection pattern, to match the reference mortality rate.

In our scenario model the basis for computing these F-values is VPA-estimates for the spawning stock biomass (SSB) and the number of recruits (3-year old). The VPA-file includes data from the last 30 years. However, for the first 3 years we do not have SSB, and for the last 2 years one does not yet trust the estimated number of recruits. The F-values thus are computed on the basis of 25 empirical SSB per recruit ratios. In computations outside the scenario program a longer period is used, and in the special cod quota computations in this section data for the whole period from 1946 are available.

We will show an example of the computations of the F-value for the three strategies. The VPA data for cod in 1993[10] are used in the computations.

Let R be the ratio between the number of recruits and the spawning stock biomass (SSB). In figure 1 the ratio (R) and SSB are shown for cod in the period 1946-1990. The figure shows that the ratio number R increases when SSB decreases.

If most of the observations are in the domain where the spawning stock biomass is low, the ratio number will be high. Contrary if most of the observations are in the domain where

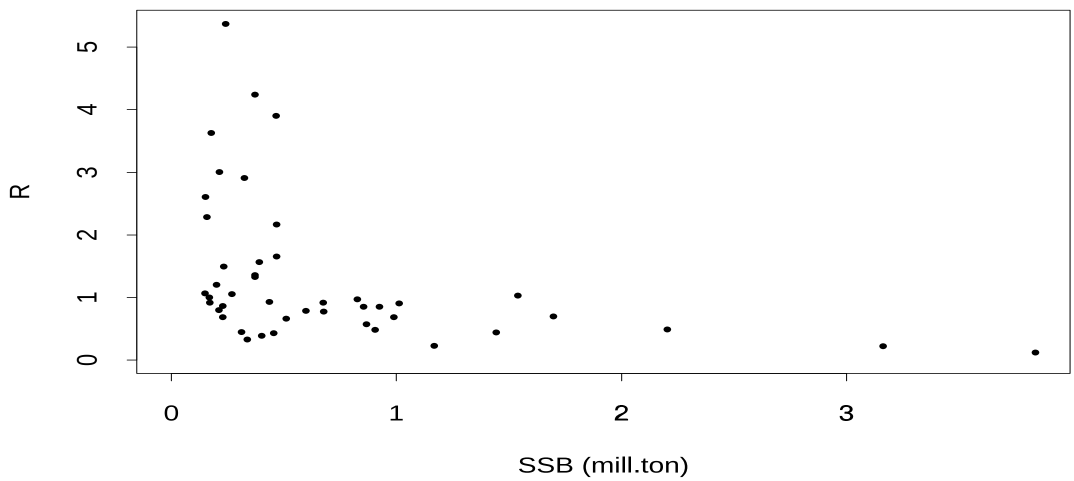


Figure 1: *Ratio number (R) of recruits and SSB for cod 1946-1990*

the spawning stock biomass is high, the ratio number will be low. This indicates that if the quota is determined in a period when the spawning stock is low, the ratio number and the quota will be high. If the observation period consists mainly of high values of the spawning stock biomass, the ratio number and the quota will be low. This may indicate that to determine a reasonable quota for cod, observations with low and high spawning stock biomass are needed.

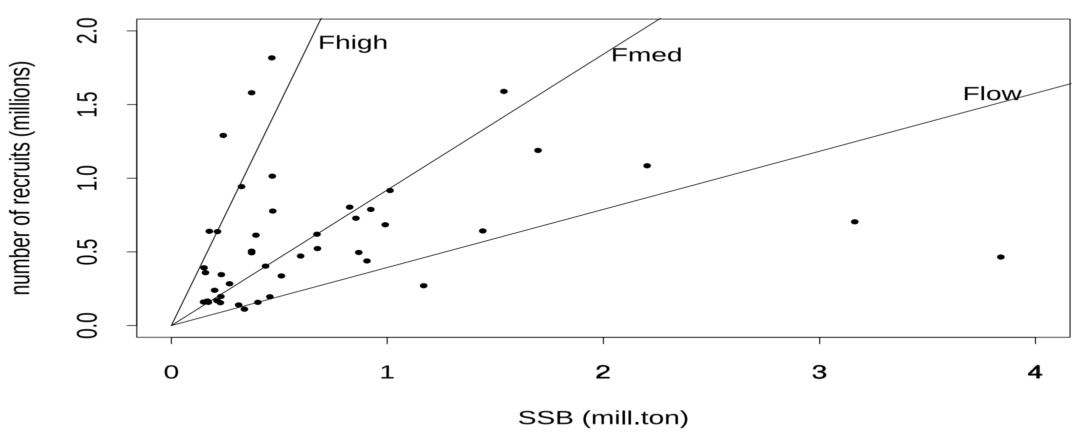


Figure 2: *Recruits and SSB 1946-1990, cod.*

If there is a linear dependence between the number of recruits (N_3) and the spawning stock biomass ($N_3 = k \cdot SSB$), then the ratio number would have been independent of the size of spawning stock. But the cod data for 1946-1990 indicates that there is not a linear dependence between recruitment and the spawning stock for cod. In the scenario model therefore a Beverton-Holt function is used as recruitment function.

In figure 2 the number of recruits and SSB for the period 1946-1990 are plotted. The lines which determines the ratio number (R) for F_{high}, F_{med} and F_{low} are drawn. From the ratio number the corresponding F-values with quotas are determined.

Strategy	Ratio	F-value	Quota
F_{high}	3.007	1.000	0.975
F_{med}	0.921	0.584	0.670
F_{low}	0.394	0.363	0.457

Table 2: *Ratio, F-value and quota in mill.ton for cod. VPA data from the years 1946-1990 are used for computing the ratios, and the quota is computed according to the VPA-estimated cod stock in 1993.*

In the scenario model data from a shorter period are used to determine the ratio values. When the quota for 1993 is determined, the SSB values from the period 1964-1988 are used. The mean size of the spawning stock in the period 1946-1990 is greater than in the period 1964-1988. So the ratio values are expected to be higher when using only the last 30 years as a basis. Table 3 shows that this is the case, but the differences are small. Mean F-values and quotas computed are slightly higher than the corresponding values in table 2.

Strategy	Ratio	F-value	Quota
F_{high}	3.007	1.000	0.975
F_{med}	1.059	0.625	0.705
F_{low}	0.432	0.386	0.480

Table 3: *Ratio, F-value and quota in mill.ton for cod. VPA data from the years 1964-1988 are used for computing the ratios, and the quota is computed according to the VPA-estimated cod stock in 1993.*

The ratio values in table 3 are higher than the corresponding mean values in the simulations, but the F-values also depend on mean weight in age classes, the size of the mature stock and the selection pattern. Varying these parameters may give other results. In the reference simulations with low growth, a ratio of 0.51 gives a mean realized F-value of 0.24, while high growth gives a mean F-value of 0.38.

The quotas and F-values computed by F_{high}, F_{med} and F_{low} vary considerably over time. The high values based on the 1993 VPA data illustrate this. F_{med} is designed to keep the spawning stock at the current level, but the quota computed for 1993 is so high that it reduces the spawning stock.

The computed F-value is also dependent on the natural mortality, but in the reference computations natural mortality has been set at M=0.2 in accordance with the nominal natural mortality in VPA. In section 2.4.3 we discuss the dependency of the natural mortality.

2.4.2 About F_{max} and F_p

The management strategy F_{max} maximizes the yield per recruit. F_p matches a point where the slope of the yield-recruit curve is p times the slope at the origin. This gives a lower F-value. In table 4 theoretical 1993 quotas for cod are shown. The quotas are much lower than the quotas for F_{high}, F_{med} and F_{low}.

Strategy	F-value	Quota
F_{max}	0.267	0.349
$F_{0.05}$	0.208	0.280
$F_{0.1}$	0.174	0.237
$F_{0.3}$	0.100	0.140

Table 4: *F-value and quota in mill.ton for cod, based on the VPA-estimate in 1993.*

The strategies F_{max} and F_p are stable. The quotas and the F-values in table 4 are about the same as the values we get in the reference simulations.

Strategy	F-value	Quota
F_{max}	2.250	1.777
$F_{0.05}$	0.500	0.979
$F_{0.1}$	0.375	0.809
$F_{0.2}$	0.188	0.473
$F_{0.3}$	0.125	0.333

Table 5: *F-value and quota in mill.ton for herring, based on the VPA-estimate in 1993*

Table 5 shows theoretical 1993 quotas for herring. The F_{max} quota is very high. It is probably too high to be an interesting strategy for herring. In the simulations the strategy F_p is used with parameter values from 0.1 to 0.3. In table 5 the natural mortality varies in the age classes. The M-values are in the interval from 0.13 to 0.23 and are highest for the oldest herring.

The yield per recruit based strategies F_{max} and F_p seem to be more stable than the other group of strategies. They do not intend to preserve the spawning stock. For cod, F_{max} is an alternative to F_{med} etc., and for herring F_p appear to be favourable, $p \geq 0.1$.

2.4.3 Natural mortality dependence

All the strategies that we have discussed so far depend on the nominal natural mortality. Table 6 shows how the F-values change when the natural mortality rate in the VPA computations is varied from 0.1 to 0.4.

	Natural mortality M-value			
Strategy	0.1	0.2	0.3	0.4
F_{high}	1.156	1.000	0.844	0.680
F_{med}	0.770	0.625	0.481	0.338
F_{low}	0.523	0.386	0.250	0.114
F_{max}	0.200	0.267	0.395	0.656
$F_{0.1}$	0.140	0.174	0.223	0.297

Table 6: *F-values for cod 1993 with varying natural mortality rate*

For the recruitment/spawning stock based strategies F_{high}, F_{med} and F_{low} the F-value decreases when the natural mortality increases. F_{med} tries to keep the spawning stock at a fixed level, and when the natural mortality increases, the fishing mortality has to be reduced. The total mortality is kept approximately at the same level.

For the yield per recruit based strategies F_{max} and F_p the F-value increases when the natural mortality rate increases in the domain $0.1 - 0.4$. When the natural mortality is high, the maximization of the yield per recruit will produce high catches of young fish with low weight, and so the fishing mortality will be high. When the natural mortality is low, it is better to wait until the fish has grown, and so a low fishing mortality is set. The strategies F_{max} and F_p do not take into consideration the size of the spawning stock.

In addition to the natural mortality the strategies also depends on the weights in the age classes and the selection pattern.

3 Probing scenarios

We organize the scenarios in two categories: probing scenarios and uncertainty scenarios. The probing scenarios are used to probe the model for the purpose of increasing our understanding of the model. These are not selected according to an experimental plan, but rather on the basis of the current debate over management options. They are also to some degree found by interactive search.

A number of scenarios have been run mainly to study the management procedures: how they react when parameters are varied or some of the assumptions are wrong. In the simulations presented in this section, it is natural mortality and fishing mortality that are varied. The parameters for recruitment and growth are kept fixed.

The results from the simulations are highly dependent on the parameter values that are set. The mean stock and quota values that result from the simulations may easily be changed by altering the growth, recruitment or mortality parameters. If parameters for growth or recruitment are set to give a higher growth or recruitment, then the mean values of the stock, and the catch will be higher in the simulations. In the reference simulation the growth parameters are set rather low, and the parameters in the recruitment function are based on data from the period 1946-1990. A reference simulation is taken as basis, and a few parameters are changed in the different simulations which are compared. In most of the simulations only one or two factors are altered.

In the simulations a VPA based management strategy is used to set the cod and herring quotas. For herring, stock estimates not based on VPA are available. If accepted as a reliable estimate, then both stock size and total mortality is known. The actual fishing mortality then is computed from the reported catches, and natural mortality is computed as the difference between total mortality and fishing mortality. If no stock estimate is available, then the fishing mortality will be estimated using survey data, assumptions about natural mortality and a tuning algorithm. In the scenario model cod management is based on VPA with Laurec-Shepherd tuning.

The two ways to perform the VPA computations will be referred to as simulations with and without tuning in the management procedure. In the scenario model the cod management is always with tuning, and herring management is without tuning. In simulations with tuning the survey data is generated from the stock size (section 2.1.6).

All summary statistics presented in this section are mean values from 100 years in one single simulation. The presented simulations are "normal", that means presenting average results according to the actual scenario specification.

3.1 Simulation with and without tuning

Simulations with and without tuning will be different when studying special factors, for example when analyzing the effect of an extra fishing mortality. Assuming known the size of the stock every year, then the total mortality is also known. If total fishing mortality is greater than the reported catch, then the extra fishing mortality is added to the natural mortality. This high natural mortality is used when the quota is computed.

In simulations where a tuning algorithm is used to determine the fishing mortality, the natural mortality is given. If there is an extra fishing mortality which is not reported, the fishing mortality rate (F-value) will be kept, but the stock estimate will be adjusted to match the catch.

It is important to distinguish between the two methods when discussing management procedures for cod and herring.

3.2 Simulation with F_{high}, F_{med} and F_{low}

These management strategies are interesting to study for cod, but not for herring since recruitment of herring is characterized by high recruitment about every tenth year, while in other years the recruitment is low. In the simulations where F_{high}, F_{med} and F_{low} are used as management strategies for cod, the parameters are set to give low growth. The recruitment parameters in the Beverton-Holt function are estimated using the data for 1946-1990.

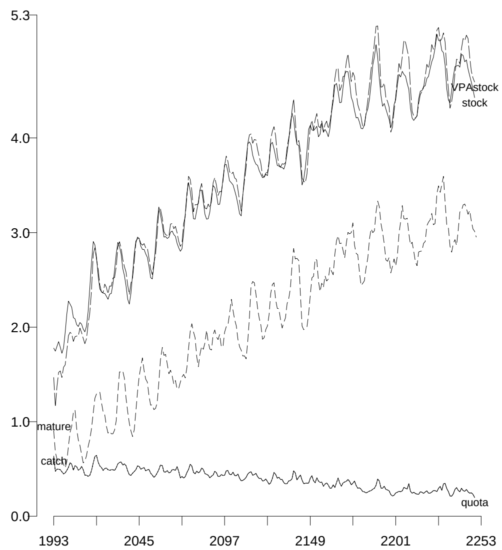


Figure 3: *Simulation with strategy F_{med}, and without SSB limit.*

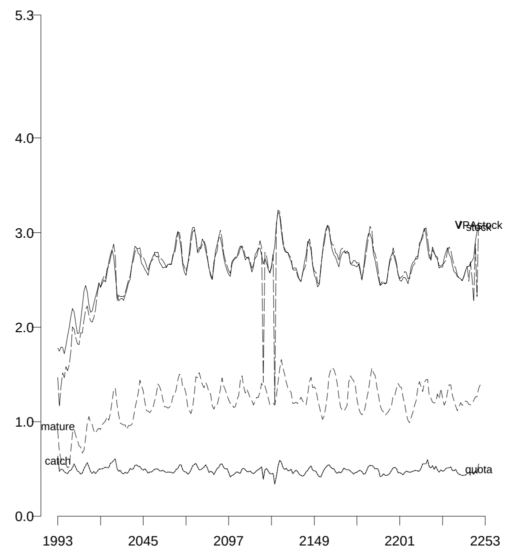


Figure 4: *Simulation with strategy F_{med}, and SSB limit of 1 mill.ton.*

In the simulations we have made an assumption that the recruitment does not increase when the spawning stock biomass is greater than 1 mill.ton. When computing the ratio between the number of recruits and the spawning stock, the size of the spawning stock is nominally reduced to 1 mill.ton when exceeding this limit. This is done because we do not want low quota values when the spawning stock is large. The problem with high spawning stock biomass is discussed in section 2.4.1. When the spawning stock biomass increases, the estimated F-value for the quota decreases. This includes that even if the stock increases, the quota will not increase, it might even decrease.

Figure 3 shows a simulation with F_{med} where there has been no nominal limitation in the spawning stock when computing the ratio number and the quota. The figure shows that the stock grows slowly, but steadily during the simulation period, and the growth continues until the quota is nearly zero, and the stock is very large. This simulation has been run for about 250 years, and it illustrates that the growth of the stock is very slowly. In this simulation the tuning indices are generated without noise.

F_{med} sets a quota which nearly preserves the stock. An extra fishing mortality of about 10 per cent will stabilize the stock soon.

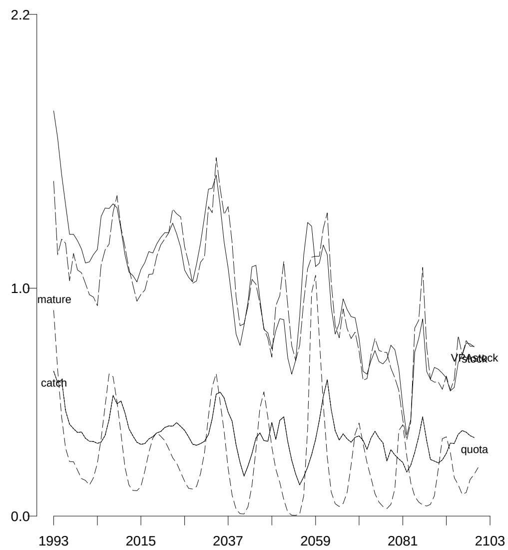


Figure 5: *Simulation with management strategy F_{high} for cod.*

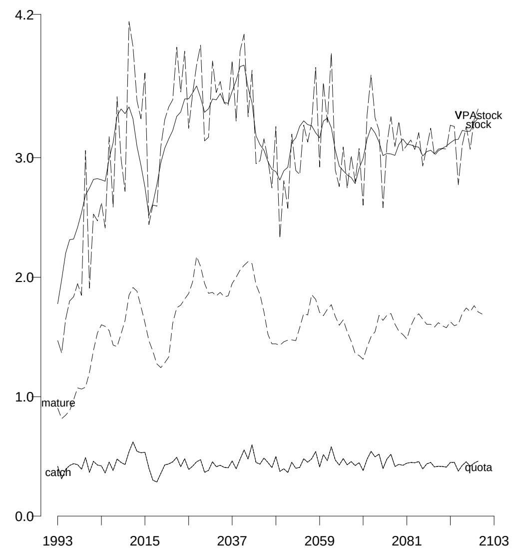


Figure 6: *Simulation with management strategy F_{low} for cod.*

Figure 4 shows a simulation with F_{med}, but with SSB nominally set at 1 mill.ton when the limit is exceeded. The stock stabilizes on a stock size of about 2.7 mill.ton and a quota of 0.49 mill.ton. Also in this simulation, the tuning indices are generated without noise. The lower dotted line shows the size of the mature stock, and the lower solid line shows the quota which is equal to the catch. In the sequel the SSB limit is imposed.

Figure 5 shows a simulation with F_{high}. There are great fluctuations in the stock size during the simulation. Several times the mature stock is nearly zero. Then the quota will be set very low, and the stock begins to grow. After having grown for some years, the quotas will be set to higher values, and the stock will decrease. The great fluctuations indicate that the F_{high} quotas are too high.

Figure 6 shows a simulation with F_{low}. During the first period of the simulation the stock grows to about 3.3 mill.ton. Then the stock stabilize for the rest of the simulation. The stock size is higher than for F_{med}, but the mean catch is lower (0.44 mill.ton). The stock would not have stabilized if the spawning stock had not been nominally limited to 1 mill.ton in the quota computations. If there had been no limitation, then the stock would have grown during the whole simulation period. This growth would have been much faster than the growth with F_{med} as management procedure (figure 3).

In the simulations presented in figures 5 and 6, noise has been included in the tuning indices. However, as easily seen from the curves comparing the model stock (upper solid line) and the VPA-estimated stock (upper dashed line), there are more noise in the indices in the F_{low}-simulation than in the F_{high}-simulation.

3.3 Simulations with F_{max} and F_p

This type of management strategies are interesting both for cod and herring. Management of herring based on these strategies are treated sections 3.9 and 3.10. Figure 7 shows a simulation with F_{max} as management strategy. As shown in the figure the stock size and the catch stabilize. The mean stock size is 2.9 mill.ton, and the mean catch is 0.49 mill.ton. This is probably near the optimal stock size.

Strategy	Stock	Mature	Catch	Recruit	F-value
F_{max}	2.9	1.19	0.49	0.76	0.24
$F_{0.1}$	3.5	1.80	0.43	0.74	0.16
F_{med}	2.7	1.07	0.49	0.77	0.27
F_{low}	3.3	1.61	0.44	0.72	0.18

Table 7: *Cod management. Stock, mature stock and catch are biomass in unit mill.ton, while recruit are the number of recruits in unit billion.*

A simulation with the strategy $F_{0.1}$ gives a higher stock size and a lower mean catch than F_{max}. The results are about the same as for F_{low}. The mean stock size is 3.5 mill.ton, and the mean catch is 0.43 mill.ton. See table 7.

The results from simulations with F_{max} and F_{med} are approximately equal. The mean catch is the same, but the stock size is slightly better and the fluctuation in the estimated F-value is less with F_{max} than with F_{med}.

3.4 Stability of the tuning routine

In all simulations the Laurec Shepherd algorithm is used as tuning routine in the VPA analysis for cod. Using a tuning routine to estimate the fishing mortality from survey data, makes the simulation less stable.

The reference simulation with F_{med} is shown in figure 4. In this simulation there is no noise in the survey data. If noise is introduced into the survey data, the VPA-estimate would fluctuate around the value of the model stock, as illustrated in figure 6.

In the simulation with F_{max} shown in figure 7, there is no noise in the survey data. Most of the years the difference between the deviation in the VPA estimate is small, but there is one year when the deviation is about 1 mill.ton. The reason is that the tuning estimate of the fishing mortality is wrong this year, and it gives a great deviation in the VPA estimate of the stock. Figure 4 gives an other example of such a situation.

Figure 8 shows a simulation with F_{med} where the individual growth is lower than in the reference simulation. In this simulation the difference between the model stock and the VPA estimate of the stock is greater. Most of the time the stock is overestimated, and

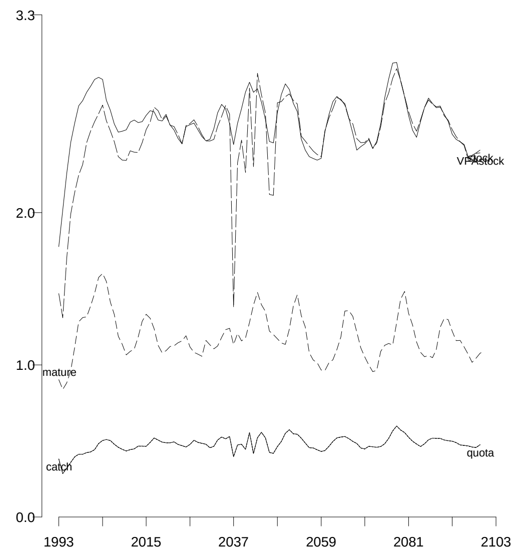


Figure 7: *Simulation with strategy F_{max} for cod.*

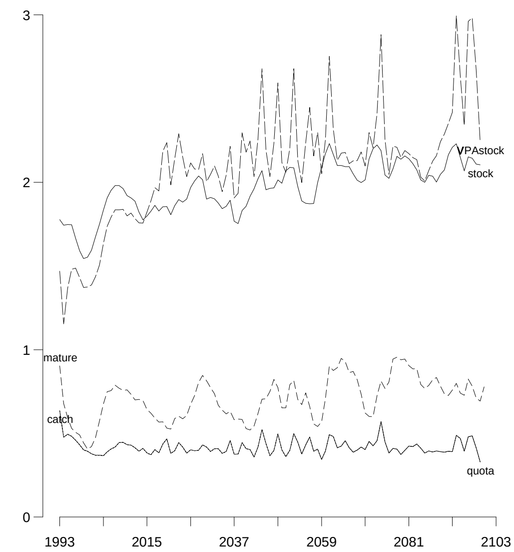


Figure 8: *Simulation with strategy F_{med}, and with low growth, cod.*

there are several years where the deviation in the VPA estimate is substantial.

Simulations where the quota and fishing mortality are very low, may also give VPA estimates with great deviations.

If we suppose survey data are correct, the Laurec Shepherd tuning routine normally gives a good estimate of the fishing mortality in years where the growth is normal, and the fishing mortality is not too small. There may however be single years with great deviation in the estimate of the fishing mortality. In years with low growth the tuning routine will underestimate the fishing mortality. If there is noise in the survey data, there will also be deviation in the estimate of the fishing mortality, but the mean value of the fishing mortality for all years in the simulation will be correct.

3.5 Varying natural mortality in the model

In the simulation runs discussed above, the management strategy F_{max} was found to be slightly better than F_{med}. The real natural mortality was given by M=0.2. In this section we will study how the management strategies behave when the true natural mortality has another value. The nominal M-value is still set to 0.2 in the VPA computations.

Taking the reference simulation as starting-point and varying the M-value in the model with 0.1, 0.2 and 0.3, the optimal mean catch will vary. Table 8 shows the optimal catch values.

Natural mortality (M)	Optimal catch (mill.ton)
0.1	0.7
0.2	0.5
0.3	0.3

Table 8: *Optimal catches when the nominal natural mortality rate in the VPA computations for cod is set to M=0.2, and with varying real natural mortality.*

Natural mortality with M=0.3 in the model

When the natural mortality in the scenario model is 0.3, the stock size will be underestimated in the VPA computations.

F_{med} gives a mean stock of 2.2 and a catch of 0.28 mill.ton. This appears to be about optimal, when regarding the high natural mortality. The result would in fact have been about the same when running the simulation with the correct natural mortality in the VPA computations. The low estimate of the size of the stock is compensated by a higher F-value which is computed by the tuning routine.

F_{max} gives about the same result as F_{med} with mean stock size and catch of respectively 2.5 and 0.24 mill.ton. A simulation run with the correct natural mortality in the VPA computations gives a mean stock and catch of 1.7 and 0.28 mill.ton. The resulting catch is thus rather high, but the stock size is very low.

Strategy	Stock	Mature	Catch	Recruit	F-value
VPA-M = 0.2					
F_{max}	2.5	0.98	0.24	0.84	0.24
F_{med}	2.2	0.77	0.28	0.80	0.30
VPA-M=0.3					
(correct VPA-M)					
F_{max}	1.7	0.40	0.33	0.75	0.34
F_{med}	2.4	0.90	0.26	0.83	0.18

Table 9: *Varying natural mortality rate in the VPA for cod. Real natural mortality rate in the simulation model is* $M = 0.3$.

Natural mortality with M=to 0.1 in the model

When simulating with real natural mortality rate equal to 0.1, the stock size are overestimated in the VPA computations.

F_{med} gives a mean stock size and catch of 2.8 and 0.78 mill.ton. When simulating with a correct natural mortality, the values will be the same. The results are however bad. In this case it is better to use a lower F-value and increase the size of the stock. This will in fact give better catches.

Simulations with F_{max} give a mean stock size and catch of 3.2 and 0.80 mill.ton. When simulating with a correct value for the natural mortality, the result will be a much higher stock of 4.9 mill.ton, but the mean catch is not higher.

Strategy	Stock	Mature	Catch	Recruit	F-value
VPA-M=0.2					
F_{max}	3.2	1.39	0.80	0.69	0.24
F_{med}	2.8	1.01	0.78	0.70	0.31
VPA-M=0.1					
(correct VPA-M)					
F_{max}	4.9	2.92	0.78	0.65	0.20
F_{med}	3.1	1.25	0.79	0.70	0.36

Table 10: *Varying natural mortality rate in the VPA for cod. Real natural mortality rate in the simulation model is* $M = 0.1$.

F_{max} gives a slightly better result than F_{med} when the M-value in the model is 0.1. F_{med} computes a F-value which is too high, while F_{max} sets a lower F-value which allows the stock to grow larger.

Conclusion about varying natural mortality in the model

The management strategies F_{max} and F_{med} both depends on the natural mortality (section 2.4.3), the dependence is however different. The F-value computed by F_{max} increases when the natural mortality increases, while the F-value set by F_{med} decreases.

In the reference simulation with M=0.2 the results of F_{med} and F_{max} are about equal, (see section 3.3). When the real natural mortality rate is lower than 0.2, F_{max} will be the best of the two strategies because F_{med} will give a stock size which is too low. When the real natural mortality is much greater than 0.2, then F_{med} will be better than F_{max}.

3.6 Varying natural mortality in the VPA

In this section we will look at simulation where the natural mortality in the VPA computations varies. The real natural mortality rate in the simulation model is kept fixed (M=0.2). The state of nature is thus fixed, and we will see how the management strategies behave when using wrong natural mortality in the VPA computations.

Strategy	Stock	Mature	Catch	Recruit	F-value	VPA-M
F_{max}	4.2	2.42	0.33	0.73	0.19	0.1
F_{max}	2.9	1.20	0.49	0.76	0.24	0.2
F_{max}	1.8	0.43	0.47	0.69	0.36	0.3
F_{med}	2.7	1.06	0.47	0.76	0.36	0.1
F_{med}	2.7	1.07	0.49	0.77	0.27	0.2
F_{med}	2.4	0.84	0.51	0.77	0.23	0.3

Table 11: *Management by different M values in the VPA computations for cod.*

Simulations have been run for the strategies F_{max} and F_{med} with the M-values 0.1, 0.2 and 0.3 in the VPA computations. The results are shown in table 11.

The results show that the F_{med} strategy gives about the same results for stock and catch when the M-value in the VPA varies. The wrong VPA stock estimates are compensated by choice of F-values in the opposite direction.

F_{max} gives very different results for the stock size, because the F-value increases when the natural mortality increases. When the M-value 0.1 is used, the stock size is very high (4.2 mill.ton), and the catch is much lower than when M is equal to 0.2. When the M-value is set to 0.3, the mean stock size is reduced to 1.8, while the mean catch is slightly lower than when M is equal to 0.2.

3.7 Cod management with overfishing

In cod management the size of the stock is not known. The fishing mortality (F-value) will be computed from the tuning algorithm based on survey data. The stock size is computed from the reported catch, natural and fishing mortality. The reported catch is usually equal to the quota, but the quota may be overfished. Therefore the total catch may be greater than the reported catch. Figure 9 shows a simulation with 40 per cent overfishing. In this figure, overfishing is equal in all length groups, and is included in the catch curve.

The VPA procedure manages the simulation by reducing the quota. The mean value of the catch and the model stock size will be about the same as in the reference simulation. The reason why the procedure behaves this way is that the VPA stock estimate will be lower than the model stock size.

Strategy	Stock	VPA stock	Catch	Quota	F-value	Overfishing
F_{max}	2.9	1.19	0.49	0.49	0.24	0
F_{max}	2.8	1.12	0.48	0.34	0.24	40
F_{med}	2.7	1.07	0.49	0.49	0.27	0
F_{med}	2.7	1.10	0.47	0.34	0.27	40

Table 12: *Cod management with overfishing*

But if there is a sudden strong increase in the underreporting, the stock size will decrease the first years, before the management procedure begins to reduce the quota.

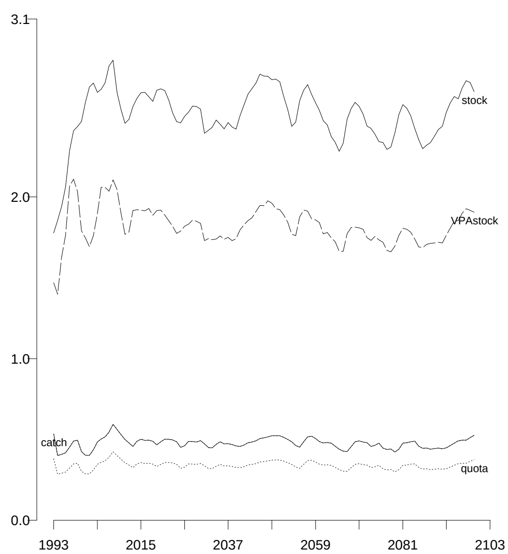


Figure 9: *Simulation with strategy F_{max} for cod, with 40% overfishing.*

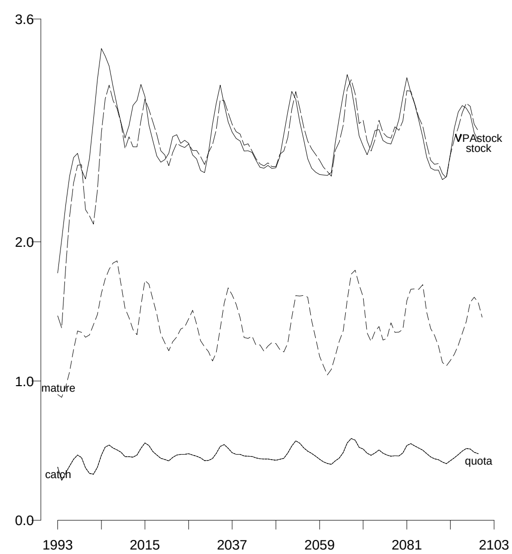


Figure 10: *Simulation with strategy F_{max} for cod, and lower catch limit 35cm.*

Table 12 gives the results for the strategies F_{max} and F_{med}. The mean stock size and catch are about the same when overfishing, but the quota or the reported catch is much lower when overfishing. The VPA estimates of the stock are too low in the simulations with overfishing.

3.8 Different selection patterns

In the reference simulation no catch is allowed when length of cod is lower than 45 cm. Cod with length greater than 55 cm has the same fishing mortality, while length group 45-55 cm has intermediate fishing mortality. This pattern and the fishing mortality coefficient

(F-value) determine a selection pattern.

Strategy	Stock	Mature	Catch	Recruit	F-value	limit
F_{max}	3.0	1.40	0.47	0.80	0.19	35 cm
F_{max}	2.9	1.19	0.49	0.76	0.24	45 cm
F_{med}	2.7	1.14	0.46	0.80	0.22	35 cm
F_{med}	2.7	1.07	0.49	0.77	0.27	45 cm

Table 13: *Varying lowest allowable catch limit in cod management.*

In some simulations the lowest allowable length is set to 35 cm, and table 13 shows the results. The mean catch are lower (0.02-0.03 mill.ton) when the length limit is lowered 10 cm, but the mean stock size are about the same. The mature stock are higher and the immature lower. The main reason for the lower catch is that the changed selection pattern gives lower F-values when the quota is computed. The higher fishing mortality on the young cod is compensated by a greater mature stock and a higher recruitment.

To reduce the lowest allowable length will reduce the mean catch and will not give a better result.

3.9 Management of herring

In the management of herring the strategy F_p is used. In the probing simulations the values of p are 0.1 and 0.3. The recruitment of herring shows great fluctuations. Approximately every tenth year the recruitment is extremely high compared to most of the other years. The number of years between high recruitment is stochastic. In this way the number of years with high herring recruitment may vary in the simulations, and therefore the resulting mean stock and mean catch will vary.

In table 14 some results are shown. The simulations presented there are single simulations, and with average results. Due to the varying recruitment, results from single simulations may vary substantially, as explained above. When simulations are run with the strategy $F_{0.1}$, the mean size of the stock is 4.2 mill.ton, and the mean catch is 0.48 mill.ton. The result may however vary from simulation to simulation. When the strategy $F_{0.3}$ is used, the mean stock size is 6.2 mill.ton, and the mean catch is 0.44 mill.ton. The strategy $F_{0.1}$ seems to give a better catch than $F_{0.3}$, but the stock size is much lower.

When using the strategy $F_{0.1}$ the catch varies from 0.20 to 1.26 mill.ton. This reflects the variations in the recruitment. To reduce the yearly fluctuation in the catch, the strategy could be modified by introducing an upper catch limit of 0.6 mill.ton. The results from the simulations with this catch limit are shown in table 15.

The upper catch limit has a positive effect for the strategy $F_{0.1}$. The mean stock size is 4.7 mill.ton, and the mean catch is 0.50 mill.ton. The mean stock size becomes higher when

Strategy	Total stock	Mature stock	Catch Mean	Catch Min	Catch Max	F-value
$F_{0.1}$	4.2	1.9	0.48	0.20	1.26	0.19
$F_{0.3}$	6.2	3.4	0.44	0.17	0.83	0.11

Table 14: *Herring Management (all numbers in mill.ton).*

Strategy	Upper catch limit	Spawning stock limit	Total stock	Mature stock	Catch Mean	Catch Min	Catch Max
$F_{0.1}$	0.6	None	4.7	2.3	0.50	0.27	0.60
$F_{0.3}$	0.6	None	6.0	3.3	0.42	0.17	0.60
$F_{0.1}$	0.6	2.5	6.4	3.6	0.41	0.04	0.60
$F_{0.3}$	0.6	2.5	6.2	3.5	0.36	0.04	0.60

Table 15: *Herring Management with restrictions (all numbers in mill.ton)*

introducing a catch limit of 0.6 mill.ton and has no negative effect on the catch.

When using the strategy $F_{0.3}$ an upper catch limit of 0.6 mill.ton has no effect. Without an upper catch limit in $F_{0.3}$-simulations over a period of 100 years, the maximum catch is about 0.8 mill.ton. In addition, there is only a few years when the catch exceeds 0.6 mill.ton.

Another restriction that has been discussed, is to set the quota very low when the spawning stock biomass is below a limit (2.5 mill.ton). This improves the mean stock size and the mature biomass, but the mean catch gets lower. The fluctuations in the catch are greater.

The herring simulations seem to indicate that the best strategy is $F_{0.1}$ with an upper catch limit of 0.6 mill.ton. An example of a simulation with this strategy is shown in figure 11. Figure 12 shows a simulation with $F_{0.1}$, but without catch limit. The figure shows that the quota varies more than in the simulation with upper catch limit.

3.10 Management of herring with overfishing

In the herring management the correct stock size and the total mortality are supposed to be known. The fishing mortality (F-value) is computed from the reported catch, and no tuning routine is used. The natural mortality is computed as the difference between total mortality and fishing mortality. The fishing mortality which is not reported, will therefore be included in the natural mortality. Managing the herring when overfishing the quota is therefore the same as managing the herring with a higher natural mortality.

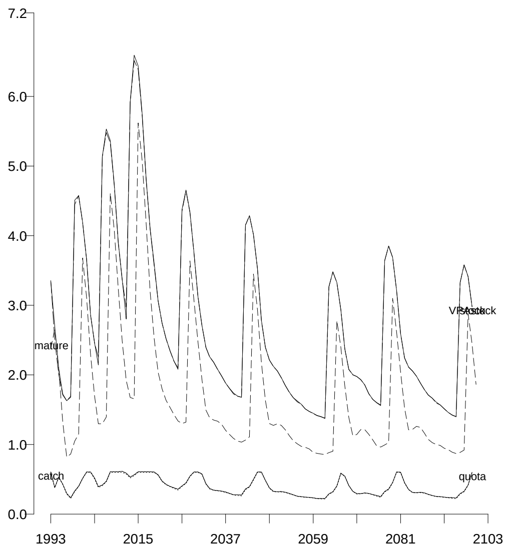


Figure 11: *Strategy $F_{0.1}$ for herring, upper catch limit 0.6 mill.ton.*

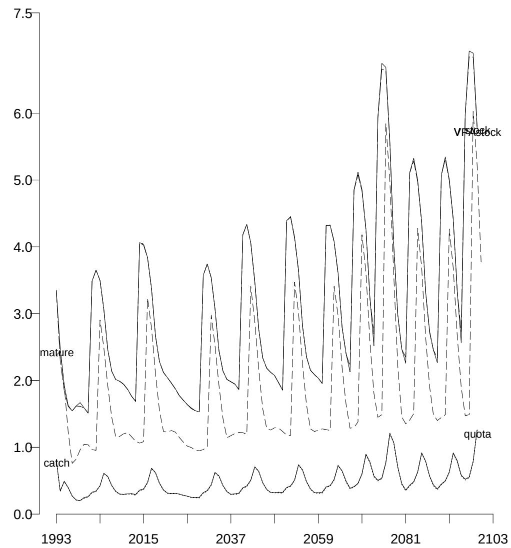


Figure 12: *Strategy $F_{0.1}$ for herring, no upper catch limit.*

Strategy	Upper catch limit	Total stock	Mature stock	Catch			
				Total	Quota	Min	Max
$F_{0.1}$	None	3.3	1.3	0.50	0.36	0.18	1.28
$F_{0.3}$	None	4.7	2.3	0.47	0.34	0.23	1.11
$F_{0.1}$	0.6	3.2	1.3	0.47	0.34	0.14	0.85
$F_{0.3}$	0.6	4.7	2.3	0.46	0.33	0.19	0.86
$F_{0.1}$	0.43	3.7	1.7	0.46	0.33	0.16	0.62
$F_{0.3}$	0.43	5.5	2.8	0.49	0.35	0.19	0.62

Table 16: *Herring Management with 40 % overfishing*

Table 16 shows the results from simulations where the quota is overfished with 40 %. In the results from the simulations the mean value of the total catch is always 40 % greater than the quota.

The result shows that the mean catch has about the same value as in the simulation without overfishing, but the stock is much lower. An upper catch limit of 0.6 mill.ton has no effect in the simulations, but an upper catch limit of about 0.43 mill.ton works better. The simulations then give higher stock, and the mean catch is about the same.

3.11 Management of capelin

The capelin procedure is not based on VPA computations, but uses the CapTool method[2]. Quota is only set for the mature stock in the winter fishery. Since the mature stock dies after the spawning, the fishery has only effect on the recruitment and the predation in other species. An autumn fishery on the immature capelin would have greater dynamic impact on capelin.

The regulation condition is to maintain the spawning stock at a given size which usually is 0.5 mill.ton. Some simulations have been made where the size of the mature stock has been varied. There has also been run a simulation with a minimum quota of 0.1 mill.ton. The results are shown in table 17.

Mature stock limit	Minimum quota	Stock	Spawning mort.	Catch	Years with low catch
0.5	None	3.2	0.43	1.0	40
0.5	0.1	2.9	0.35	1.0	40
0.1	None	2.8	0.10	1.0	50

Table 17: *Capelin management, mean values from 100 years.*

The effect of varying the management criteria is rather small. When simulating with a minimum quota, the mean stock stock size is reduced by 0.3 mill.ton, but the mean catch is about the same. When the mature stock limit is set to 0.1 mill.ton, the stock is reduced, and the mean catch is the same. The number of years with low catch is however increased. In both cases the mean quota is higher than the mean catch. Some years it is not possible to reach the quota.

The effect of varying the management criteria is small. The main reason for this is that the dependence between the size of the spawning stock and the recruitment is weak. The halfvalue in the Beverton-Holt function is supposed to be low, and a small spawning stock may give a great recruitment when the environments are good.

Figure 13 shows the fluctuations in the stock and the catch during a simulation with mature stock limit 0.5, and no minimum quota.

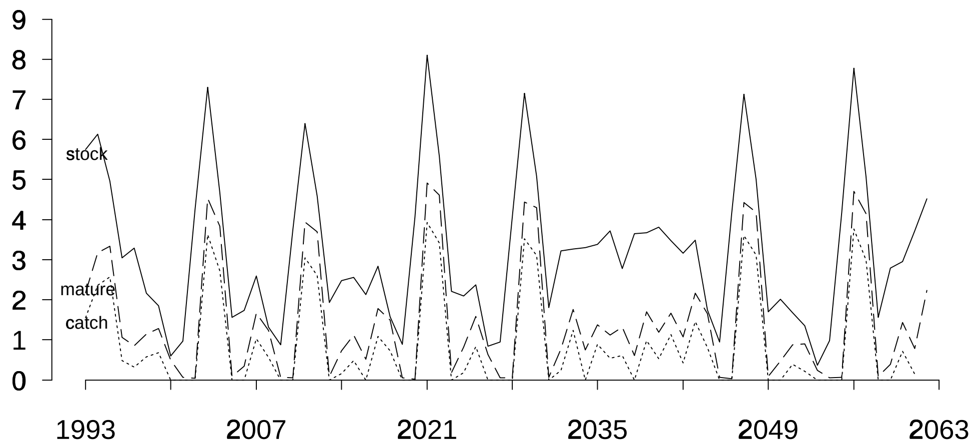


Figure 13: *Capelin, CapTool management.*

4 Uncertainty scenarios

In addition to probing scenarios, a set of uncertainty scenarios will be simulated. The uncertainty scenarios aims at spanning a plausible region in the state space, and their purpose is to obtain an understanding of robustness and efficiency of management procedures when uncertainty in knowledge is taken into account. The variation in performance measures over scenarios will, in fact, be informative with respect to issues of robustness (the likelihood of severely depleting the ecosystem) and efficiency (the mean performance in scenarios central in the plausibility region). Probing scenarios will, to some degree, give basis for hypotheses to be tested by appropriate designed uncertainty scenarios. Uncertainty scenarios are designed in co-operation with a reference group of experts.

4.1 Experimental factors

In this uncertainty experiment we will differ between three kinds of experimental factors:

1. Biological factors, like recruitment.
2. "Human" factors with consequences in management, like overfishing.
3. The management strategies.

In the simulation experiment the first two groups of factors will be defined binary, while management strategies not necessarily are so. In this section the experimental factors are described, and in the next section the whole experimental design is outlined.

4.1.1 Biological factors

In the present system of uncertainty scenarios, only recruitment-related factors are included. Recruitment is modeled according to Beverton-Holt-functions subjected to stochastic vari-

Factor	Abbr.	Reference level	Alternative level
Level of recruitment cod	RCOD	MAXR = 1.02(1.74) bill. H = 0.18 mill. t	MAXR = 0.77(1.31) bill. H = 0.14 mill. t
Level of recruitment herring	RHER	MAXR = 26.52(280.63) bill. H = 1.29 mill. t	MAXR = 19.89(210.47) bill. H = 0.97 mill. t
Variation in recruitment cod	VCOD	σ_{cod} = 1.75 bill.	σ_{cod} = 3.5 bill.
Variation in recruitment herring	VHER	$\sigma_{herring}$ = 3.0 bill.	$\sigma_{herring}$ = 6.0 bill.
Variation in recruitment capelin	VCAP	$\sigma_{capelin}$ = 200 bill.	$\sigma_{capelin}$ = 400 bill.

Table 18: *Table summarizing the biological factors. MAXR and H are the parameters in the Beverton-Holt-function (Maximum level and half-value, respectively), while $\sigma_{species}$ is the standard deviation in the distribution giving the stochastic variation in recruitment. The numbers in parenthesis are the values in years of extreme recruitment.*

ation. The "level of recruitment " is given by the actual function value, while the "variation of recruitment" is given by the variance (standard deviation) in the distributions giving the stochastic variation. We have chosen 5 recruitment-related factors, one capelin-factor (recruitment variation) and two herring- and cod-factors (both level and variation). All these factors are binary, and are summarized in table 18.

4.1.2 "Human" factors

With the name "human" factors, we mean all factors that are not biological, except the management strategies. Factors that are not biological do have a human touch, in one way or another, and that explains the name. In this simulation experiment we have only defined "human" factors that directly involves the cod stock, and more specific the factors includes fishery, research surveys and VPA about the cod stock. Table 19 presents a summary of these factors, and we will also give a closer description below.

VPA
When running the VPA-program to estimate the cod stock, the natural mortality rate M is looked upon as a known constant. In our simulations the true natural mortality rate is set to M=0.2, as this is the most commonly used value. When running the VPA in the simulations, we define the VPA-value of M to be an experimental factor. The reference level will be the ideal situation where the VPA-constant matches the real mortality exactly, and the alternative level will be a situation where the two values differ.

Research surveys
Each year, Norway and Russia have research surveys in the Barents Sea, and data from these surveys are (among other things) input to the VPA. We have modeled 5 sets of sur-

vey data, meant to describe the cod stock at different seasons. The data are indices for the age groups 3-7, and in these simulations the total index for each survey is a linear function of the total cod stock subjected to some noise ($I = a \cdot B$, B total stock number in unit 1000). The function parameter are specific for each survey, and so is the standard deviation in the noise distribution. The age distribution is, however, correct in all simulations. The standard deviation is modeled $\sigma_{survey} = k \cdot s_{survey}$, with k being a common factor to all the surveys. We have defined this k-value to be an experimental factor, with $k = 0$ as reference level. This is identical to the survey indices being generated without noise. The following parameter values are a result from analyzing VPA-data and historical survey indices [10], and are used in the simulations (unit of standard deviation is 1000):

Survey:	1	2	3	4	5
a	0.00015	0.00025	0.00010	0.00020	0.00050
σ_{survey}	50	200	50	25	300

Fishery

The cod fishery is divided into 6 independent fisheries (fleets). First the total quota is distributed to 3 national groups: Norway (45%), Russia (45%) and other nations (10%). Then the Norwegian quota is distributed to 4 groups of fishing gears: trawl (27%), net (37%), hand line (18%) and seine (18%). Each fishery has its own selection pattern, and there are individual tendencies to overfishing and discards. The length distributed selection patterns are roughly computed from age distributed patterns and age-length distributions. Both the distribution of quotas and the individual selection patterns are constant through all simulations, while the amount of overfishing and discards are defined as experimental factors, together with the age distribution of the reported catches. The amount of overfishing is set to a percentage of the legal quota. With discard is meant that all fish under a lower length are dumped, and sufficient catch is taken to fill the quota with fish of legal size. When there is discard, this strategy is followed throughout the cod fishery. If there also is overfishing, the discard strategy is followed for the overfished quantity. The age reporting has consequences primarily to the VPA-estimation of the cod stock, where age distributed catches are the main data. At reference level there is correct age reporting, but at the alternative level the old age groups are overreported (-estimated) at the expense of the young ones. The skewness in age reporting is constant (a constant percentage of the true catch in each age group), but roughly computed so that the total reported biomass will be approximately correct. The following percentages are used when age-reporting is on alternative level:

Age	3	4	5	6	7	8-12	13+
Reported %	9.5	1.7	1.7	45.5	105	110	100

4.1.3 Management strategies

In the uncertainty scenarios the total management strategy will be a combination of 3 single-species strategies. We define each such strategy to be an experimental factor. The capelin strategy is based on a spawning target, and the experimental factor has 2 levels.

Factor	Abbr.	Reference level	Alternative level
Natural mortality rate (in VPA)	M	M=0.2 (true value)	M=0.1 (underestimating)
Survey indices, noise	I	k=0 (no noise)	k=1
Overfishing	O	No overfishing	Norwegian and Russian 50% Other nations 200%
Discards	U	No discards	Discard of cod less than 47 cm
Age reporting of catches	A	Correct	Young fish under-reported Old fish over-reported

Table 19: *A summary of the "human" experimental factors. All factors include only the cod stock (fishery). See section 4.1.2 for a closer description of the factors.*

	Management strategy		
	Capelin	Herring	Cod
Reference level	500000 tons	$F_{0.3}$	F_{med}
Alternative 1	100000 tons	F = 0.12	F_{high}
Alternative 2	–	F = 0.20	F_{low}
Alternative 3	–	–	F_{max}
Alternative 4	–	–	F=0.26

Table 20: *A summary of the management strategies. The capelin strategy gives the spawning stock target, while the herring and cod strategies give the fishing mortality F.*

Both the cod and the herring strategy is based on VPA-estimates for the stock, and these experimental factors have 3 and 5 levels, respectively. The herring strategy is either a constant fishing mortality or based on the yield-per-recruit function. The cod strategy might in addition to those two, be based on the spawning biomass per recruit function. Both strategies based on the yield-per-recruit function and strategies based on spawning biomass per recruit are updated yearly during the simulations. Table 20 gives a summary of all three management factors.

4.2 Experiment design

The 13 factors described above are combined in the system of uncertainty simulations. Since the number of combinations is too high, combinatorial methods of experimental design[4] are used to find a system of balanced combinations of managable size. When defining the experiment design, we will make a distinction between the management strategies on the one hand, and the remaining factors on the other. The last group consists of 10 binary factors, and for these we will make a design set with the following combination:

1. One scenario with all factors on reference level.
2. 10 scenarios with only one factor on alternative level.
3. A 2^{10-5} fractional factorial design.

This gives a total of 43 different scenarios to simulate. In the management strategy group there are only 30 possible combinations. These 30 combinations, plus a random sample of 13 from the 30 (to make a total of 43), has been randomly combined with the 43 "binary combinations". The result is given in table 21. All scenarios will be simulated with at least 3 replicates.

4.3 Results

The 43 uncertainty scenarios are currently being simulated. This takes considerable computer time (minutes each 75-300, machine dependent), and we expect the simulations to be ready for analysis by April 1995.

	Binary factors										**Management**		
	RCOD	RHER	VCOD	VHER	VCAP	M	O	U	I	A	SCAP	SHER	SCOD
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	4
3	0	1	0	0	0	0	0	0	0	0	0	2	3
4	0	0	1	0	0	0	0	0	0	0	1	0	4
5	0	0	0	1	0	0	0	0	0	0	0	1	4
6	0	0	0	0	1	0	0	0	0	0	1	2	3
7	0	0	0	0	0	1	0	0	0	0	1	1	4
8	0	0	0	0	0	0	1	0	0	0	0	2	4
9	0	0	0	0	0	0	0	1	0	0	1	2	4
10	0	0	0	0	0	0	0	0	1	0	1	1	0
11	0	0	0	0	0	0	0	0	0	1	0	2	0
12	0	0	0	0	0	1	1	1	1	1	1	0	1
13	0	0	0	0	1	1	1	1	0	0	1	2	0
14	0	0	0	1	0	1	1	0	1	0	0	1	1
15	0	0	0	1	1	1	1	0	0	1	0	2	1
16	0	0	1	0	0	1	0	1	1	1	1	0	2
17	0	0	1	0	1	1	0	1	0	0	0	1	2
18	0	0	1	1	0	1	0	0	1	0	0	0	3
19	0	0	1	1	1	1	0	0	0	1	0	2	2
20	0	1	0	0	0	0	1	1	1	1	0	1	4
21	0	1	0	0	1	0	1	1	0	0	1	1	4
22	0	1	0	1	0	0	1	0	1	0	0	2	4
23	0	1	0	1	1	0	1	0	0	1	1	0	0
24	0	1	1	0	0	0	0	1	1	1	0	1	0
25	0	1	1	0	1	0	0	1	0	0	0	0	1
26	0	1	1	1	0	0	0	0	1	0	1	1	0
27	0	1	1	1	1	0	0	0	0	1	0	2	0
28	1	0	0	0	0	0	0	0	0	1	1	0	1
29	1	0	0	0	1	0	0	0	1	0	1	2	0
30	1	0	0	1	0	0	0	1	0	0	0	1	1
31	1	0	0	1	1	0	0	1	1	1	1	1	1
32	1	0	1	0	0	0	1	0	0	1	0	0	2
33	1	0	1	0	1	0	1	0	1	0	0	2	1
34	1	0	1	1	0	0	1	1	0	0	1	0	2
35	1	0	1	1	1	0	1	1	1	1	1	2	1
36	1	1	0	0	0	1	0	0	0	1	0	1	2
37	1	1	0	0	1	1	0	0	1	0	1	1	2
38	1	1	0	1	0	1	0	1	0	0	0	0	3
39	1	1	0	1	1	1	0	1	1	1	0	2	2
40	1	1	1	0	0	1	1	0	0	1	1	0	3
41	1	1	1	0	1	1	1	0	1	0	1	2	2
42	1	1	1	1	0	1	1	1	0	0	0	1	3
43	1	1	1	1	1	1	1	1	1	1	1	1	3

Table 21: *A table summarising all scenarios to simulate. 0 means that the factor is on reference level, while a positive integer gives the alternative level.*

A Predation and growth for cod

The predation model is developed for cod predating on capelin, herring and young cod. Modelling is done in three steps. First total stomach content is made dependent on relative abundance of the various stock components. Then the distribution of stomach content is made dependent on the same relative abundance vector. Finally relative and total stomach contents are converted to realized predation. A more detailed description of data, analysis and resulting model is found in [7].

Data

We have used half yearly data from 1984-1992. Stomach data for cod and stock data for capelin, herring and cod have been used in the analysis. Since 1-2 year old cod is a potential prey for older cod, and 1 and 2 year old cod have different predation pattern, the stock of cod is divided in three components. Capelin is also subdivided in 3 components. The stock structure is then

CAP_1	% number of immature capelin which is shorter than 10 cm
CAP_2	% number of immature capelin which is greater than 10 cm
CAP_3	% number of mature capelin
HER	% number of herring
COD_1	% number of 1 year cod
COD_2	% number of 2 year cod
COD_3	% number of cod which is 3 year or more

The abundance vector is recorded in relative units, where the percentage is relative to the total number of fish.

Stomach fill

Stomach fill for cod 3-9 years, R_3, is assumed dependent on relative stock abundance and season (H=0 for 1. halfyear, H=1 for 2. halfyear).

$$\begin{aligned} R_3 = \ & A_0 + A_1 \cdot log(CAP_1) + A_2 \cdot log(CAP_2) + \\ & A_3 \cdot (1 - H) \cdot log(CAP_3) + A_4 \cdot log(HER) + \\ & A_5 \cdot log(COD_1) + A_6 \cdot (1 - H) \cdot log(COD_1) + \\ & A_7 \cdot log(COD_2) + A_8 \cdot log(COD_3) \end{aligned}$$

Stomach fill is here measured as the ratio weight of total stomach to the weight of the cod. The parameters of this model are estimated by linear regression ($R^2 = 0.73$). Observed and predicted stomach fill (%) is shown in figure 14.

Stomach fill for cod 1-2 years is assumed to follow the same model and estimated by linear regression ($R^2 = 0.56$).

Figure 14: *Stomach content of 3-9 årig cod, observed and estimated values.*

Stomach composition

Stomach content is decomposed in 6 groups:

$PCAP_1$	capelin shorter than 10 cm
$PCAP_2$	capelin greater than 10 cm
$PCAP_3$	mature capelin
$PHER$	herring
$PCOD_1$	1 year cod
$PCOD_2$	2 year cod

The components are measured in relative units (% of total). Let P be any one of these prey components. Then P is modelled as

$$\begin{aligned} P = \; & A_0 + A_1 \cdot log(CAP_1) + A_2 \cdot log(CAP_2) + \\ & A_3 \cdot (1 - H) \cdot log(CAP_3) + A_4 \cdot log(HER) + \\ & A_5 \cdot log(COD_1) + A_6 \cdot (1 - H) \cdot log(COD_1) + \\ & A_7 \cdot log(COD_2) + A_8 \cdot log(COD_3) \end{aligned}$$

The coefficients are estimated separately for each components, without ensuring that the components sum to the total. In the simulation model negative predicted percentages are replaced by 0, and the resulting sum is scaled to 100

Predation mortality

Predicted stomach fill and stomach composition are converted to consumed total according to Santos 1990 [17] and an unpublished article of Santos of 1994:

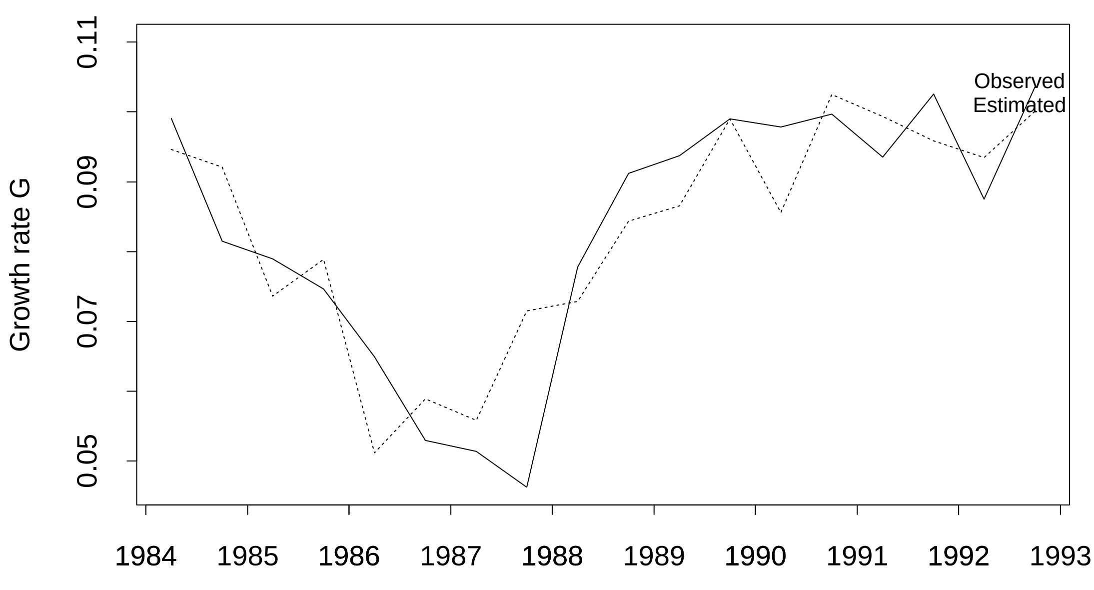
$$C_i = \frac{ln2 \cdot S_i \cdot e^{0.13 \cdot T} \cdot B^{0.26}}{\alpha_i \cdot S_0^{0.52}}$$

C_i	is the weight of the consumption of prey species i
T	is the temperature
B	is the weight of cod
S_i	is the relative stomach content of prey component i
S_0	is the stomach fill
α_i	is a prey specific constant which indicates the halfvalue time for prey species i

The consumed totals are subtracted from the various stock components as predation mortality.

Individual growth

Figure 15: *Observed and estimated values for the cod growth model*



Individual cod is assumed to grow in length according to a linear function of the relative abundance vector (CAP_2 includes both immature and mature capelin):

$$G = A_0 + A_1 \cdot COD_1 + A_2 \cdot COD_2 + A_3 \cdot COD_3 + A_4 \cdot CAP_1 + A_5 \cdot CAP_2 + A_6 \cdot HER$$

The growth rate G is defined by

$G = (L_{t+T} - L_t)/(L_\infty - L_t)$

L_t denotes the cod length at time t, T denotes the interval length, and L_∞ is the maximal length of the cod. In the computations L_∞ is supposed to be 160 cm.

The model is fitted by linear regression separately for each of the first 6 age classes of cod. Observed and predicted aggregated linear growth is shown in figure 15.

References

[1] von Bertalanffy, L. (1938). *A quantitative theory of organic growth.* Hum.Biol. (10)2: 181-213.

[2] Bogstad, B., Gjøsæther, H., Tjelmeland S. (1992) *CapTool – a versatile aid in Barents Sea capelin catch quota options calculation* Working document to the 1992 meeting of the ICES Atlanto-Scandian Herring and Capelin Working Group.

[3] Bogstad, B. and Tjelmeland, S. (1993) *A method for estimating predation mortalities on capelin using a cod-capelin model for the Barents Sea.* Unpublished manuscript.

[4] Box, G.E.; Hunter, W.G.; Hunter, S. (1978) *Statistics for Experimenters.* J. Wiley& Sons, New York

[5] Hagen, Gro; Hatlebakk, Einar; Schweder, Tore; (1994) *SCENARIO BARENTS SEA A tool for evaluating Fisheries Management regimes* NR-note STAT/07/1994.

[6] Hagen, Gro; Hatlebakk, Einar; Schweder, Tore; (1994) *SCENARIO BARENTSHAV: Simuleringsresultater (1)* (in Norwegian) NR-note STAT/08/1994

[7] Hagen, Gro; Hatlebakk, Einar; Schweder, Tore; (1995) *SCENARIO BARENTSHAV, Predasjonsmodell* (in norwegian) NR-note STAT/02/1995

[8] Hilborn, R. (1992). *Current and future trends in fisheries stock assessment and management* S.Afr.J.mar.Sci. 12: 975-988

[9] Hylen, Arvid; Nakken, Odd; Sunnanå, Knut (1986). *The use of acoustic and bottom trawl surveys in the assessment of north-east arctic cod and haddoc stocks* M.Alton (ed) A workshop on comparative biology, assessment and management of gadids from the North Pacific and Atlantic oceans; Northwest and Alaska Fisheries Center, Seattle, 1986.

[10] ICES. *Report of the Arctic Fisheries Working Group* Copenhagen 1993

[11] IWC (1993) Report of the Scientific Committee, *Rep. Int. Whal. Commn 43,* 57-64

[12] Jakobsen, T. (1992). *Biological reference points for North-East Atlantic cod and haddock* ICES J.mar.Sci., 49: 155-166.

[13] Laurec, A. and Shepherd, J.G. (1983). *On the analysis of catch an effort data.* J. Cons. int. Explor. Mer, 41: 81-84

[14] Pope,J.G. and Shepherd,J.G. (1982).
A simple method for the consistent interpretation of catch-at-age data.
J. Cons. int. Explor. Mer, 40 176-184

[15] Pope,J.G. and Shepherd, J.G. (1985). *A comparison of the performance of various methods for tuning VPAs using effort data.*
J. Cons. int. Explor. Mer, 42: 129-151

[16] Raftery, S.E. and Zeh, J.E. (1993) Estimation of Bowhead Whale, *Balaena mysticetus,* Population size.*in* Gatsonis, C., Hodges, J.S., Kass, R.E. and Singpurwalla, N.D. (Eds) *Case Studies in Bayesian Statistics. Lecture notes in Statistics no 83,* Springer-Verlag.

[17] Santos dos Jorge. (1990). *A model to describe gastric evacuation in cod, Gadhus morhua, fed natural prey.* ICES Journal. mar. Sci.