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Evaluation of candidate management plans, with reference to North-East Arctic Cod

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Abstract
We here discuss the scope, nature and quality standards of simulation models that may be used in order to evaluate proposed or candidate management plans, including their parameters (reference points). A recently proposed management plan for North-East Arctic cod is used as a working example.

We discuss some generic designs of management plans, in particular with respect to performance in relation to different kinds of objectives, including adherence to the precautionary approach. We further discuss simulation tools to evaluate the performance of management plans and to select appropriate values for their key parameters, and suggest some quality criteria for such tools. In particular, we stress the need to have unbiased stochastic parameters and to have realistic levels of errors in the basis for future decisions according to the plan.

A new management plan for North-East Arctic cod (*Gadus morhua*) was agreed by the management agency (Joint Norwegian/Russian Fishery Commission) in 2002. The main elements in this plan are:

- Estimate the average TAC-level for the 3 following years based on F_{pa}. TAC for the following year is set on the basis of this average TAC level.
- The following year the estimation of the TAC-level for the next 3 years is repeated based on updated information on stock development. However, the change of TAC from one year to the next cannot be more than +/-10%.

This relatively complex plan is used as an example, and aspects that need to be considered in order to evaluate how it can be expected to perform, are discussed.

1. Introduction

It has become increasingly clear that management of fish stocks by setting quotas from year to year on the basis of annual assessments of the stock, as has been common practise in the ICES area for the last decades, often has been unsuccessful, leading to sudden ‘crises’ and emergency measures, as well as unpredictable fluctuations in the catches and catch opportunities. Further, there has been an increasing awareness that year-to-year TAC setting seriously hampers long-time planning within the fishing industry.

In recent years, managers in many areas have suggested, and in some cases implemented, more or less detailed pre-agreed plans for how the fishery shall adapt to the state of the stock. Examples in the ICES area include North Sea herring (*Clupea harengus*) (Anon., 1997; ICES 1999a), Norwegian Spring Spawning herring (Bogstad *et al.*, 2000; Røttingen, 2003). Both Iceland and the Faeroe Islands have such arrangements for their domestic stocks (Jakobsson and Stefánsson, 1998; ICES 1998). Ideas of similar arrangements (termed multi-annual TAC arrangements in the EC terminology) are being considered in the European Community in connection with the revision of the common fisheries policy (Commission of the European Communities 2000, 2001)

Management plans should ideally include all aspects of the management of fisheries in an area (FAO, 2002), and include both management objectives and how these are to be achieved. Biological science can only cover parts of this range, but biological science will have the responsibility to inform on how compatible objectives are with proposed ways to achieve them, within the constraints set by biological reality. The requirement of sustainability and of being risk aversive, inherent in the precautionary approach to fisheries management (FAO 1995) will to most managers represent constraints to the freedom in the design of management plans.

Management plans can be of variable complexity, but generally have elements to restrict (directly or indirectly) the fishing mortality to an optimal (by some criteria) sustainable level, measures to rebuild the stock if it becomes smaller than acceptable, and often measures to avoid large fluctuations in the annual catches. The tools to implement these elements vary, and include TACs, effort control, constraints on fishing gears, area and seasonal closures etc.

Biological science can contribute by evaluating to which extent a management plan can be expected to work when applied to the biological world. That requires that the plan is specified in such a way that once the state of the stock presumably is known, the level of exploitation can be derived. Such a specified decision rule is commonly termed a harvest control rule, e.g. by ICES (1999b). A harvest control rule can be evaluated by simulation. This may be done to evaluate already proposed plans, or in dialogue with managers when formulating plans, i.e. by evaluating the gains and losses in terms of amounts that can be caught, stability and risk-avoidance when attempting to reach different, sometimes conflicting objectives. In such evaluations, bio-economic models should be used to evaluate gains and losses. We will not discuss use of bio-economic models in the present paper. An overview of the state of the art of bio-economic advice on TAC in Norwegian fishery management is given by Sandberg *et al*. (1998).

The current advisory practise in ICES, as it mostly is interpreted by managers, represents a very simple harvest control rule: Recommend TACs in accordance with a constant $F = F_{pa}$ and the most recent estimate of stock abundance, unless the estimated SSB is below B_{pa}. If that happens, reduce F so that the predicted SSB comes above B_{pa} in a certain number of years. In some cases, e.g. for several demersal stocks in the North Sea, this rule has been adopted by managers as an agreed management plan (Anon, 1999).

Management plans that have been implemented have been successful to variable extent. Some management plans have been quite successful so far, like for several pelagic stocks in the ICES area. Others have not succeeded in preventing the stock from being reduced to unacceptable levels, they have been difficult to implement and enforce or they have had unwanted side effects.

According to 'The format of ICES advice' (ICES, 2002a), managers are 'invited to develop management strategies, and ICES will comment on these and consider if they are in accordance with the precautionary approach'. Thus, ICES should be prepared to evaluate proposed management plans.

However, to evaluate a candidate management plan is not straightforward. Even when the plan itself is simple, the complexity of nature and the uncertainty by which both the stock can be monitored and the regulations can be implemented makes it naive to rely on intuition and common sense. We therefore claim that before management plans are adopted, their performance needs to be properly tested by simulations to ensure, as far as possible, that they will work as intended with respect to the underlying management objectives, and that they will lead to a management that is compatible with the precautionary approach. This should preferably be done as part of the development process of such plans, in a dialogue between management and science. A powerful tool for such simulations is stochastic medium- and long-term predictions, where the harvest in each prediction year is decided according to the harvest control rule of the plan, and uncertainty in assessment as well as in implementation are accounted for.

We here discuss more specifically various kinds of harvest control rules and outline some advantages and disadvantages of different types, and what it takes for them to work properly. Furthermore, we discuss simulation tools, with special emphasis on quality control of the elements that go into such tools.

2. Generic types of harvest control rules

The simplest kinds of rules just aim at keeping something constant. This can be to keep the TAC fixed, to keep the fishing mortality fixed or to attempt to keep the spawning biomass fixed.

2.1. Fixed F regimes

Keeping the F fixed may be taken as the archetype of a simple control rule. It has the advantage that it corresponds to keeping the effort constant, and that the yield from the fishery fluctuates according to the stock abundance. If the main implementation tool is effort control, a fixed F regime is the natural rule to adopt. In a TAC regulated fishery, implementation of an F-based harvest control rule requires an estimate of the stock abundance in order to translate the F to a TAC.

The maximum long-term yield that can be achieved with a fixed F regime is quite close to the maximum yield that can be obtained by more adaptive regimes, at least for relatively long-lived species. Thus, more adaptive regimes should in general only be considered to reach other objectives than maximising long-term yield and stabilising effort.

2.2. Constant catch regimes

Regimes where the catch is kept fixed are sometimes considered. A very naive interpretation of the MSY concept is to adopt the MSY value as a standard yearly catch. However, since the recruitment always fluctuates and the MSY relates to mean recruitment, there will be periods where the MSY will lead to a higher fishing mortality than the optimum one, which again reduces the stock to less productive levels. More generally, if a constant catch regime shall be safeguarded against reducing the stock to unacceptable levels, the catch level must be set low enough to correspond to a sustainable F even in periods with the lowest likely recruitment. Thus, even though stability in the supplies of fish to the market is obtained, the price to pay is a relatively low yearly yield.

2.3. Attempting to keep SSB at a certain (often minimum sustainable) level

Such regimes are even more problematic, because even small reductions in recruitment will easily lead to large reductions or full stop in the fishery. The only case where this can be feasible are for short-lived species where only one or two year classes contribute both to the fishery and the spawning biomass, and the fishery will have to adapt to the annual fluctuations in recruitment anyway. This leads to a target escapement strategy, where the TACs are set to ensure that there is enough left to spawn, and the remaining maturing fish can be caught. Typical examples are capelin (*Mallotus villosus*) stocks (Gjøsæter *et al*., 2002; Gudmundsdottir and Vilhjalmsson, 2002).

These regimes are simple to simulate because the HCR is simple, and their properties are relatively well known.

2.4. Adaptive regimes

The regimes above can be extended and combined in various ways. In general, the motivation will be to achieve some additional objective.

If the purpose is to have a higher average yield, one may consider a higher fishing mortality than the one that implies a low risk with a fixed F, provided one is willing to reduce the fishing mortality if the stock becomes smaller than a trigger value. The reduction can be abrupt or gradual. A linear reduction in fishing mortality below a trigger level of SSB is currently being considered as a standard in the NAFO area (Serchuk *et al*., 1997). In the agreed management plan for Norwegian spring spawning herring the B_{pa} reference point for spawning stock biomass is used as a trigger point for a linear reduction in fishing mortality (Røttingen, 2003).

Some properties of such arrangements are well understood. The higher the F one wants at SSB above the trigger point, the higher will the trigger point have to be and the larger will the probability be that the trigger point is passed. This leads to less stable catches, but higher yield in periods with high productivity. In particular for stocks with a relatively short life span and large fluctuations in recruitment, such fluctuations in the annual fishing mortality and yield may be feasible. The overall gain may not be large compared to a fixed F regime.

Such adaptive regimes require parameters like levels of fishing mortality, levels of SSB where action is taken etc. These parameters are conceptually different from precautionary reference points, and need not have the same values. In particular, the *pa* reference points as used by ICES, which represent a safety margin to the limit points needed because of the assessment uncertainty, may not be the obvious trigger points in a harvest control rule. However, there needs to be a bottom line specifying at least a level of biomass, and perhaps also a fishing mortality, that shall be avoided with high probability. Then, for the rule to be in accordance with the precautionary approach, evaluation of the rule must demonstrate a low risk of passing these limits.

2.5. Catch stabilising regimes.

Several designs have been proposed recently that aim at stabilising the catches. These are basically fixed F rules, but with constraints on the year-to-year variations in the catches. The constraint can be that the catch in one year shall not deviate from that in the previous year by more than a certain percentage, or that the TAC shall be set for several years ahead and revised at longer than annual intervals. These regimes may lead to temporary increases in the fishing mortality and decrease in the stock below acceptable limits, which requires that the

TACs are low enough to avoid coming into a situation where drastic measures will be necessary. In a rebuilding situation, such regimes may delay recovery. On the other hand, when the stock is in a good condition, such constraints may be beneficial by preventing inappropriate increasing of TAC caused by uncertain assessments (ICES, 2002b). The last effect can also be obtained in another variant of a catch stabilization rule, introducing a combination of a maximum fishing mortality together with a catch ceiling, i. e. the catches are not allowed to exceed an agreed level even when this leads to a fishing mortality below the standard value.

In rebuilding situations, it is sometimes suggested to set the TAC so that the predicted SSB increases by a certain percentage from one year to the next. The performance of such rules has been studied to some extent, and the results are not convincingly promising (Anon., 2002).

3. Simulation tools

The tools discussed here are stochastic stock projection models. Such models consist of two main parts, an *operating model* which generates data for a known model stock, and a *management model* which is an implementation of the decision rule. There are links between the two models in both directions. The management model sees a distorted picture of the true model population as emerging from monitoring and assessing the stock and it generates management decisions according to the decision rule under study. The feedback to the operating model is what is actually removed from the stock, which is again distorted by implementation error.

This is illustrated schematically in Figure 1 below:

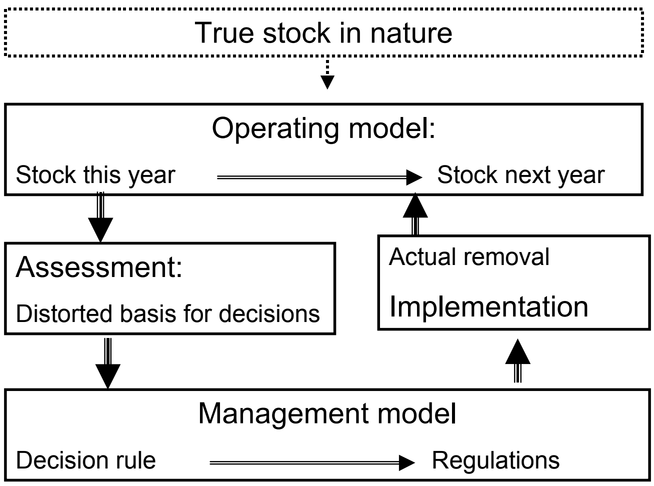

Figure 1. Simulation model overview

The model stock is the true population in the simulation context. If a certain stock in nature is under study, the model stock should have similar properties to that stock. However, it is the model stock that is actually subject to study, and the relevance of the inferences made depends on how well the model stock imitates the true stock in nature.

Many of the elements that go into this framework are not exactly known, but can be assumed to have certain statistical properties. Hence, they are modelled as stochastic terms. The whole model is operated as a Monte-Carlo simulation, where multiple runs are made with random values for the stochastic elements, and the uncertainty emerges as the variability between the runs. The time frame is may be the the medium term, e.g. about 10 years, or a long term stochastic equilibrium. The terminology for evaluation of harvest control rules by simulation is outlined e.g. in ICES (1997).

3.1. The operating model

This is a model of the evolution of a stock, by projecting the numbers by year class forwards according to given mortalities, and adding a new year class each year. As such, it describes an artificial population, and its usefulness in simulating a real population is conditional on its similarity with that population. We concentrate here on age-structured populations, where each year class constitutes a closed cohort. This is the common construction when there are data to assess the stock with an age structured assessment tool, but it is not the only possible population model. An outline is given in Figure 2 below:

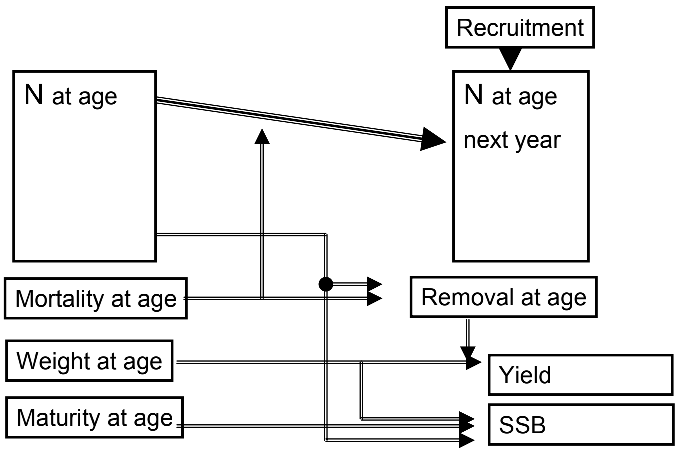

Figure 2. Operating model

The model is usually for a single species, but multispecies simulation tools also exist, and are relevant if there are interactions between the species in the model.

3.1.1. Elements of the operating model

Stock – recruitment relation: This commonly consists of a deterministic relation between spawning biomass (SSB) and the number of recruits, to which is added a stochastic term. The stochastic term accounts for the assumed inter-annual variation in the recruitment due to other factors than the SSB.

Mortality: Throughout each time step in the simulation, the number in each cohort is reduced from N_0 at the start of the time step to N_1 at the end of the time step according to a specified mortality $Z = log(N_0/N_1)$. The mortality Z is partitioned into additive components $Z = M + F$, where the number of fish removed by the fishery is represented with F while M accounts for all other removal.

Weight and maturity: Weights at age in the catch are needed to translate catches in number to catches in weight and vice versa. Weights at age in the stock and maturity at age is needed to derive the spawning stock biomass from the stock abundance in numbers. All these parameters tend to vary over time, and are commonly treated as random variables in the simulation.

Fishing pattern: The fishing mortality F is commonly described as a product of a selection at age and a year factor, the latter representing the intensity of the fishery. When simulating regimes where F is the prime target, common practise is to adjust the year factor to the desired level and assume that the selection is constant. If some of the regulations (minimum size, mesh size, closed areas, access to EEZs) are likely, or even intended, to influence the selection at age, some model for the selection needs to be included.

Initial numbers: The forward simulation starts with numbers representing the present state of the stock. These are normally taken from a recent assessment, and are as such uncertain. The initial number of the age groups in the stock which have not yet entered the fishery (e.g. age 0-2 for Northeast Arctic cod) will generally be calculated by different methods than the older age groups and be more uncertain. When evaluating the future development of the stock and risks of future events, the uncertainty in the initial stock number needs to be taken into account by treating the initial numbers at age as stochastic and as correlated. Several ways of doing this are possible, e.g. assuming a parametric distribution for each number, with parameters either assumed or estimated as part of the assessment process, or numbers emerging from a bootstrap run of the assessment model. Stochastic stock numbers in the terminal assessment year are correlated with the terminal fishing mortalities at age, so the selection at age may also have to be treated as stochastic.

3.1.2. The operating model vs. reality

In order to refer the inferences from simulation studies to a specific stock, great care needs to be taken to ensure that the operating model represents the actual stock properly. We here discuss some critical factors.

Recruitment

A representative stock-recruitment relationship is crucial to inferences about future management, since both future SSBs and yields are closely correlated to the mean recruitment, being weighted means of previous recruitments. The stock-recruitment function should be able to reproduce unbiased sequences of recruitments for the history of the stock, given spawning biomasses at historical levels.

If a stock-recruitment function is used, one should make sure that it is unbiased at all levels of SSB. This will not be the case if the stock-recruitment function is inadequate, which may easily happen if some standard function is used uncritically, or if the distributional properties of the residuals are mis-specified.

The source of information about the stock-recruitment relation will typically be stock-recruit pairs from historical assessments. When the year-to-year variation is large compared to the effect of SSB, the number of pairs is small or the range of SSB-values is narrow, single years' recruitment may heavily influence the estimates of the parameters of the function. Also, the parameters of the stock-recruit function can be quite strongly correlated. It should be noted that for the Ricker function in particular, estimates of recruitment at low SSBs may be heavily influenced by the level of recruitment at very high SSB. The result is a fair risk that the function will not be representative at the extremes of the SSB-range, even though it captures the recruitment over the central parts of the range quite well. In e.g. a recovery situation, where the SSB is low, this may lead to quite misleading advice.

An additional problem is the distribution of error around the function. Quite often, a log-normal distribution is assumed, but it should be controlled that this distribution is actually representative. Alternatively, residuals (mostly on a log scale) are drawn randomly, which causes problems if the distribution is dependent on the SSB, e.g. because the variance is higher at low SSBs.

Finally, there may be trends in the recruitment due to long term fluctuations in the production conditions for the stock. Such trends may be visible in a long enough time series. For example, for the North Sea herring, the recruitment in the early 1980s was abnormally successful. For quite a number of stocks, very good year classes appear with almost regular intervals, e.g. for Norwegian Spring Spawning herring where the intervals are 8-10 years. To what extent such fluctuations shall be assumed for the future, is an open question.

Weight and maturity at age
Weights and maturities can also fluctuate, and failure to recognise variations in weight and maturity can also lead to considerable bias in the results (ICES, 2003a). Again, it is an open question to what extent one shall attempt to model underlying processes. Although much is known about such processes, e.g. on climatic influence and multispecies effects, there is still a risk that more uncertainty is introduced than removed. The estimated uncertainty is reduced if modelled values are substituted for stochastic values, unless the model uncertainty can be taken into account.

A particular problem is caused by density dependence. For many of the stocks in the ICES area, mortality has been rising and the stock declining over several decades. Weights and maturities were often not measured directly in the past. Rather, mean values from later periods are used in assessments. First, this may lead to overestimates of the SSB in the past. Secondly, the expected increase in stock biomass when reducing the fishing mortality in the future may be over-estimated.

Reality checks
For all stochastic parameters that go into the operating model, one should apply reality checks wherever possible. Thus, the distribution of future recruitments can be compared with the distribution of recruitments in the past, if needed for selected intervals of SSB. Likewise, the distribution of future weights and maturities at age should compare with those in the past. Such reality checks are not standard practise in ICES, and can give quite surprising results. As an example, Figure 3 below shows how the distribution of recruitments generated by a standard bootstrap program can deviate from the historical distribution for a stock where recruitment is assumed to be independent of SSB. In such a case, the estimates of future development of the stock will be too optimistic compared to the history, even though the median of the assumed distribution is quite close to the historical one.

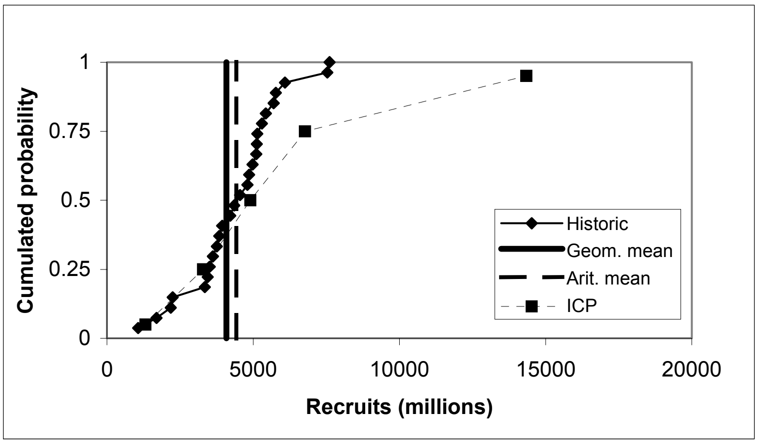

Figure 3. Cumulative distribution of recruitment for North-east Atlantic mackerel (*Scomber scombrus*), together with the distribution of recruitments in prediction year 10 by the standard medium prediction program ICP. Taken from ICES (2003d), slightly amended.

3.2. The management model

The management model part of the simulation tool is a computer implementation of the decision rule under consideration. As outlined in Section 2, such rules can be quite complex, and during a design process, it may be expected that quite creative ideas for designs may appear. The objective provided by managers are typically multiple, covering objectives like high yield from the fishery and low risk of bringing the fish stock down to low-productive levels. Although such objectives may be conflicting in the short term, they should be merging in the long term into "highest possible sustainable yield". Dialogue with manageres is essential to translate such objectives into a programmable rule.

In order to be useful, the simulation tool should be flexible enough to explore a wide range of management decision rules. A rather generic management decision algorithm may contain the following elements:

1. A basic HCR: Apply a certain fishing mortality, depending on the spawning stock biomass (SSB) (see below), but do not allow more than a certain catch. This allows for catch constraint regulation (give a very high F by which the catch constraints becomes limiting unless there is insufficient fish left), F regulation (give a very high constraining catch) or combinations of these. Different values for F and catch constraint may be set for different levels of SSB.
2. A constraint on year to year change in catch of the form:

   Min c-ratio < Catch this year/Catch previous year < Max c-ratio

   unless this leads to a fishing mortality above a highest permissible F
3. A constraint on SSB variation of the form:

   SSB this year/SSB previous year ≥ S-ratio

This rule can be programmed as the following sequence:

1. Derive an F according to the basic HCR.
2. If the catch ratio becomes too high, reduce F.
3. If catch ratio becomes too low, increase F, but not above the F set as the highest permissible F.
4. If SSB ratio becomes too low, reduce F

However, one should also be prepared to program new routines that are suggested. The North-East Arctic cod case described below is an example of a management rule that is unlikely to be covered by software developed for general use, because of the use of a 3 years average catch to set the present years TAC.

3.3. Links between the operating model and the management model

3.3.1. Assessment

The input to the management model will be the current perception of the state of the stock, which is derived from the operating model, but with possible errors. The decision rule may use these data directly, or use them to e.g. project the stock forwards and use the projection as a basis for decisions. The latter is probably the most common in practise – the TAC is decided from the outcome of a short-term prediction. This projection will then be part of the management decision model.

There has to be a link from the operating model to the management model which takes care of uncertainty in the assessment process (assessment error in the SGPA terminology).

There are two principal ways to derive the manager's perception of the state of the stock from the operating model, both having advantages and disadvantages.

1. Derive input data for an assessment from the operation model, with appropriate noise added. Use the data to perform an assessment, and use the results to make decisions.
2. Assume that the perceived state of the stock deviates in some specified way from the real situation.

The first alternative gives the most direct simulation of the real procedure, which may be more satisfactory from a scientist's point of view. Accordingly, this kind of procedure has been implemented in several evaluation tools, see e.g. Butterworth and Punt (1999). It may be difficult to reproduce the assessment problems as we often see them, however, since the causes of errors in assessments are not always well understood. In particular, retrospective bias is a common problem, which is not straightforward to reproduce in artificial data (Mohn, 1999; ICES 2002c). A relatively safe way of inducing retrospective bias is to include a trend in the survey catchabilities in the artificial data, but even that may fail (ICES, 2003a) and if this really is the cause in the case under consideration, it is hard to quantify it correctly. On the other hand, if part of the simulation is to evaluate aspects such as sampling strategies for surveys and commercial catches etc., simulating the assessment may be necessary.

The second alternative is simply an exploration of the robustness of the harvest control rule. One would then simulate a range of deviations, to explore how the management regime performs when the management decisions are based on a skewed perception of the real state of the stock. For a management plan to be satisfactory, it should not break down if the knowledge about the state of the stock is as imperfect as it appears to have been historically. An advantage with this approach is that it is far simpler to program and run.

3.3.2. Implementation

To complete the simulation tool, there is a need for a link from the manager's decision back to the model stock. For the stock, what matters at the end of the day is the amount of fish that is actually removed by the fishing activity. What is actually removed may deviate from what is decided by managers. This deviation is commonly referred to as implementation error. The removal includes not only recorded landed quantities, which may be the parameter decided by the managers, but all sorts of removal by fishing activities.

In a modelling context, and analogous to the assessment uncertainty, one may either attempt to model important processes leading to deviation of the real harvest from the intended one, or one may assume some statistical distribution for this deviation and test the robustness of the management plan to these kind of problems. It may also be worth noting that the overall effect on the stock of a higher than intended fishing mortality will be the same whether this is due to overestimation of the stock abundance or to overfishing of the quotas.

Given the complexity of factors involved in the implementation of management rules, a realistic model of the implementation error may be difficult to achieve. Thus, for practical purposes, it may be more rewarding to ensure a sufficient robustness of the management plan. However, in some contexts, e.g. in a rebuilding situations, new strong regulations may lead to changes in e.g. discarding practise which may have an important impact on the efficiency of the recovery plan. Explicit modelling of such dynamics may be worth considering, and we here give a brief overview of mechanisms that may be considered.

In addition to the recorded landings, the fishery may cause additional removal of the fish stock through e.g. the following processes:

1. Mortality induced on fish which have been in contact with gear, but not been captured by the vessel. A typical example will be mortality due to e.g. a sorting grid or burst of the purse-seine.
2. Discards at sea, either through highgrading of the catch, or through discards of fish, which are not fulfilling legal catch. This may be either undersized fish or bycatch of fish where the quota has been exhausted.
3. Wrong conversion factors. Demersal fish are usually gutted and sometimes decapitated before deliveries. Since it is the final product delivered which is weighed and recorded in the catch statistics, the live weight of the fish must be recalculated by the use of conversion factors. If these are too low, the actual live weight of the catch will be higher than the (recalculated) recorded catch.
4. Wrong correction factors for water content. In pelagic fisheries, a correction factor for water content will be deducted from the catch. If this factor is too high, more fish will be delivered than what is recorded (Røttingen *et al*., 2002).
5. Illegal, unregulated, unreported fishery.

In addition to these, fishery-induced error terms, there are errors made when calculating the effect of the fishery on the stock through deviation in age composition from what was actually fished. The importance of all these factors will vary in space and time, and may be a function of several different relationships. There is however a need for further research to understand these processes more thoroughly.

Generally, it is reasonable to expect that violations of fishery regulations, leading to fishery in excess of the quota, stem from several factors. Some of these are:

- Economic incentives
- Lack of adequate control
- Complex structure of stock
- Mixed fishery

In several fisheries, there is a huge overcapacity of fleet relative to the resource base it is exploiting. In such fisheries, the fishermen have a strong economic incentive to exploit the biomass in the most profitable way possible. Although this may lead to violation of regulations, this situation is not unique to fisheries, but is a more general feature relevant to many industries. A feature that may be specific for the fishery is its common-property characteristics. Will this characteristic imply that regulations are less respected than in an industry with well-established property rights?

Fishery regulations, especially output regulations, are often quite knife-edge sharp when broken down to the level of what the individual fishermen are allowed to catch. Once at sea, the fisherman may be restricted by quotas for individual species, and by restraints to catch specimen below specific lengths. If the actual composition of the catch deviates either from his portfolio of quotas or from the legal intermixture of juveniles, he will have to change area of fishing or otherwise try to adapt to the existing regulations. This may not be easy, and the honest fisherman may find himself in a situation where there are two alternatives; either stop fishing or bend the regulations. Under such circumstances, it should not come as a surprise that some fishermen will continue fishing to exploit their legitimate rights but bending the regulations regarding the catch they are not allowed to take.

Further research is of course necessary to establish how these mechanisms work. Even though it may be difficult to establish the quantities of excess catch due to these mechanisms, there may be some rules of thumb to follow:

- In mixed fisheries, compare assessed composition of species with composition of quotas for the fishermen. If the quota-mix for two species X and Y is 50/50 but the assessed composition of stocks are 75/25, expect the catch figures for X and Y to err on the negative and positive side respectively.
- In fisheries where the catch targets various age groups, the catch at age recorded in the catch may deviate from the assessed age-structure of the stock. If the mixture of catch above and below minimum landing size is 50/50 whereas the corresponding mixture in the stock is assessed to be 25/75, expect the catch figures of fish below the minimum landing size to err negatively.

In addition to these elements, if knowledge exists about wrong conversion factors (live weight/gutted weight) or wrong correction factors for content of water in deliveries of pelagic species, these should be assessed and included in the stock assessment.

3.4. Measures of performance
The parameters of interest will vary depending on the objectives underlying the management regime. Some general points can be noted, however:

- There should be some measure of the state of the stock and exploitation level with relevance to the precautionary approach. Traditionally, these will be the SSB and the level of fishing mortality.
- Both the state of the real stock and the perceived state of the stock as seen by managers should be followed.
- If there are specific management objectives, measures of performance (indicators) relative to the objectives should be given. For example, if stabilising the catches is an objective, some measure of stability should be presented.
- Most output parameters will be stochastic, and have to be presented as distributions. It may be advisable to avoid emphasising the extremes of the distribution, except for events that should have a very low risk of being encountered.
- It is often feasible to show the probability of something happening as a function of parameters in the decision rule, e.g. the risk of reaching an SSB limit as function of the fishing mortality applied as a standard.
- If rules are included to cope with unwanted events, like rules for reducing F when the SSB estimate is below some reference value, the probability of having to apply such rules should be one of the parameters of interest.

4. Application to the agreed harvest control rule for NEA cod

4.1 Historical overview of stock development and management history

Nakken (1998) gives an overview of the stock development and management history of Northeast Arctic cod. This stock has been subject to a high exploitation rate since the mid-1950s. F_{5-10} has been in the range 0.50-1.05 in all years since 1955 except 1960 and 1990-1992, when F_{5-10} was < 0.50 (ICES, 2003c). Since the 1970s, the fixing of a total allowable catch (TAC) for Northeast Arctic Cod the forthcoming year has been one of the most important tasks on the agenda for the Joint Norwegian – Russian Fisheries Commission (hereafter denoted as the Commission). The first TAC on Northeast Arctic cod was agreed upon by the Commission in 1978.

In the period when TAC advice has been given, there has been a tendency that the agreed or set TAC has been equal to or higher than the advised one. The reported catch has in some years exceeded the agreed one, but it has also happened that the fleets have not succeeded in taking the agreed TAC. Also, the advised TACs have in most years been based on too high estimates of current stock size (Nakken, 1998).

From 1991 onwards, ICES gave options when fish stocks were assessed to be above Minimum Biological Acceptable Level (MBAL) and clear advice if not. The “top option” was restricted by the reference point F_{med}, which then was estimated to 0.46. MBAL was set to 500,000 tonnes. The assessment of NEA cod during the period 1991-1996 showed a stock, which was growing, and the “top options” increased sharply during the period. The Commission fixed TAC levels, which generally were close to the “top options” offered by ICES. For 1997, the “top option” gave an advice of 994,000 tonnes, corresponding to F_{med}. This advice was based on a stock estimate which later was shown to be a considerable overestimate. That year, the Commission fixed the TAC to 850,000 tonnes.

In 1997 ICES changed its form of advice to using precautionary reference points (F_{pa}, B_{pa}, F_{lim}, B_{lim}). This form of advice is still in use and is described e. g in ICES (2002a).

At its 1997 and 1998 meetings, the Commission agreed that there was a need to further develop long-term strategies for shared stocks in the Barents Sea. Until such a strategy was agreed upon, the Commission agreed that the fishing mortality should be such that the spawning stock was kept above 500,000 tonnes (B_{pa}) and that F should be reduced to F_{med}=0.46 at latest in 2001. In 1999, the Commission confirmed the goal of quickly rebuilding the SSB to above 500,000 tonnes and to reduce the fishing mortality to below F_{pa}=0.42. In 2000, a fixed TAC (395,000 tonnes) was agreed upon for the period 2001-2003.

The assessment of the stock during the first part of the period 1998-2003 showed a stock, which was declining. In addition to the change to precautionary reference points in terms of F_{pa} and B_{pa}, ICES based the advice on the rebuilding goals formulated by the Commission. This led to a sharp reduction in the TAC levels advised by ICES from 994,000 tonnes for 1997 to 110,000 tonnes for 2000.

The Commission cut back the TAC sharply during the same period, but not enough to comply with the advice given by ICES. Consequently, in relation to the annual assessments, the fishing mortality imposed by the TAC level far exceeded the reference points recommended by ICES.

In the advice and decision process from 1997 onwards, medium-term simulations of stock development for various harvest control rules (fixed F, fixed TAC etc.) played an important role. In these simulations, the operating model assumed error only in the initial stock size and the recruitment. Because only medium-term (5-year) simulations were performed, the stock-recruitment relationship was of little importance for this stock which recruits to the fishery at age 3, and where survey data for ages 0-2 are used in stock projections. Also, it was assumed that the perceived state of the stock in each year deviates in some specified way from the real situation (alternative 2 discussed in section 3.3.2).

4.2 Existing management plan for Northeast Arctic cod

A new management plan for North-East Arctic cod was agreed by the Commission in 2002. The main elements in this plan are:

- Estimate the average TAC-level for the 3 forthcoming years based on F_{pa}. TAC for next year is set on the basis of this average TAC level.
- The following year the estimation for the TAC-level for the next 3 years is repeated based on updated information on stock development. However, the revision of TAC cannot be more than +/-10% of the TAC-level given for the following year.

In the framework outlined above, this management plan specifies a harvest control rule as its main element. Thus, it is not a complete management plan as outlined in (FAO, 2002) but a rule for deciding on the TAC for next year, given the perceived current state of the stock and its exploitation, as well as presumed weights and maturities at age.

It is stated that if SSB falls below B_{pa}, some additional action has to be taken. It is not specified what that actions should be, which makes the rule incomplete as a HCR and in relation to the precautionary approach. It is part of the task to evaluate which measures will be relevant to offer a sufficient protection, and if the currently adopted value of B_{pa} is the appropriate trigger point for such action. At the meeting of the Study Group on Biological Reference Points for Northeast Arctic Cod (ICES, 2003b), new reference points were calculated (F_{pa}=0.40, F_{lim}=0.74, B_{pa}=460,000 t, B_{lim}=220,000 t).

The rule can roughly be categorized as a constant F-rule with a constraint on catch variation, but it has the additional element that the catch to be applied in the coming year is derived as the average catch emerging from applying a constant F over 3 years. Thus, the simulation framework can be outlined as follows:

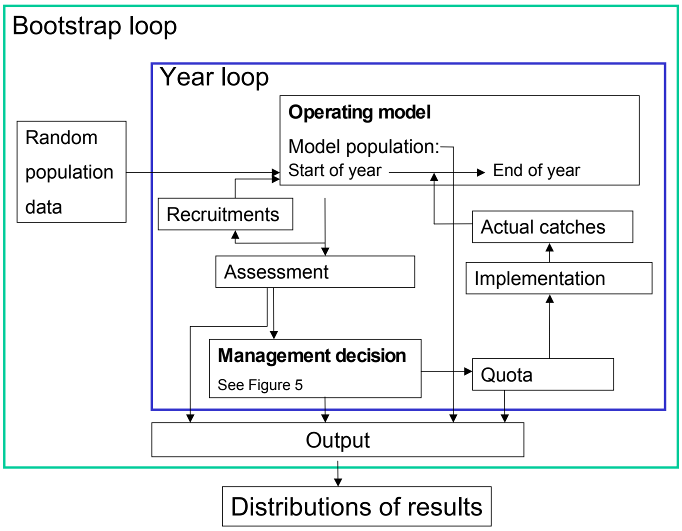

Figure 4. General layout of simulation model for the harvest rule for North-East arctic cod.

4.3. Operating model

The operating model is designed as outlined in Section 3.1 with the following specifications (stochastic elements are denoted with *):

Input

- *Initial population numbers at age
- *Selection at age
- *Weight at age in the stock
- *Maturity at age
- Natural mortality
- Recruitment parameters
- *Recruitment variation

Modelled internally:

- Stock numbers next year
- Recruitment as function of SSB (stock-recruitment function and a parametric distribution of noise)

Feedback from decision model:

- Annual catch in weight, adjusted for implementation error.
    - Convert to catch in numbers at age using selection at age and weights at age from the operating model.
    - Add on discards and other unreported catch.

The link to the management model includes assessment noise, where the likely distribution of noise is derived from retrospective runs, and the link from the management decision model to the operating model is through the realised catches at age, which are derived from the catches at age in the management model with additional implementation noise.

4.4. Management decision model

The link from the operating model to the management model includes assessment noise, where the likely distribution of noise is derived from retrospective runs.

The management model projects the population forwards through the intermediate year (decision year) and 3 years forwards, applying an intended $F = F_{pa} = 0.40$, and the selection at age from the last assessment year. In this sub-model, recruitment is at age 3, which is standard practise for this stock. The recruitment in these years are derived, with noise, from the recruitments generated in the operating model. Catches at age are derived, and converted to yield using weights derived from the operating model. The average yield over the 3 years is compared with last years' quota, and the quota for the prediction year is adjusted according to the rule if necessary to keep the change in quota within the agreed bounds. The management decision process is outlined in Figure 5 below.

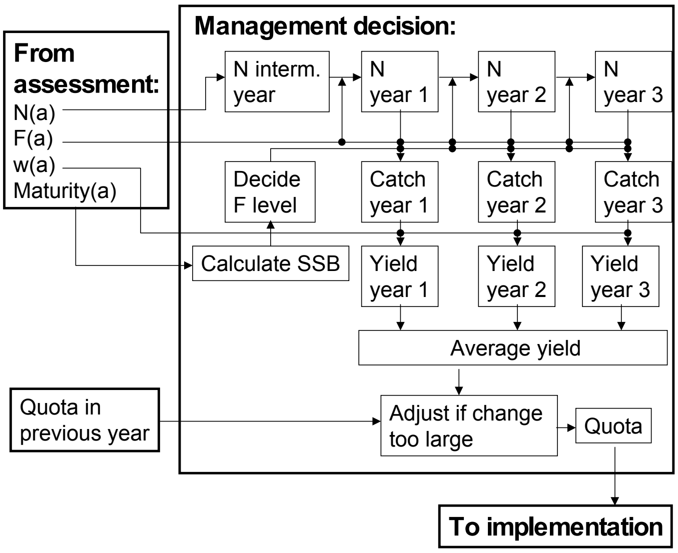

Figure 5. Outline of the management decision process.

4.5. Discussion of the simulations of the agreed harvest control rule for NEA cod

The simulation model outlined here is relatively simple and pragmatic, but is assumed to take account of the most essential elements that determine the efficiency of the harvest rule under consideration.

We have decided not to let the model perform assessments in each year, but rather investigate the robustness to assessment errors that can be expected. The assessment error has been quite well studied recently by the ICES SGBRP (ICES, 2003b). The results of that study may be a good indicator of the kind of distributions to apply for this error.

Some elements have not been included so far. These would increase complexity, and it is not considered likely that they will lead to great differences in the perception of the performance of the harvest rule:

- The operating model does not include cannibalism. The variable natural mortality at young age is implicitly included in the recruitment variation.

- There are strong variations, with some periodicity, in growth and recruitment, associated with variations in the temperature, capelin abundance and other environmental and ecological factors in the Barents Sea. This implies that the noise terms in stochastic weights and recruitments are not identically and independently distributed (iid).

- Discards are only included in the current assessments for years where there is relatively solid documentation. Assuming some discard should be part of the implementation error, but one can probably not do more than explore the robustness of the system to various levels of discarding.

- Selection at age has varied over years, and should probably be treated as a stochastic parameter. Year class effects in the selection have been suggested, and may be taken into account.

There is still some doubts about whether managers intend to apply the constraint on catch variation in the first TAC year for which this management plan will be applied (2004). A desicion at this point is expected before the simulation studies are made.

This management arrangement was agreed by the Joint Norwegian Russian fisheries commission, with the condition that it should be evaluated by ICES. Managers have agreed to manage the stock within the framework of the precautionary approach. At first sight, this would imply that the fishing mortality should not be deliberately increased above the adopted F_{pa}. The rule as it stands inevitably will imply a higher F in some years, whenever the stock is increasing. However, as noted in Section 2.4, the standard reference points F_{pa} and B_{pa} to some extent become redundant if it can be demonstrated that the rule in itself implies a low risk of attaining the limit reference points. One crucial question is whether the measures taken to reduce year-to-year variations in the catches are feasible, and if the adopted basic value 0.4 for the fishing mortality is appropriate. The simulation framework outlined here is intended to enable ICES to evaluate whether this is true in the present case, and to suggest modifications of the rule if the results indicate that the risk appears to be unacceptable.

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