Helsinki University of Technology
Systems Analysis Laboratory Research Reports
Espoo 1998

A75, September 1998

IMPLEMENTATION OF THE NORWEGIAN SPRING-SPAWNING HERRING STOCK DYNAMICS AND RISK ANALYSIS

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ISBN 951-22-4252-4
ISSN 0782-2030

Edita Oy
Espoo 1998

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This report is a part of the FAIR Project PL 96.1778 "The Management of High Seas Fisheries", funded by the European Commission. We acknowledge valuable comments from Ragnar Arnason, Trond Bjørndal and Janica Ylikarjula. Correspondence to:

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1 Introduction

This technical report presents part of the work achieved for tasks 2.1.2 and 2.2 of the FAIR-CT96-1778 research project "Management of high seas fisheries". A biological modelling and parameter estimation of the Norwegian spring-spawning herring stock dynamics has been completed by PATTERSON [7]. It constitutes the basis of this study, which aims at implementing and analyzing this model.

The biological model has been coupled with a very simple economic model: fixed fish price and basic cost function that will require further developments. However, it is used as a preliminary version of the more sophisticated model. Although, in this report, some work has been done for the simulation and the equilibrium study of the bioeconomic model, the emphasis is on the risk analysis. We are interested in studying whether some variables, e.g. the spawning stock biomass, will decrease under a certain critical value. We want to assess this risk and study the risk distribution.

This report is organized in the following way: Section 2 is a presentation of the bioeconomic model and Section 3 briefly describes the data available. Section 4 is dedicated to the technical implementation of the bioeconomic model in MATLAB, simple simulations, equilibrium study and risk analysis. Some results are then exposed in Section 5. Finally conclusions are drawn and perspectives for further work are proposed.

2 Model

The biological modelling presented here stems from PATTERSON's report [7]. Its main features have been summarized in order to understand the MATLAB procedures described in Section 4 and displayed in appendix B. The seasonal and spatial distributions that are part of the initial model, have not been implemented and are only briefly exposed in appendix A.

To ease the reading of the report, the first part of this section compiles most notations. In addition, a table is attached to each of the following subsections describing the values and units of the parameters. Subsections 2.2, 2.3 and 2.4 concern the biological model, whereas subsection 2.5 introduces harvest and profit. Finally, a simplified and more conventional model is exposed.

2.1 Notations

Table 1 summarizes the notations used in this report and hereunder are some general remarks about the model.

- The population is distributed in *17 age classes*, beginning with age class 0.
- The *time step* considered is 1 year, but the quarter variable actually introduces a smaller time step of $1/4$ year $= 3$ months. It allows seasonal effects to be taken into account (cf. appendix A).
- To calculate the flow into the first age class (0), a classical stock-recruitment relationship is used (either BEVERTON–HOLT or RICKER, cf. Section 2.4) linking the number of recruits R to the spawning stock biomass SSB. It should rather be considered as a *spawning function*, as all juvenile stages are included in the model. Thus, the recruits are in fact eggs.

Subscripts	definition	range	
a	age	$\{0, 1, 2, \dots, 16\}$ years	
y	time	current year	
q	quarter, i.e. season	current year quarter $\{1, 2, 3, 4\}$	
i	EEZ	zone number	
yc	reference year class	year $\{1950, 1959, 1972, 1983\}$	
Variables	definition	unit	subscripts
N	abundance	numbers	a,y,q,i
B	biomass	kg	a,y,q,i
SSB	spawning stock biomass	kg	y
R	recruitment	numbers	y
Y	yield, catch in weight	kg	a,y,q,i
CW	individual weight at age in the catch	kg/numbers	a,y
SW	individual weight at age in the stock	kg/numbers	a,y
MO	maturity ogive (rate)	percentage	a,y
ε	stochastic variable	none	y
F	fishing mortality	none	y,q,i
S	selectivity	none	a,i
Parameters	definition	value & unit	
m	natural mortality	*cf. table 2*	
$w_0, w_\infty, k_0, \alpha$	stock weights at age parameters	*cf. table 3*	
$w'_0, w'_\infty, k'_0, \alpha'$	catch weights at age parameters	*cf. table 3*	
a, b, g	stock-recruitment parameters	*cf. table 4*	
c_a, d	maturity coefficients	*cf. table 4*	
h	fish price per kg	*cf. table 5*	
q_1, q_2	fixed and proportional costs	*cf. table 5*	
$p_{a,y,q,i}$	spatial distribution rates	*cf. appendix A*	
$\pi_{a,yc,q,i}$	spatial distribution reference rates	*cf. appendix A*	

Table 1: Notations

2.2 Population dynamics

We consider a population dynamics model, known in the fisheries literature as the RICKER model. It is a discrete time and age-structured model:

$$\begin{aligned} N_{0,y} &= R_y \\ N_{a+1,y+1} &= N_{a,y} e^{-m - S_a F_y} \qquad \forall a \in \{0, 1, \dots, 15\} \\ N_{a,0} &\quad \text{known} \qquad \forall a \in \{1, 2, \dots, 16\} \end{aligned} \tag{1}$$

The whole population is represented through 17 age classes, from age 0 to age 16. Usually, only the harvested fraction of the population is considered, i.e. the stock (mainly because most data available concern the stock). Especially, the juvenile stages are excluded since they are too small for harvesting.

The input in the stock is called the *recruitment* (R). It is defined as the number of juveniles entering the exploitable phase. In this model, however, the recruitment happens in age class 0, so we should rather consider it as a spawning function, described in

Section 2.4.

All age classes are submitted to natural mortality (constant rate m) and possibly to harvest. The latter is introduced by the means of a fishing mortality term F_y, related to the effort applied to the stock each year, and a selectivity rate S_a, that describes the vulnerability of each age class; see the more thorough discussion in Section 2.5.

Parameter	value	unit
m	0.15	none

Table 2: Natural mortality parameter

2.3 Growth and biomass

In order to describe the population growth, we need to express the *individual weights at age*. We could estimate these values by using historical data. But in this model, a density-dependent growth function has been implemented, deriving from FORD's equation [9] and assuming isometric growth. Further hypotheses are that the maximum length is genetically determined, but that the growth rate depends on food availability, and hence on the total population biomass.

This function is fitted separately to the stock and catch data. Therefore we obtain two similar functions. The stock weights at age function is the following:

$$\begin{aligned} SW_{0,y} &= w_0 \\ SW_{a+1,y+1} &= \left((1-k_y){w_\infty}^{1/3} + k_y {SW_{a,y}}^{1/3}\right)^3, \\ &\text{where: } k_y = k_0 e^{-\alpha B_y / B_{\max}} \end{aligned} \tag{2}$$

whereas the catch weights at age function is given as:

$$\begin{aligned} CW_{0,y} &= w'_0 \\ CW_{a+1,y+1} &= \left((1-k'_y){w'_\infty}^{1/3} + k'_y {CW_{a,y}}^{1/3}\right)^3, \\ &\text{where: } k'_y = k'_0 e^{-\alpha' B_y / B_{\max}} \end{aligned} \tag{3}$$

In both cases, $B_{\max}$ is the maximum observed stock size and is included for rescaling purposes.

The SW and CW are slightly different because the samples used for their estimation are not the same. CW is needed for the catch in weight defined in Section 2.5 and SW enables to express the *population biomass* in year y:

$$B_y = \sum_{a=0}^{a=16} B_{a,y} = \sum_{a=0}^{a=16} SW_{a,y} N_{a,y}. \tag{4}$$

The growth parameters are given in table 3.

Parameters	value	unit
$B_{\max}$	16218	10^6kg
w_0	0.203	kg
k_0	0.703	none
α	-0.299	none
w_∞	0.447	kg
w'_0	0.217	kg
k'_0	0.650	none
α'	-0.368	none
w'_∞	0.430	kg

Table 3: Growth parameters

2.4 Recruitment

The growing and ageing of the population are described in the previous sections, but we have not introduced any input of young individuals in the population yet. So to close the loop in the dynamic model (1), it is necessary to link the recruits, i.e. the offspring, to the spawners. Two diferent functions are used for this purpose: BEVERTON–HOLT's and RICKER's stock-recruitment relationships, which are very classical in the fishery field [5, 217-224] [6, 255-261]. To take into account the variability of the recruitment, a stochastic error term is added to these deterministic functions. First, however, the spawning stock needs to be estimated.

2.4.1 Spawning stock biomass

It is assumed that the older part of the population (from age class 7) is fully mature, whereas the younger one (until age class 3) does not spawn. The intermediate age classes are partially mature. The maturity ogive, defined as the proportion of mature individuals among an age class, characterizes the spawning level.

To assess the maturity ogives of the intermediate classes, it is possible to refer to historical data. However, here we assume that they depend on the stock size and the following function is used:

$$\begin{aligned} MO_{a,y} &= 0 && a \in \{0,1,2,3\} \\ MO_{a,y} &= \frac{1}{1+e^{-c_a} {B_{4+,y}}^{-d}} && a \in \{4,5,6\} \\ MO_{a,y} &= 1 && a \in \{7,\dots,16\}, \end{aligned} \tag{5}$$

where $B_{4+,y}$ is the biomass of the mature age classes, i.e. age class 4 and older. Thus:

$$B_{4+,y} = \sum_{a=4}^{a=16} B_{a,y}$$

The *spawning stock biomass* is given by:

$$SSB_y = \sum_{a=0}^{a=16} MO_{a,y} SW_{a,y} N_{a,y} \tag{6}$$

2.4.2 Beverton–Holt

The first stock-recruitment function is Beverton–Holt's [3]. It assumes there is food limitation and competition among the juveniles. Its shape is drawn in figure 1.

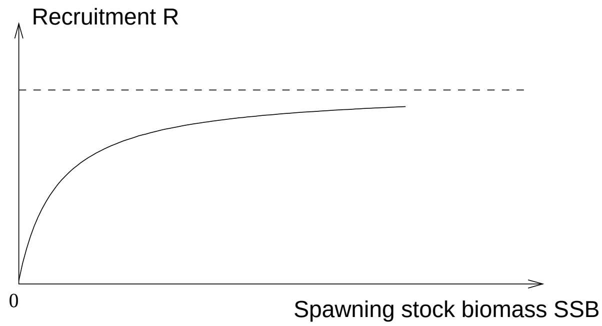

Figure 1: Beverton–Holt's stock-recruitment function

The corresponding equation, to which a log-normal error term is added, is the following:

$$R_y = \frac{aSSB_y}{1 + SSB_y/b}\ e^{\varepsilon_y + g\varepsilon_{y-1}} \tag{7}$$

The error term is introduced to reflect the high variability in recruitment due to numerous external factors (e.g. cod predation, environmental fluctuations). ε_y is a normally distributed random variable, with mean 0 and variance σ. If the parameter g is zero, the error is uncorrelated. Otherwise there is first order autocorrelation.

2.4.3 Ricker

Ricker's relationship [8] assumes cannibalism of the juveniles by the stock. This gives another stock-recruitment shape, represented in figure 2.

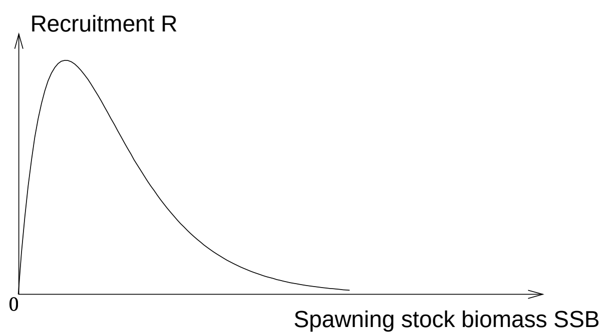

Figure 2: Ricker's stock-recruitment function

A log-normal error term, similar to the one described above for Beverton–Holt's stock-recruitment function is added. The resulting equation is as follows:

$$R_y = aSSB_y e^{bSSB_y}\ e^{\varepsilon_y + g\varepsilon_{y-1}} \tag{8}$$

N.B.: Stock-recruitment relations are commonly used because they are practical and synthetic. The two classical relations described above both derive from the integration of an ordinary differential equation representing the dynamics of the juveniles over a small time period. This process is described by Clark [5, pp217–218,229–230] and more briefly by Hilborn & Walters [6, pp257–261].

The comparison between these models and data however is often disappointing. Therefore constant or purely stochastic exogenous recruitments are used assuming a predominant influence of the environment [2]. The link between the spawning stock and its offspring may then be hidden, which leads to the "stock-recruitment paradox" [10] where no empiric relation is observed. Furthermore, stock-recruitment functions are a static summary of the development of juveniles and therefore cannot take into account the heterogeneity of the spawning stock [11].

The parameters of these four stock-recruitment relationships are shown in table 4.

Parameters	value	unit
c_4	1.356	none
c_5	2.686	none
c_6	3.977	none
d	-0.2744	none
Beverton–Holt, uncorrelated error:		
a	32.459	kg^{-1}
b	3044.867	10^6kg
σ	1.763	none
g	0	none
Beverton–Holt, autocorrelated error:		
a	31.637	kg^{-1}
b	3284.060	10^6kg
σ	1.666	none
g	-0.2553	none
Ricker, uncorrelated error:		
a	26.753	kg^{-1}
b	1.2105	10^{-10}kg^{-1}
σ	1.802	none
g	0	none
Ricker, autocorrelated error:		
a	25.760	kg^{-1}
b	1.094	10^{-10}kg^{-1}
σ	1.694	none
g	-0.2655	none

Table 4: Stock-recruitment parameters

2.5 Catch and economic yield

2.5.1 Harvest

¿From a given cohort (a cohort is constituted of the fish born the same year), if we consider the fish that have disappeared during year y and take the proportion that died of harvesting, we obtain the following catch in numbers:

$$C_{a,y} = \frac{S_a F_y}{m + S_a F_y}(N_{a,y} - N_{a+1,y+1})$$

Then, knowing the weights at age from equation (3), we only need to sum these catches over all cohorts to obtain the total catch in weight, or *yield*. Combined with equation (1), its expression is the following:

$$Y_y = \sum_{a=0}^{a=16} Y_{a,y} = \sum_{a=0}^{a=16} CW_{a,y} N_{a,y} \frac{S_a F_y}{m + S_a F_y} \left(1 - e^{-m - S_a F_y}\right) \tag{9}$$

As mentioned in section 2.2, the harvest is the result of *fishing mortality* F_y and *selectivity* S_a included in the population dynamics.

- The former is related to the effort applied by fishermen on the stock and is considered as a *control term*. Referring to the data (cf. section 3), a realistic range for the fishing mortality would be: $F_y \in [0, 2]$, 0.35 being a mean value over the recent years.

- The latter depends on the interaction between fish and gear; all age classes are not as vulnerable and each gear is more or less efficient towards the age classes. A simple *selection pattern* would be to cut the age classes into two groups:
  - age classes that are not yet harvested: $S_a = 0 \quad \forall a < a_1$;
  - age classes that are harvested: $S_a = 1 \quad \forall a \geqslant a_1$.

  a_1, the first fishing age, is generally 4.

  Another possibility is to use historical data for assessing the selectivities S_a (cf. section 3).

Even with a more detailed selection pattern, the hypothesis of separation between selectivity and fishing mortality may be too simple. For control purposes, it should be possible to modify the selectivity to reflect a change in the fishing gear.

2.5.2 Profit

To the biological model described above, we add a very simple economic model. The price per kilo h is assumed to be constant.

The harvesting costs are composed of a fixed and a variable term. The fixed costs q_1 represent long term investment, such as fishing vessels. The costs proportional to the fishing mortality (coefficient q_2) include e.g. labour, and fuel The total costs are: $Q_y = q_1 + q_2 F_y$.

Thus, the *annual profit* in year y is:

$$P_y = hY_y - (q_1 + q_2 F_y) \tag{10}$$

Parameters	value	unit
q_1	1^*	10^7Norwegian kroner (NK)
q_2	5^*	10^6NK
h	1.45^{**}	NK/kg

* Values chosen as a working hypothesis.

** 1995 mean value taken from Norges Sildesalgslag: Årsmelding, vol. 1989-1995.

Table 5: Economic parameters

2.6 Density-independent model

A *simplification* to the model presented above consists in replacing the density-dependent functions by fixed values, estimated by using the available data (cf. section 3). These functions are the maturity ogives in equation (5) as well as the stock (2) and catch (3) weights at age. They can be replaced by simple age-dependent parameters: MO_a, SW_a and CW_a.

This simplified model will be noted as the **DI** model, as opposed to the **DD** (density-dependent) model described in the previous sections.

3 Data

Some historical data concerning the herring population are available. They consist of age and year specific values, sampled from 1950 to 1986, for each of the 17 age classes and for the following variables:

- the abundances $N_{a,y}$, used for computing the initial condition of equation (1);
- the maturity ogives $MO_{a,y}$ as well as the the stock $SW_{a,y}$ and catch $CW_{a,y}$ weights at age, used in the density-independent model presented in section 2.6;
- the "fishing mortalities" $F_{a,y}$ (including the selectivity factor), that are used to define historical selection patterns, more detailed than the one proposed in section 2.5.

The maturity ogives, stock and catch weights at age are conventional stock assessment data estimated by ICES from commercial catch observation [1]; they can also be found in appendix A of PATTERSON's report [7]. The abundances and fishing mortalities have been estimated using a Bayesian approach presented in appendix B; the resulting data are shown in appendix C of the same report.

Selectivity data

To transform the fishing mortality data $F_{a,y}$ into historical selection patterns, we need to consider a reference fishing mortality $F_{ref,y}$, for each data year. The selectivities are then:

$$S_{a,y} = F_{a,y}/F_{ref,y}$$

The reference chosen in PATTERSON's report is the mean mortality among age classes 5 to 12:

$$F_{ref,y} = \frac{1}{8} \sum_{a=5,\ldots,12} F_{a,y}$$

4 Implementation

Several MATLAB procedures have been created for the density-dependent (DD) model described in section 2 and the density-independent (DI) model introduced in section 2.6. They allow us to perform simulations of the models, an equilibrium study and some risk analysis.

Each procedure requires the following input:

Data The data related to the historical abundances, maturity ogives, stock and catch weights at age as well as selectivities are respectively stored in the following files: `n.dat`, `mo.dat`, `sw.dat`, `cw.dat`, `s.dat`. File `n.dat` is used to estimate the initial condition of equation (1); `s.dat` allows the calculation of the selection pattern; for the DI model, `mo.dat`, `sw.dat` and `cw.dat` are used to calculate the maturity parameters and weights at age.

Biological parameters They are given in tables 2, 3 and 4.

Harvesting and economic parameters The economic parameters are given in table 5, but the costs are only working values. A further study would be needed to define suitable and more realistic parameters.

The fishing mortality F_y is considered as an open loop input, either constant along time or fluctuating; its value needs to be chosen. There is also a choice to be made concerning the selection pattern: data can be used (cf. section 3), otherwise the simple scheme described in section 2.5 is implemented.

Simulation parameters They need to be chosen for each procedure. They always include the following parameters:

- y_1 and y_2 are the two boundary years of the simulation period $[y_1, y_2]$ (e.g. $[y_1, y_2] = [1997, 2027]$).
- IC is the initial condition year(s) from which the data are taken; if IC is a vector, the mean value is computed. For instance if $IC = (1993, \ldots, 1996)$, the selectivities S_a are the mean historical values over the years 1993 to 1996.
- The boolean variable SR defines which stock-recruitment relationship will be used, RD whether this relation includes a stochastic error term and AC whether this term has first order autocorrelation; this is summarized in the table below.

	0	1
SR	BEVERTON–HOLT	RICKER
RD	no stochasticity	stochasticity
AC	no autocorrelation	1st order autocorrelation

NB: Any `HER1*.M` program refers to the DI model, whereas `HER2*.M` refers to the DD model.

4.1 Basic simulation

Two models have been implemented: the complete density-dependent model `HER2.M` described in section 2 and the density-independent model `HER1.M`, simplified by the assumptions made in section 2.6.

These two procedures allow the *simulation of the population dynamics* and give the following output along the simulation years:

- population abundances $N_{a,y}$,
- biomasses $B_{a,y}$,
- catches in weight $Y_{a,y}$,
- spawning stock biomasses SSB_y,
- total costs Q_y,
- profits P_y.

Several plots may be of some interest. The ones implemented are the evolution of the total biomass, the total yield and the profit along time; as well as the recruits (age class 0) as a function of the spawning stock and the cost function with respect to the catch.

4.2 Equilibrium study

The `HER1EQ.M` and `HER2EQ.M` procedures have been implemented to study the *equilibrium characteristics* of the model. For this aim, the stochastic term of the stock-recruitment relation is omitted ($RD = 0$) and a set of constant fishing mortalities F needs to be defined. A further requirement, in order to reach the steady state, is to have a "long enough" simulation period: 60 years between the first simulation year y_1 and and the last one y_2 is usually enough.

A stock dynamics simulation is performed for each fishing mortality. It produces two output matrices, defined as functions of the simulation years and the fishing mortalities:

- the total biomass $B_{y,F}$, where $B_{y_2,F}$ can be considered as the equilibrium biomass;
- the total yield (catch in weight) $Y_{y,F}$, where $Y_{y_2,F}$ can be considered as the equilibrium yield.

The following plots are produced: the total equilibrium biomass and yield along the fishing effort; several total biomass trajectories for low and large values of fishing effort. The equilibrium yield plot against fishing mortality is of particular interest, because it shows the *Maximum Sustainable Yield* (MSY), a reference value in fishery management.

4.3 Risk analysis

The risk analysis consists in determining what risk there is, for a certain yearly variable X_y to decrease under a critical value X_{crit}. The *risk variables* implemented are:

- the total biomass: $X_y = B_y$,
- the spawning stock biomass: $X_y = SSB_y$,
- the yield: $X_y = Y_y$,
- the profit: $X_y = P_y$.

For this study, a set of fixed fishing mortalities F is also needed. For each fishing mortality a number of simulations, SIM, are performed over $[y_1, y_2]$. As we deal with risk, there should be a stochastic term on the stock-recruitment relationship ($RD = 1$) and the simulation period should be rather long.

Furthermore, the number of simulations (SIM) should be quite high, so as to approximate, for each F, the *risk probability* with the number of "risky simulations".

Risk definition *A simulation is said to be risky, if there is at least one year over the simulation period, where the variable decreases under the threshold.*

For each of the above mentioned risk variables, the following output is obtained:

- As functions of the fishing mortalities F and the simulations si ($si = 1, \dots, SIM$):
  - the risk: $R_{F,si} = 1$ for a risky simulation, 0 otherwise;
  - the first year below the critical level: $T1_{F,si}$;
  - the number of years below the critical value: $Ts_{F,si}$.

  The mean value and standard deviation of these matrices over the SIM simulations are also estimated. The mean risk R_F approximates the risk probability of getting below the specified threshold. For example, if there are 100 simulations and 5 of them are risky in the sence specified above, then the mean risk is 5%.

- As functions of the fishing mortalities F and the year:
  - the mean value of the risk variable: $M_{F,y}$;
  - the mean risk distribution: $D_{F,y} = 1$ if the corresponding mean value is below the threshold, 0 otherwise.

The following 2D plots are produced: the mean values R_F, $T1_F$ and Ts_F as functions of the fishing mortalities F (figures 13, 15, 17 and 19), as well as the following 3D plots: the mean value $M_{F,y}$ and the mean risk $D_{F,y}$ as functions of the fishing effort F and year y (figures 14, 16, 18 and 20).

The first 2D plot in each figure gives the mean risk explained above. The first 3D plot of the figures visualizes the opportunities that the fisheries policymakers might have when choosing the level of fishing mortality. It can be thought of as a terrain where one has to travel by choosing the desired level of fishing mortality. The two lowest 2D plots are related with the lower one of the 3D plots: all these three plots visualize the number of years that the particular value stays under the threshold and furthermore, the first year that the value falls below this critical level.

5 Results

Considering the two main models (DD and DI) and the four different stock-recruitment relationships, there are altogether 8 different models. Discussing all the features of these models would not be very clear and synthetic, so we choose a simple *reference model*: the simplified density-independent model with BEVERTON–HOLT's stock-recruitment relationship and no autocorrelation in its stochastic term. This particular model is used in section 5.1 for some basic simulations and in section 5.3 for the risk analysis. Section 5.2 consists in a deterministic steady state approach, so it is possible there to compare the different models.

5.1 Basic simulation

The basic simulation has been made using the "reference model" introduced above ($SR = 0$ and $AC = 0$). Following simulation parameters have been used:

- $y_1 = 1997$ and $y_2 = 2117$ for the simulation period;
- $IC = (1993, \ldots, 1996)$ as initial condition years;
- a randomly fluctuating fishing mortality F: normal distribution with 0.35 as mean value and 0.2 as standard deviation, except for figures 3 to 4 where we have a constant fishing mortality 0.35;
- a simple selection pattern as described in section 2.5, $a_1 = 3$ being the first fishing age.

Figures 5 to 9 display the resulting curves. In addition, figures 3 to 4 show the deterministic values for the herring stock and harvest. The stock level is shown to be 25 billion kg.

The situation depicted in this simulation is rather satisfactory since figure 5 shows that the biomass globally increases. The highly fluctuating harvest is also rather large (cf. figure 6).

The costs shown in figure 9 are very low, so this explains why the profit in figure 8 is similar to the catch and remains positive. The economic parameters of table 5 are probably not very appropriate here.

Figure 7 displays the number of recruits entering age class 0 with respect to the spawning stock biomass. This is in fact the classical stock-recruitment curve, in this case BEVERTON–HOLT's relation (cf. figure 1). Because of the fluctuations however, it cannot be recognised.

5.2 Equilibrium study

As the equilibrium analysis is a deterministic study, there are only four different models: the density-dependent and density-independent models, with RICKER's or BEVERTON–HOLT's stock-recruitment relationship. In this Section, we compare the equilibrium properties of these models.

The parameters chosen for this study are:

- $y_1 = 1997, \quad y_2 = 2057$ for the simulation period;

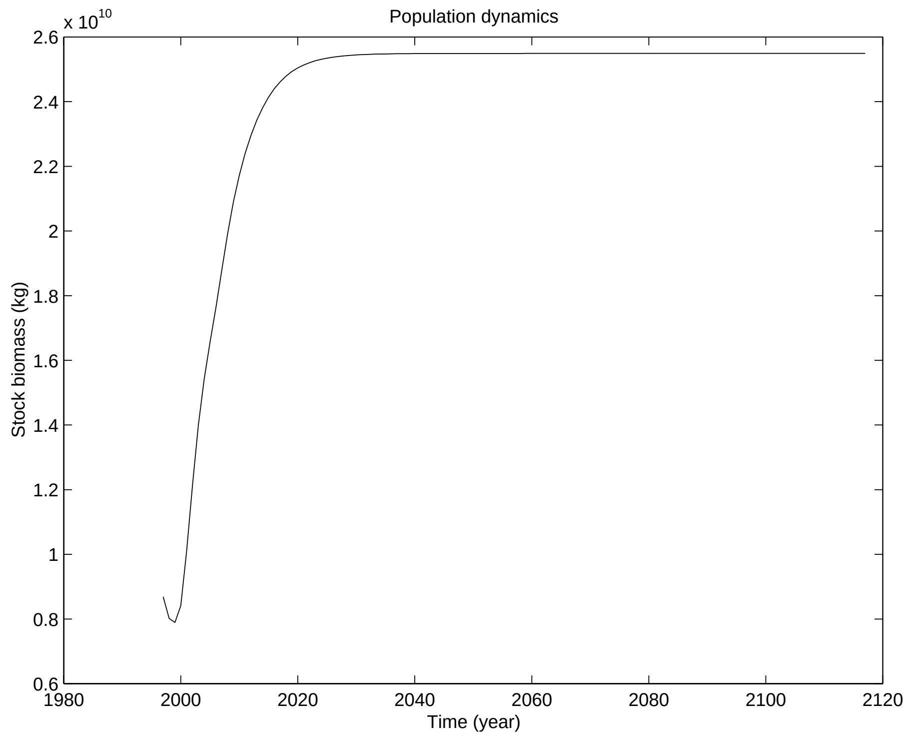

Figure 3: Deterministic Simulation of the total biomass

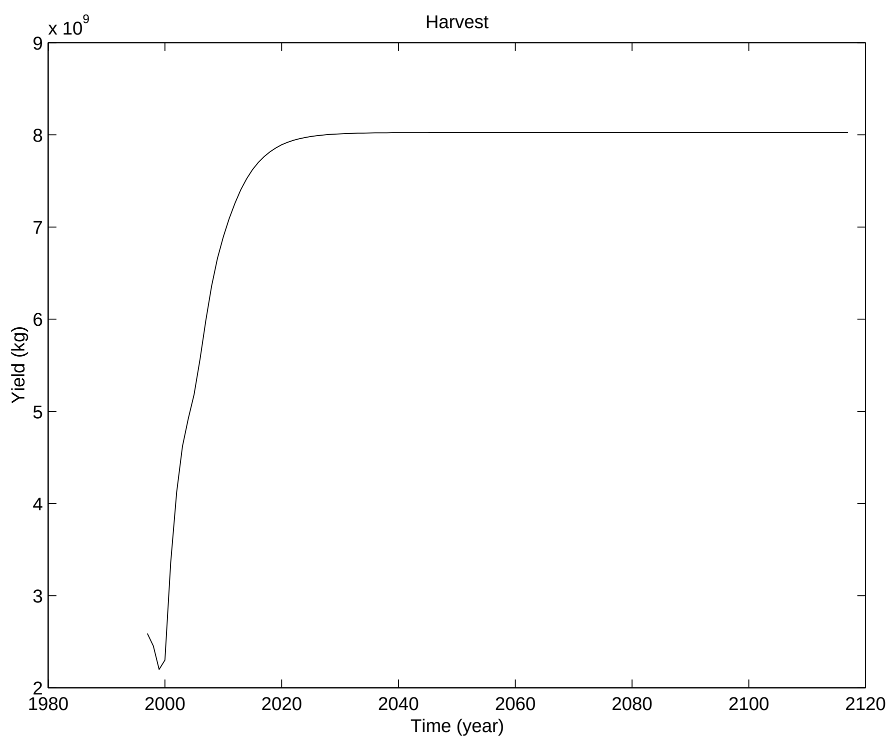

Figure 4: Deterministic Simulation of harvest

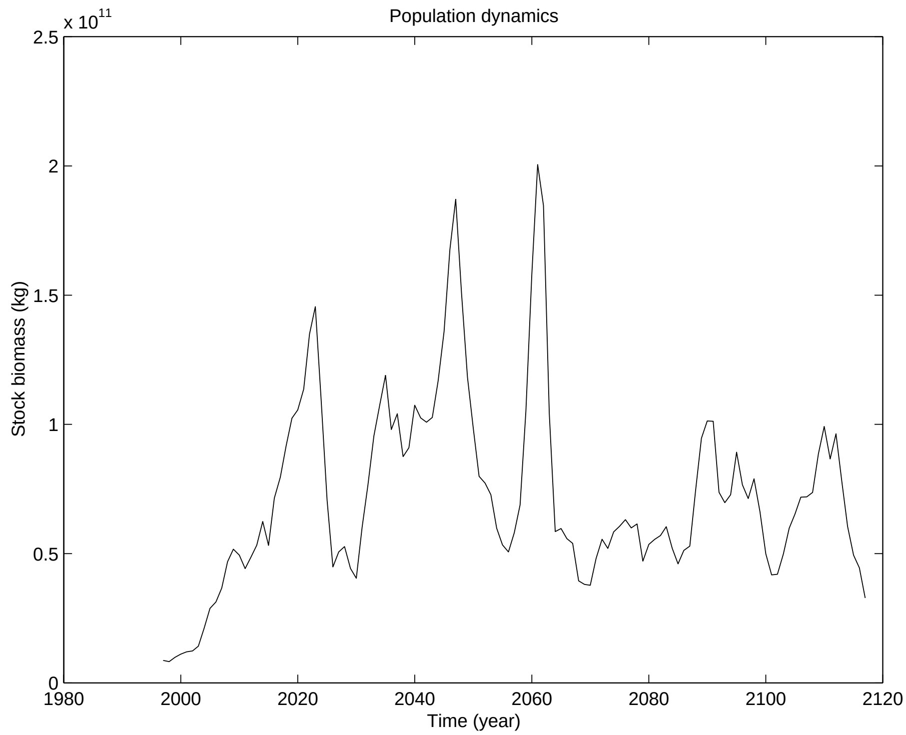

Figure 5: Simulation of the total biomass along time

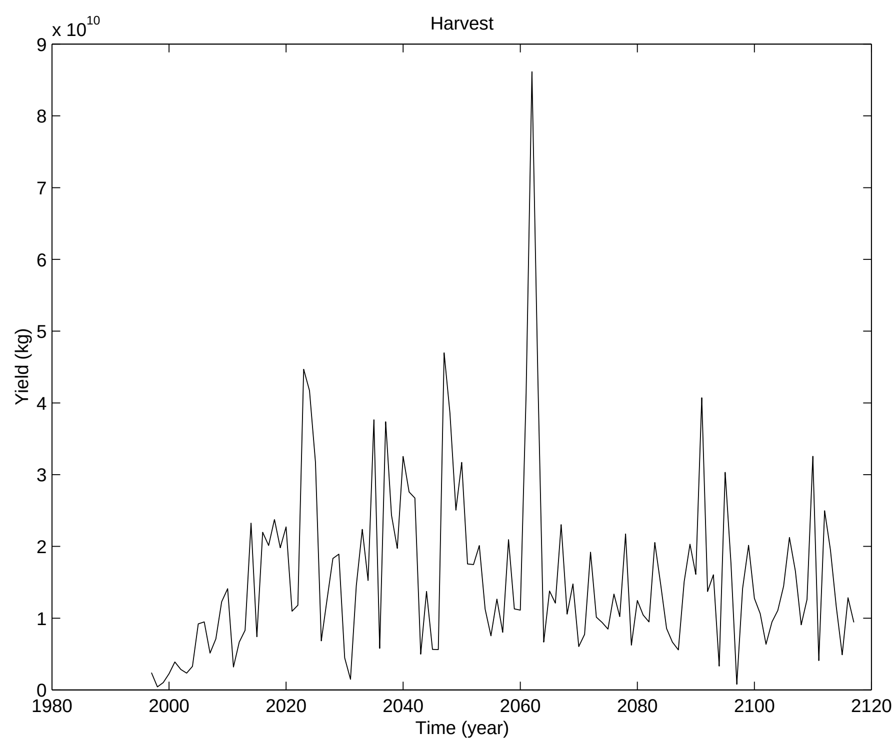

Figure 6: Simulation of the catch in weight (yield) along time

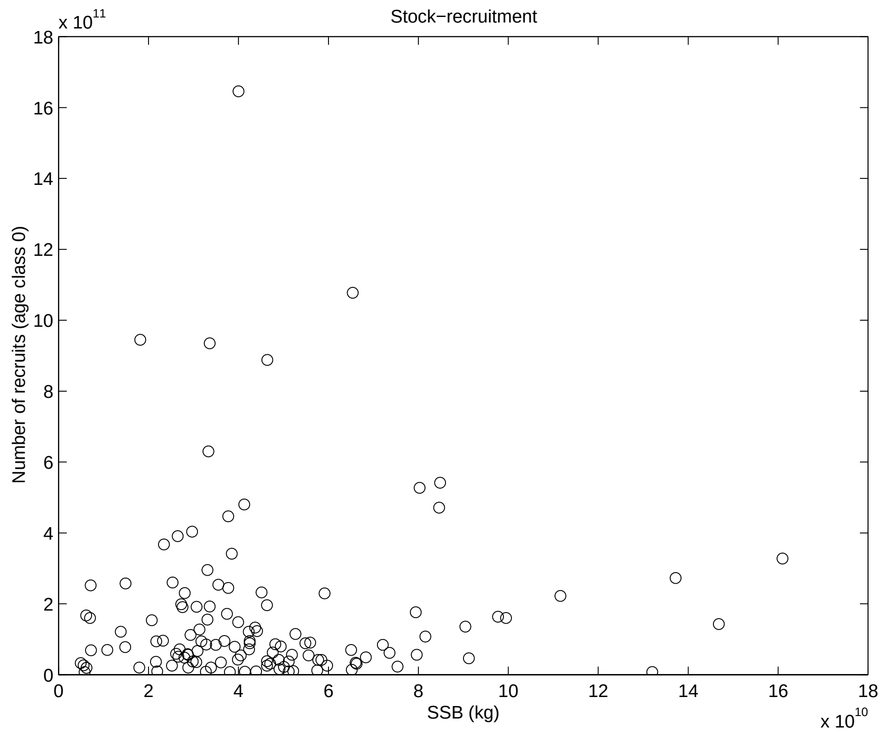

Figure 7: Simulation of the recruitment with respect to the spawning stock biomass

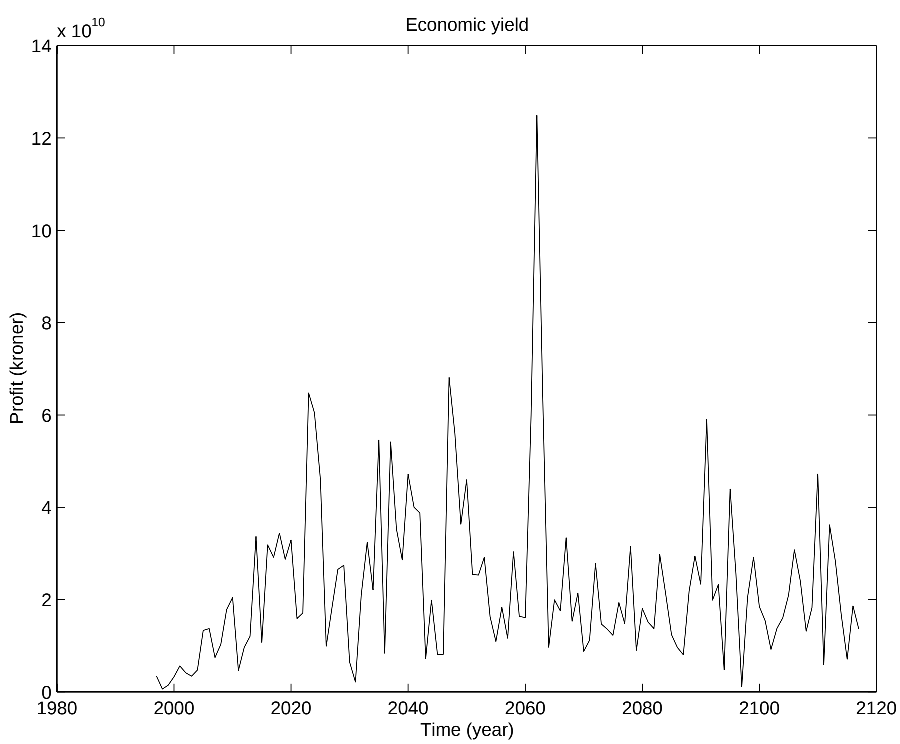

Figure 8: Simulation of the profit along time

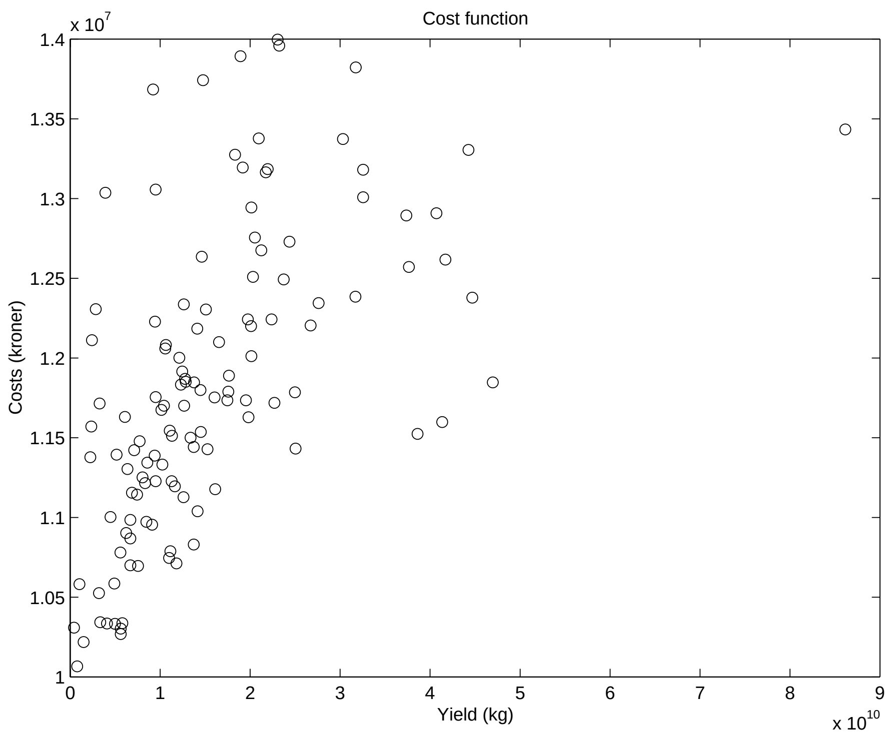

Figure 9: Simulation of the costs with respect to the yield

- $IC = 1996$ as initial condition year;

- selectivities S_a estimated from the IC data;

- a set of constant fishing mortalities F, which ranges from 0 to 2.

The initial condition N_{a,y_1} of equation 1 does not influence this study, for we are interested in the steady state. However, the IC variable is also used to determine the parameters stemming from the data, as the selectivities S_a and for the DI model, the maturity ogives and the weights at age.

Results of this comparison are shown in figure 10. A few remarks arise.

1. The rather unusual shape of the RICKER density-independent curve for small fishing mortalities shouldn't be taken into account. At this level of harvest, RICKER's recruitment induces oscillations that are not dampened yet, so the steady state has not been reached.

2. It is possible to identify a MSY for the four models. They occur for different fishing mortality.

3. The yield and biomass equilibrium values differ quite a lot from the DD models to the DI models. The MSY values are much higher for the DI models.

4. The stock-recruitment relationship has little effect on the equilibrium of the DD models.

To the previous study, we add a further assumption (it appears also in PATTERSON's draft [7]): the natural mortality of the juveniles is higher, i.e, $m_a = 0.9$ for $a = 0, 1, 2$. The new curves are shown in figure 11 and the following points are made:

1. The high juvenile mortality dampens the oscillations observed previously for the RICKER DI model. They can only be observed for high biomasses, when the global mortality is not too important.

2. The MSY is still identifiable for the four models and is much lower than in the previous case. It occurs around the same fishing mortality for the four models: between 0.15 and 0.2, which is generally lower than previously. This shows that the stock is much more vulnerable in this case.

3. The difference in biomass and yield levels between the DD and DI models is reduced with a high juvenile mortality.

4. The influence of the stock-recruitment relation on the DD model is slightly more obvious here.

We are also interested in observing the influence of the selection pattern on the equilibrium. We therefore use the simple selection pattern presented in section 2.5 and we modify the first fishing age a_1. Results are exposed in figure 12.

We notice that raising the first fishing age a_1 increases the MSY and then makes it disappear. From $a_1 = 7$, the yield does not decrease for fishing mortalities but increases slowly, probably towards a bounded value. At this point, the population survives through its younger classes, of which some are spawning, whereas the bigger fish are heavily harvested.

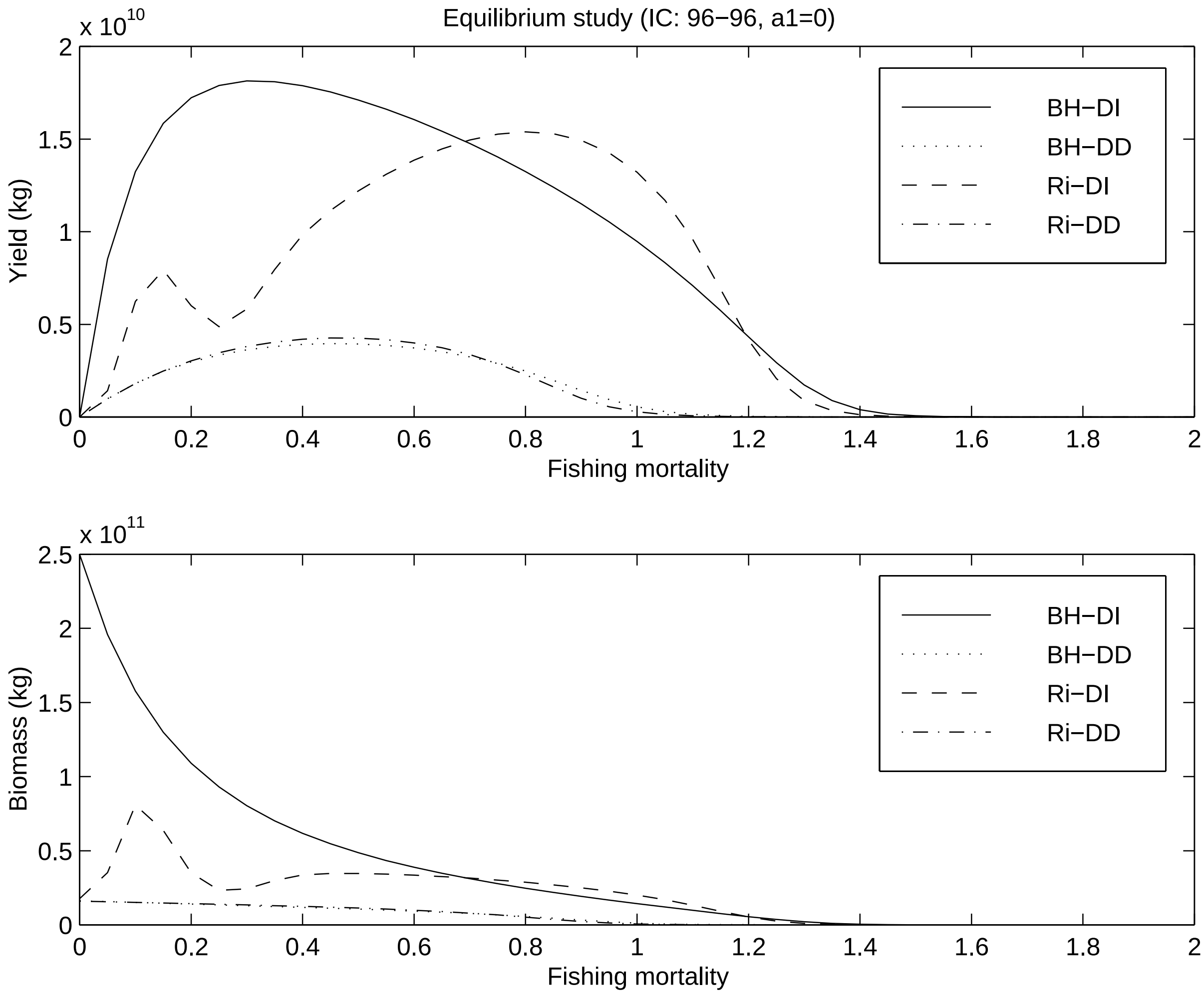

Figure 10: Comparison of the equilibrium properties for the different stock dynamics models

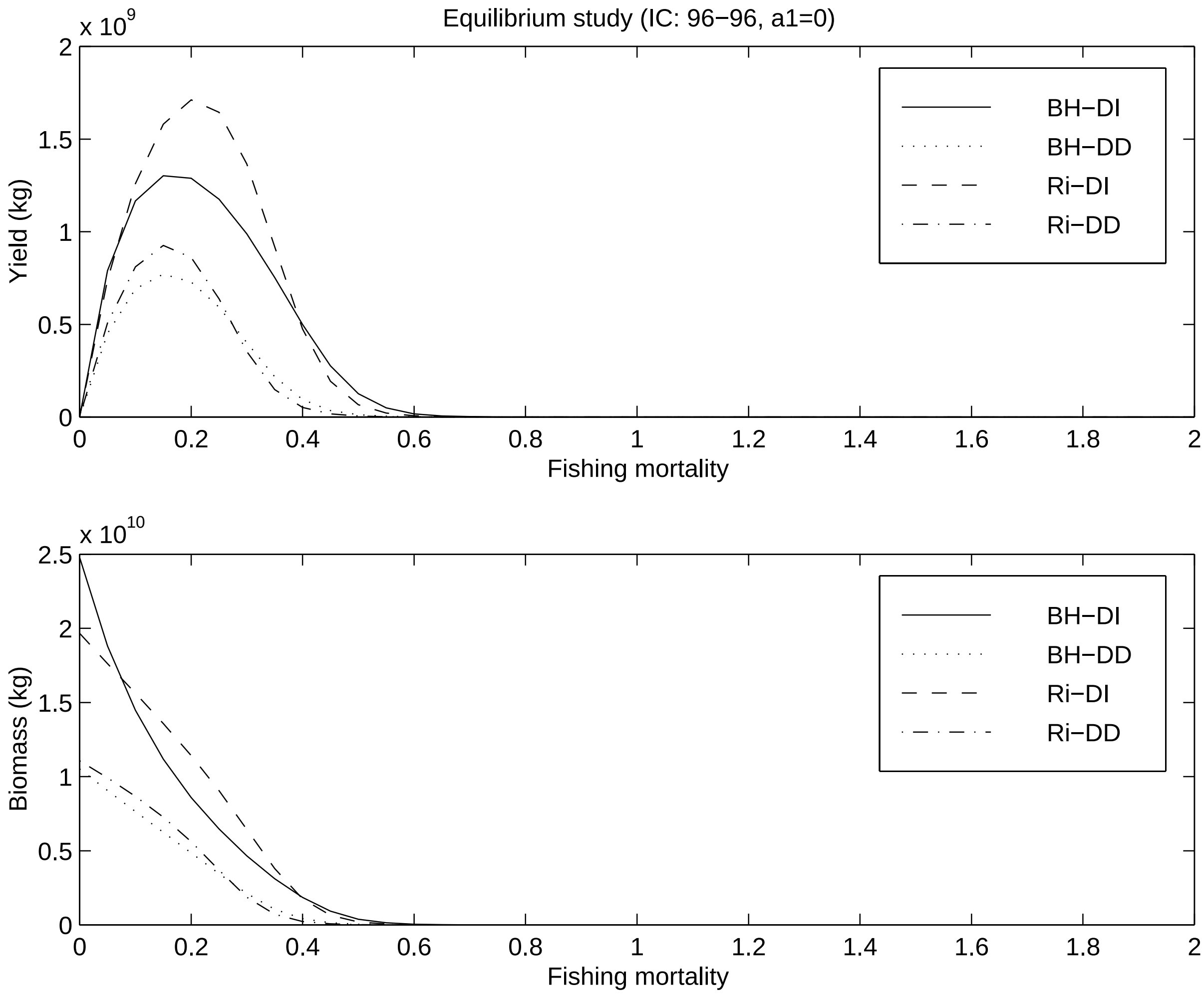

Figure 11: Influence of a higher juvenile mortality on the equilibrium properties of the different stock dynamics models

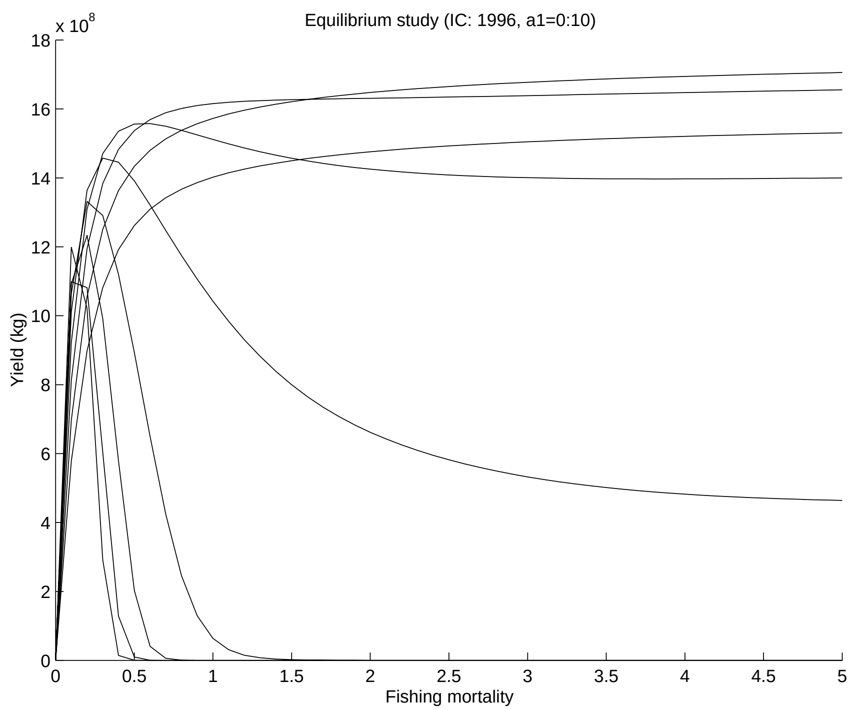

Figure 12: Influence of the selection pattern on the equilibrium properties of the density-independent model with Beverton–Holt 's stock-recruitment relationship

5.3 Risk analysis

The risk analysis has been made on the "reference model", the density-independent model with a BEVERTON–HOLT recruitment and no autocorrelation ($SR = 0$ and $AC = 0$). Following parameters have moreover been used:

- $y_1 = 1997$ and $y_2 = 2097$ for the simulation period; $SIM = 100$ simulations for each fishing mortality;
- $IC = (1993, \ldots, 1996)$ as initial condition years;
- a set of constant fishing mortalities F, that ranges from 0 to 2;
- a simple selection pattern as described in section 2.5, $a_1 = 3$ being the first fishing age;
- $B_{crit} = 5\,10^9$kg, $SSB_{crit} = 2.5\,10^9$kg, $Y_{crit} = 0.5\,10^9$kg and $P_{crit} = 0$ NK.

  The value SSB_{crit} was recommended in [4] and a zero profit assumption is quite natural. The other values are reasonable with respect to SSB_{crit}.

The discussion is organised around two topics: the biological risk concerning the total biomass and the spawning stock biomass, and the economic risk concerning the yield and the profit.

Biological risk The first plots of figures 13 and 15 show that there is no risk for the stock and spawning stock to decrease below their critical value before the fishing mortality reaches the 0.4 value. Then the risk increases rapidly for the vulnerable spawning stock and a little smoother for the total biomass.

However, the mean number of years spent under the threshold becomes significant for higher fishing mortalities, starting from the 0.6 value. For lower rates, the trespassing of the critical value is more punctual and rather appears in the early years. This is obvious in the lower plot of figure 16 concerning the spawning stock risk distribution and less in figure 14 concerning the total biomass, because the transition between no risk and 100% risk is not as sharp. Thus we can identify *three fishing zones*: the safe zone, for fishing mortalities between 0 and 0.4, the totally unsafe zone, for mortalities higher than 0.6 and the intermediate zone, where there is a risk of falling below the threshold, but it can be reversed.

For high fishing mortalities, the total biomass and the spawning stock biomass are instantaneously driven beyond their critical value and remain below this level.

Economic risk Figures 17 and 19 show the mean risk, first year and the number of years under the catch and profit criteria. These figures are quite similar. They differ from the previous curves on three points:

- The risk probability for very low fishing mortalities is 1. This is reasonable, for the catch is then negligeable.
- When the fishing mortality increases, the same transition as previously, from no risk to 100% risk is observed, but it occurs at much higher levels: 0.8 for the catch and 1 for the profit.

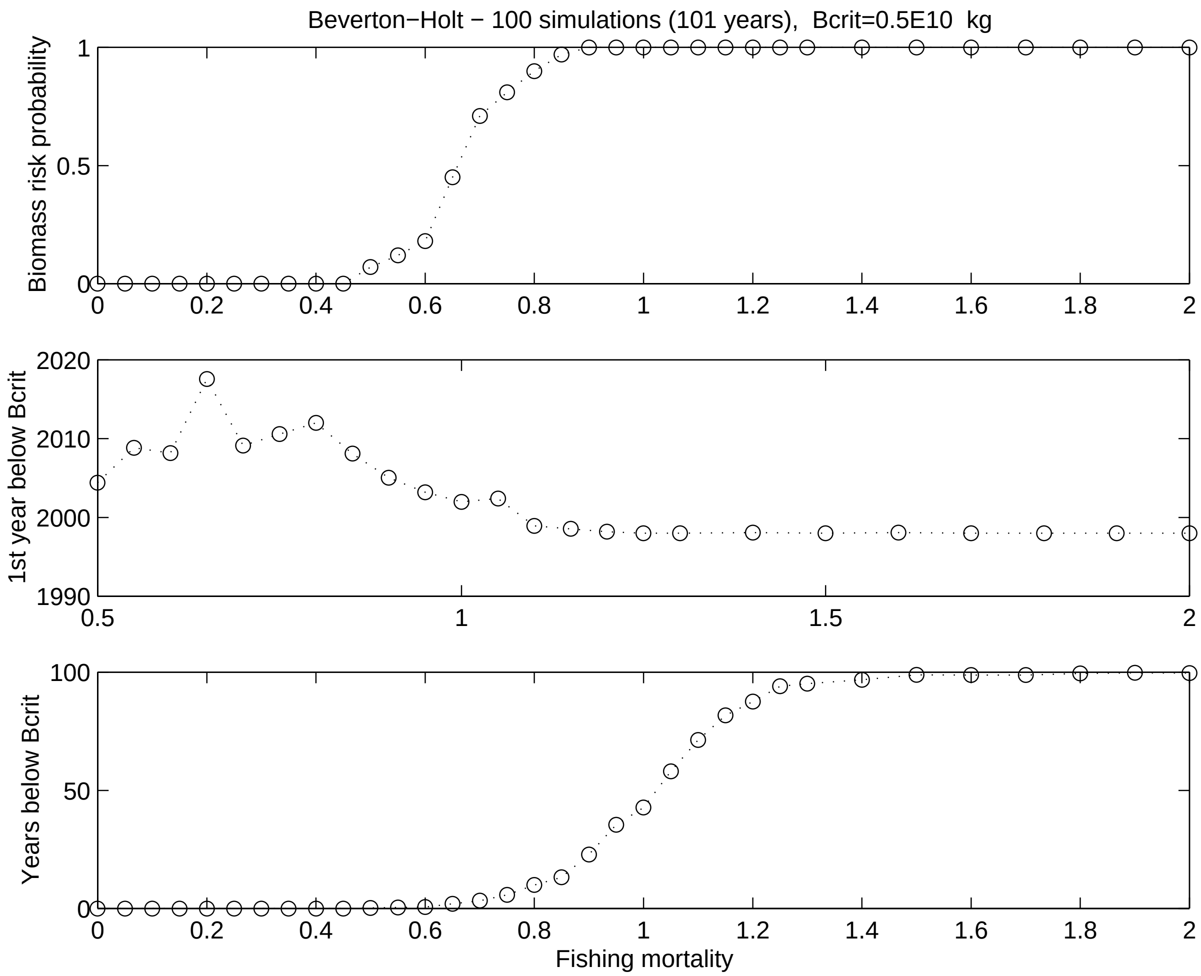

Figure 13: Risk probability for the total biomass

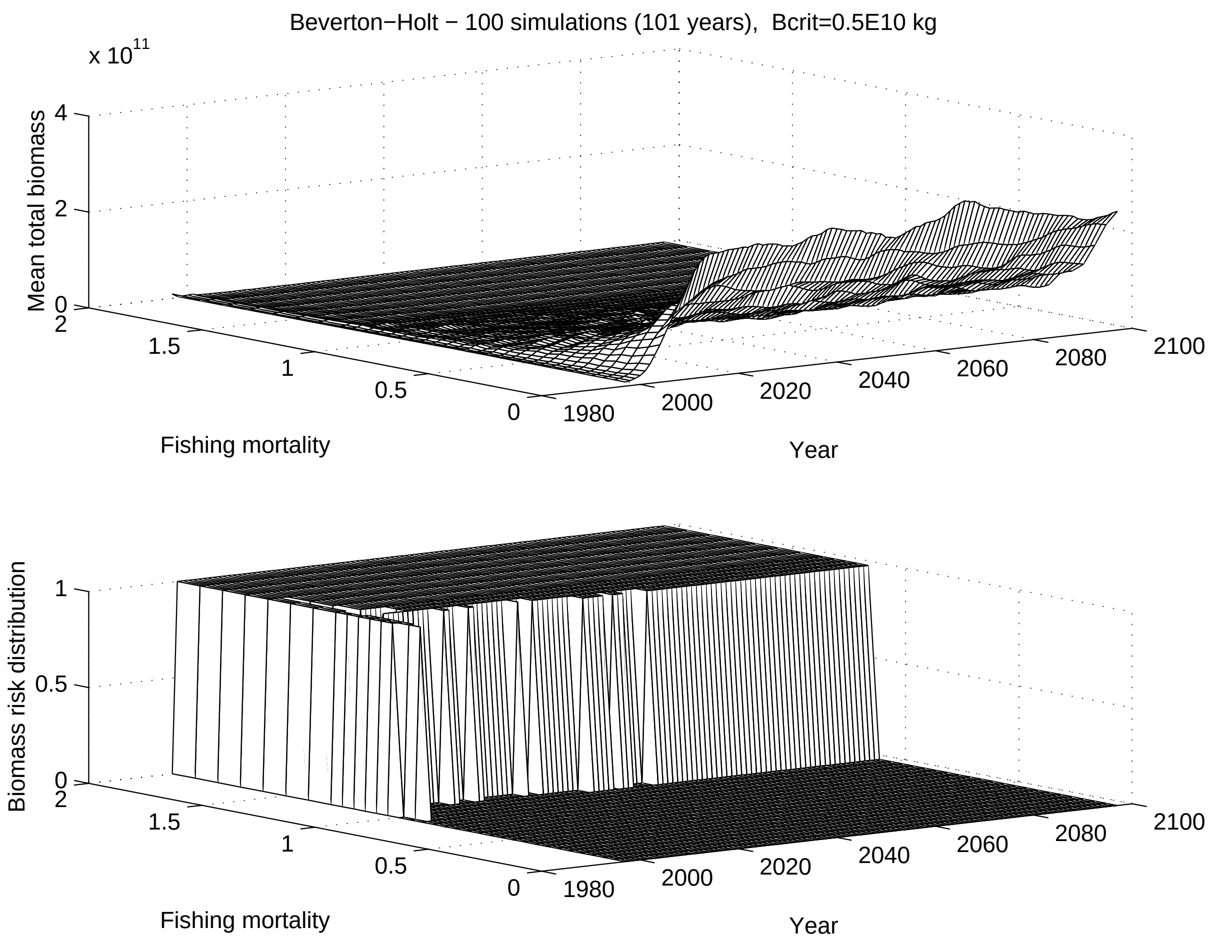

Figure 14: Risk distribution for the total biomass

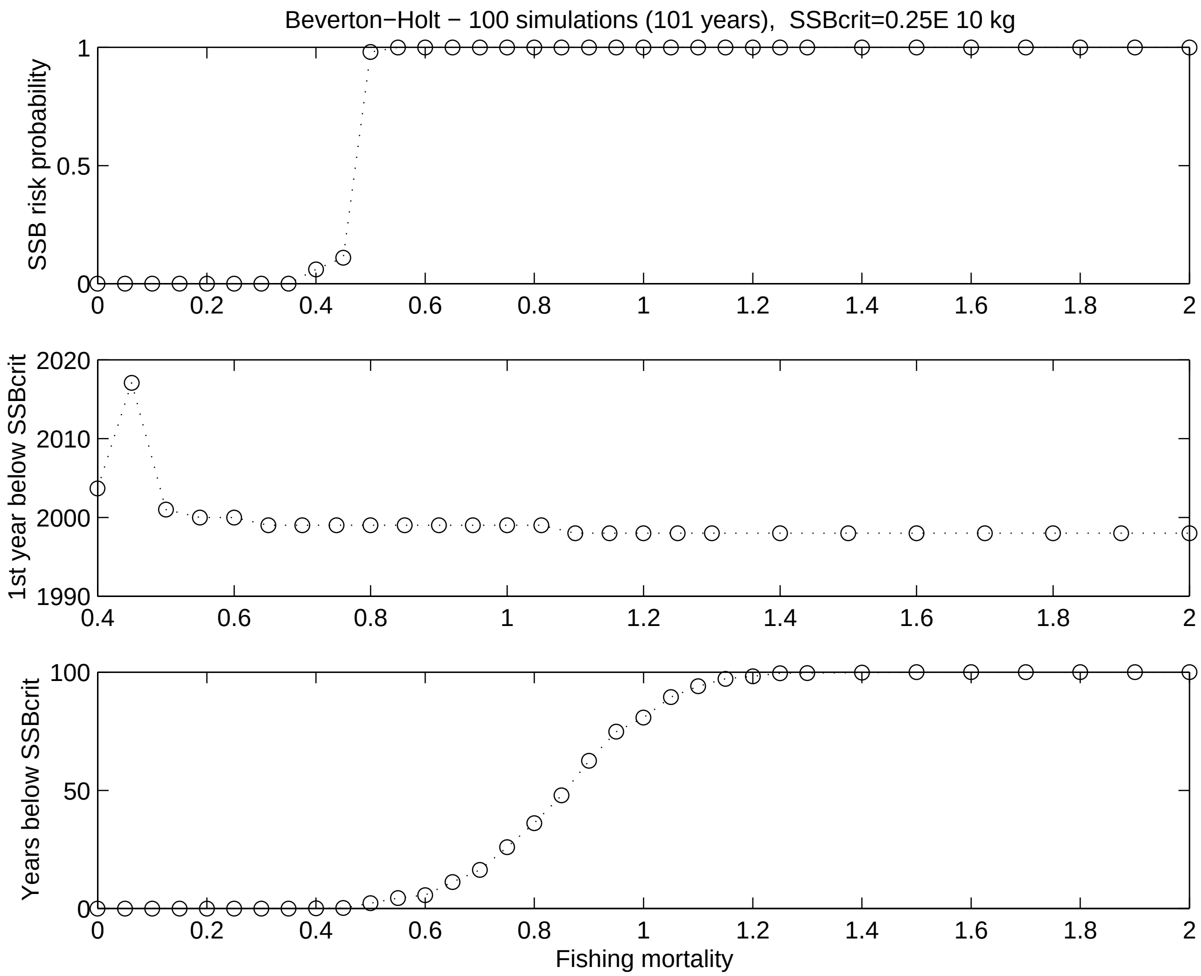

Figure 15: Risk probability for the spawning stock biomass

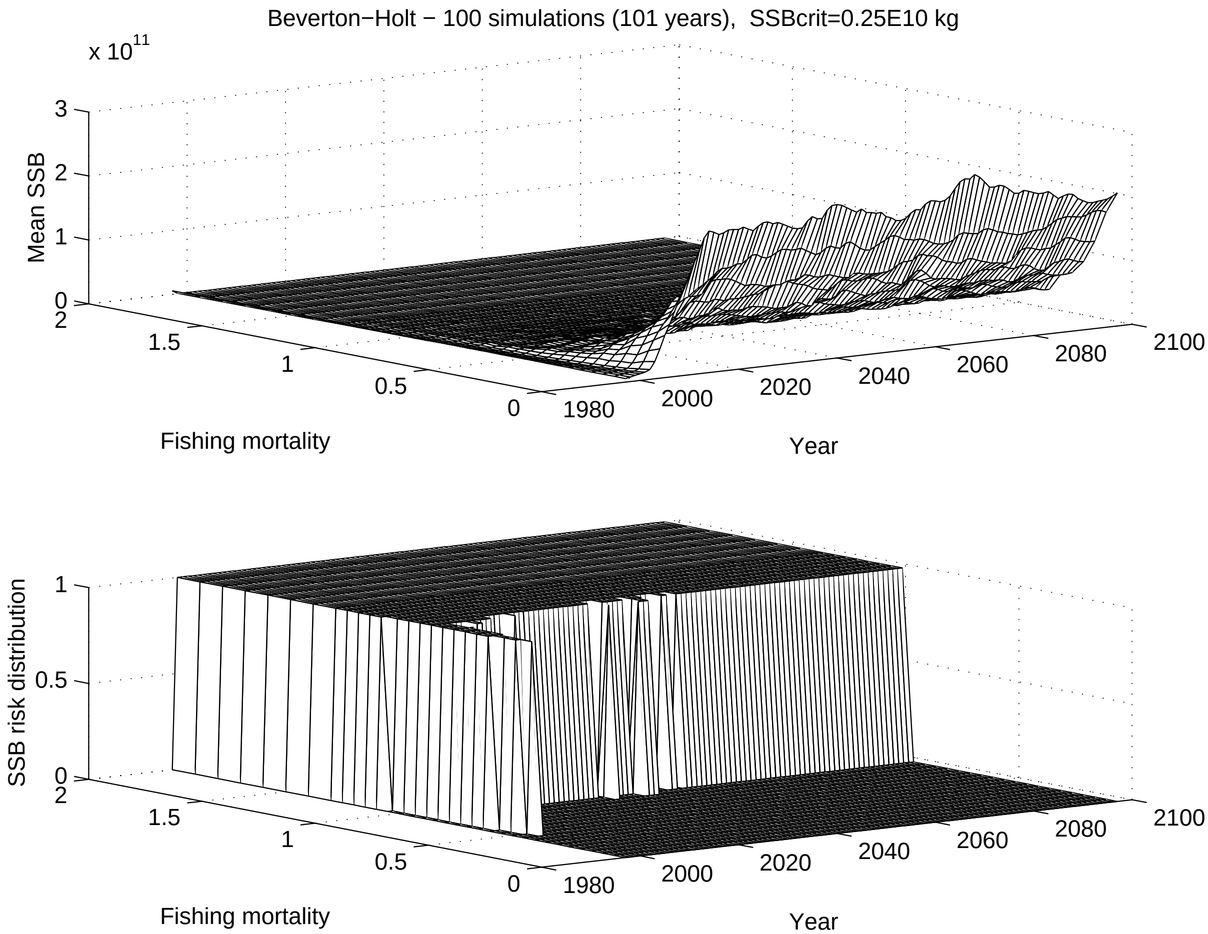

Figure 16: Risk distribution for the spawning stock biomass

- The punctual trespassing of the threshold is not noticeable here, and the mean number of years spent below this level never reaches the whole period. It can be easily observed from the risk distribution, in the lower plots of figures 18 and 20: the catch and profit are also always satisfactory during the first years.

Among other things, these remarks show that the critical value of the catch Y_{crit} might be a bit low and that the proportional costs (q_2F) might have been underestimated.

6 Conclusions and perspectives

We have presented some studies made on a biological model of the Norwegian spring-spawning herring stock dynamics, coupled with a preliminary and very simple economic model. They consisted of basic simulation, equilibrium study and risk analysis. The aim of this technical report was rather to present some methods than any in-depth analysis.

However, some interesting results have been shown, especially for the risk analysis. It has also been demonstrated that the model may be very sensitive to some parameter changes. Increasing the juvenile natural mortality for instance, produces significant alterations on the equilibrium properties. This consideration should therefore be kept in mind in any further development of the model.

Following developments would be necessary for the economic part of the model: a more realistic cost function would considerably improve the actual model. Another perspective would be to implement the spatial and seasonal distribution of the fish and the fleets. It would be very interesting to try to manage this fishery by applying some well chosen fishing mortalities on the stock (control or game theory methods).

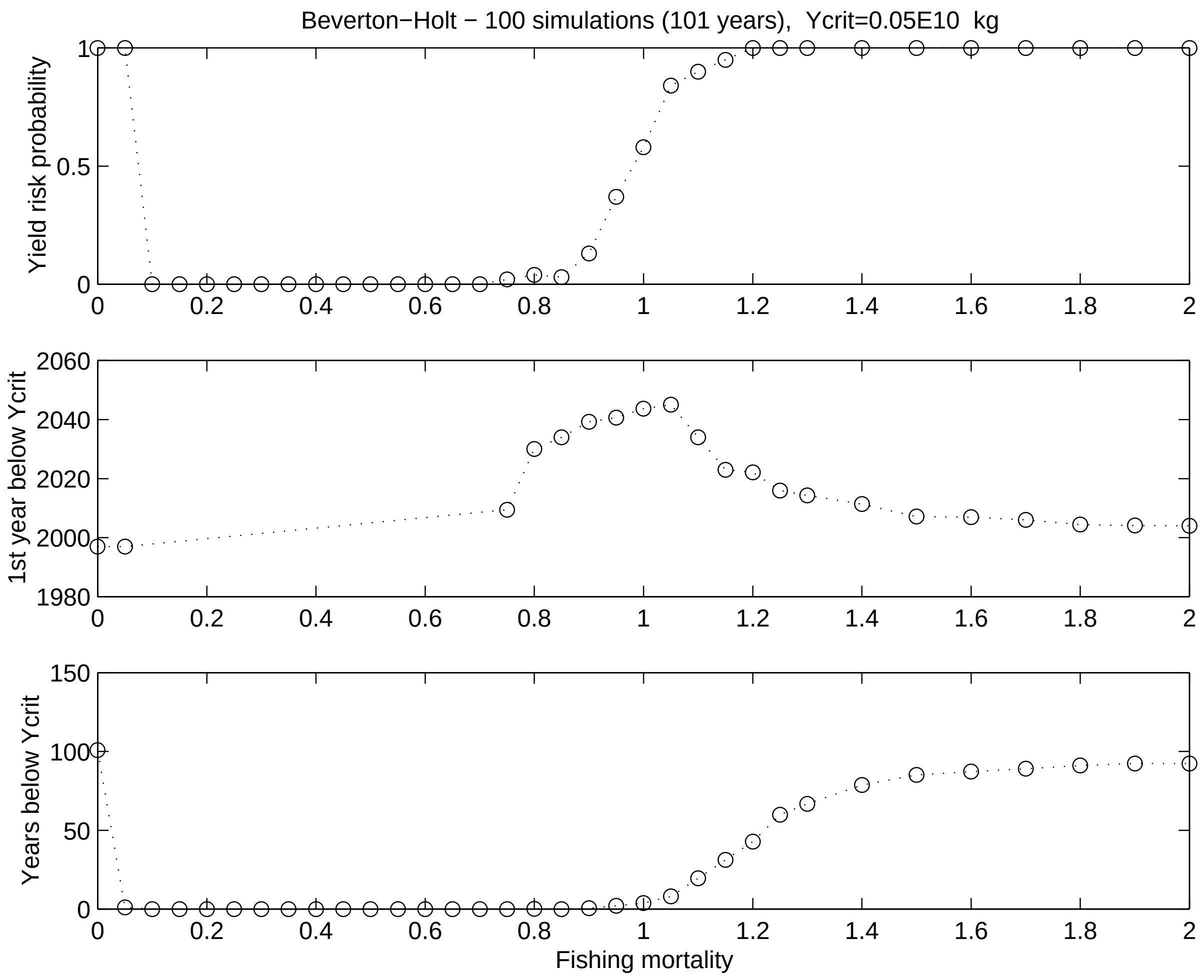

Figure 17: Risk probability for the yield (total catch in weight)

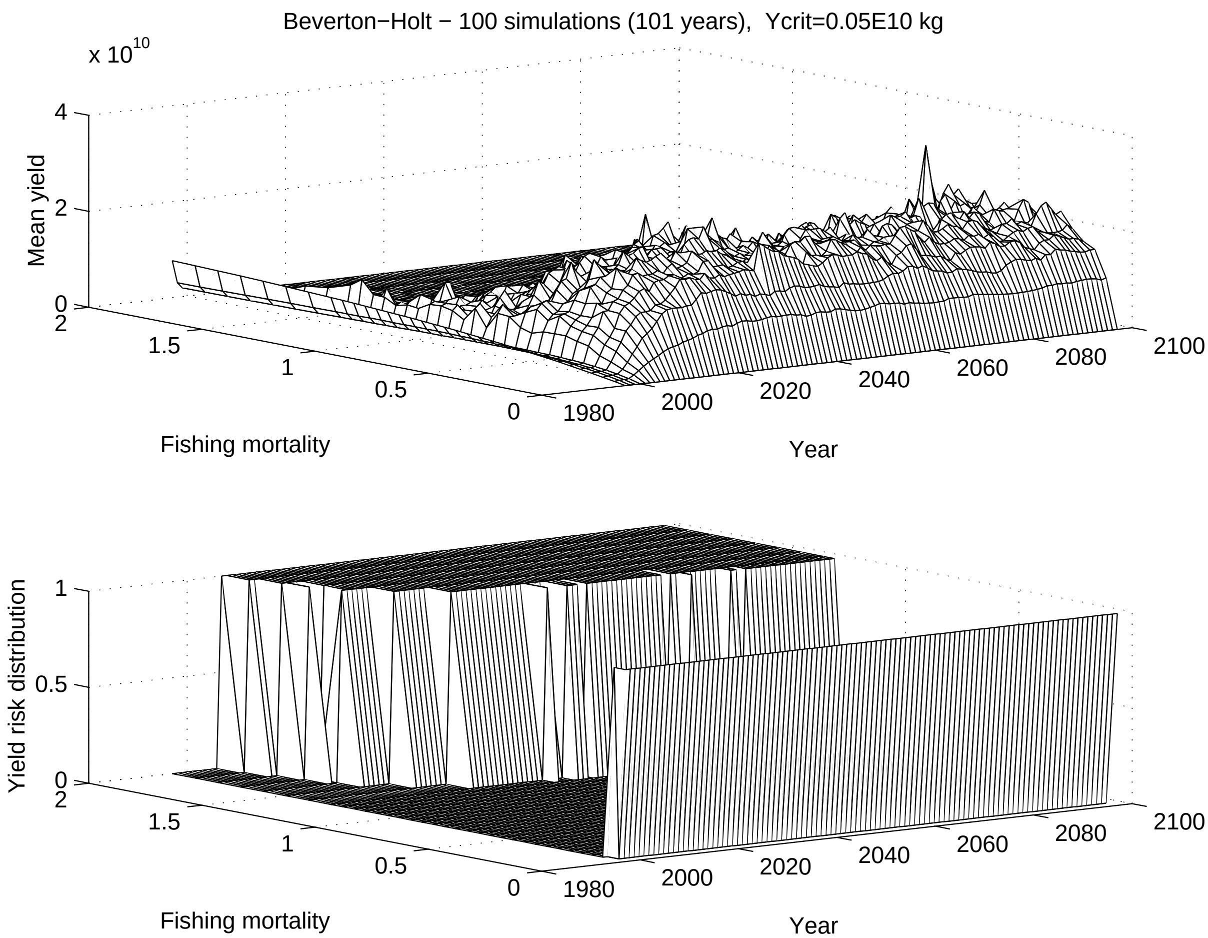

Figure 18: Risk distribution for the yield (total catch in weight)

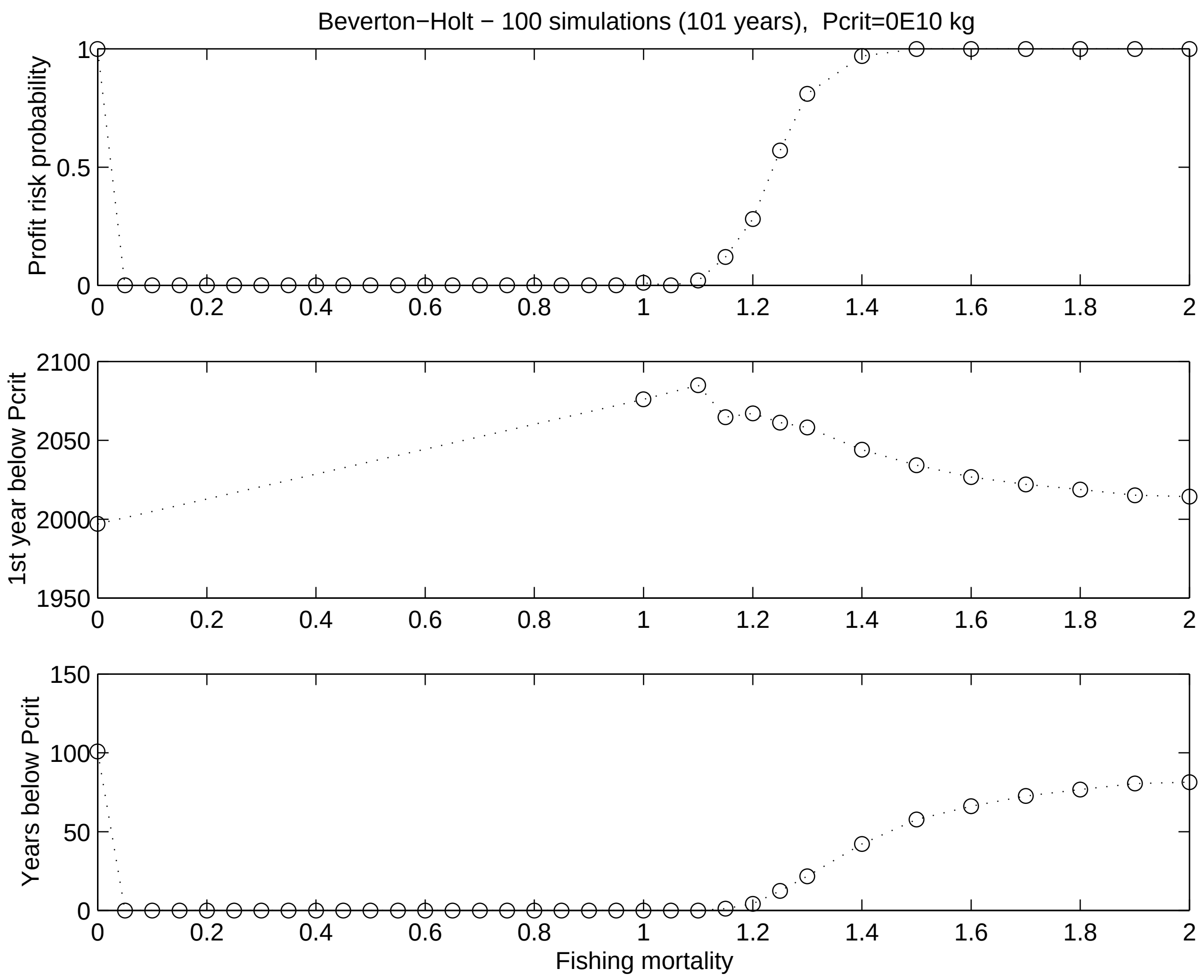

Figure 19: Risk probability for the profit

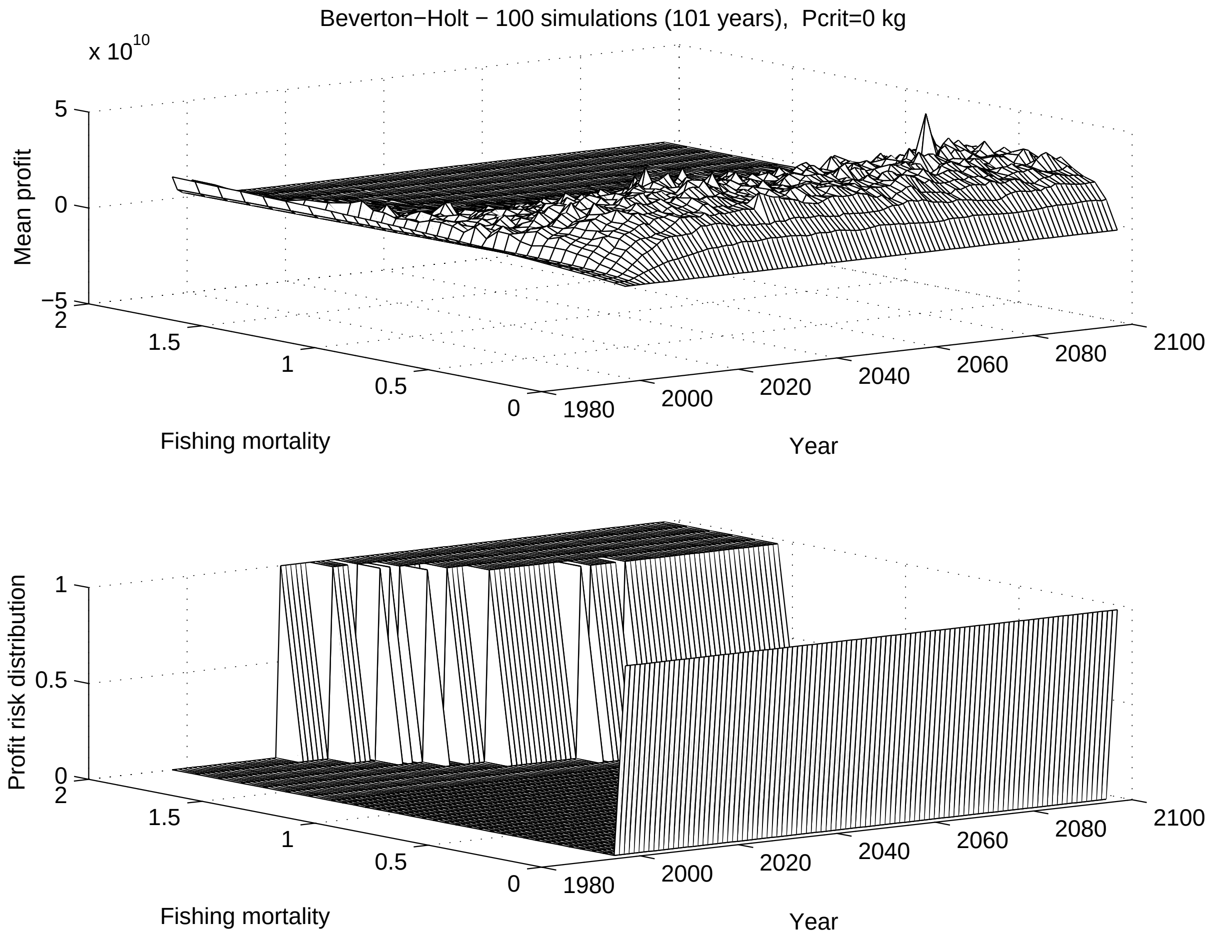

Figure 20: Risk distribution for the profit

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[1] Anonymous. Report of the northern pelagic and blue whiting fisheries working group. ICES C.M. 1996 Assess: 14, 1996.

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APPENDIX

A Spatial and seasonal distributions

We offer here a very brief presentation of the spatial and seasonal distribution of the fish and the fishing fleets. It is more detailed in PATTERSON's report [7].

The seasonal effect is introduced by the means of a quarter subscript q. One year is divided in 4 quarters, corresponding the seasons. It's a time subdivision, so there are two time variables: the year y and the season or quarter q.

The i subscript represents the EEZ[1] and adds a spatial dimension to the model. Each EEZ, more or less corresponding to a fleet, is among the following zones: Faroes, Iceland, Norway, Jan Mayen, Russia, Int.Bar. Int.Nor. Spitsberg and EU.

The repartition of the fish and fishing mortality in the different zones is introduced in the following way:

$$\begin{aligned} N_{a,y,q,i} &= p_{a,y,q,i} N_{a,y,q} \\ F_{a,y,q,i} &= S_{a,i} F_{y,q,i} \end{aligned}$$

Equation 1 of the previous model becomes:

$$\begin{aligned} N_{a,y,q+1,i} &= p_{a,y,q+1,i} N_{a,y,q+1} \\ &= p_{a,y,q+1,i} \sum_i N_{a,y,q,i} e^{-m/4 - F_{a,y,q,i}/4} \end{aligned}$$

and the catch, formerly equation 9:

$$Y_{y,q,i} = \sum_{a=0}^{a=16} CW_{a,y} N_{a,y,q,i} \frac{F_{a,y,q,i}}{m + F_{a,y,q,i}} \left(1 - e^{-m/4 - F_{a,y,q,i}/4}\right)$$

The major problem is of course the definition of the spatial parameters $p_{a,y,q,i}$. Some historical data are available on the spatial and seasonal repartition of the fish. From these data, four reference year classes yc have been chosen: 1950, 1959, 1972 and 1983. The historical distribution rates of the fish in the zones, by age and season, are noted: $\pi_{a,q,i,yc}$ (percentages).

The first and rougher approach to estimate the spatial parameters is to take the mean value:

$$p_{a,y,q,i} = p_{a,q,i} = \frac{1}{4} \sum_{yc} \pi_{a,q,i,yc} \quad \text{with: } yc \in \{1950, 1959, 1972, 1983\}$$

The stock in the early 70' was particularly low and the fish were all situated in the Norwegian coastal zone. So the previous estimate can be improved in the following way: when the spawning stock biomass is below some critical level B_{crit}, the 1972 year class data are used (coastal régime); otherwise, the mean value of the remaining data is computed. Equations follow:

$$\begin{aligned} p_{a,y,q,i} &= \frac{\pi_{a,q,i,1950} + \pi_{a,q,i,1959} + \pi_{a,q,i,1983}}{3} && if SSB(y) > B_{crit} \\ p_{a,y,q,i} &= \pi_{a,q,i,1972} && \text{otherwise} \end{aligned}$$

[1]Exclusive Economic Zone. The Law of the Sea Convention from 1982 provides the coastal states with full property rights to all marine resources within 200 nautical miles from their coastlines.

A further development consists in smoothing the transition by introducing two critical levels: B_{high} and B_{low}. If the spawning stock biomass is below B_{low}, 1972 year class data are used; if it is above B_{high}, the mean values of 1950, 1959 and 1983 data are used; in between, a linear interpolation is used. Equations are the following:

$$p_{a,y,q,i} = \frac{\pi_{a,q,i,1950} + \pi_{a,q,i,1959} + \pi_{a,q,i,1983}}{3} \qquad \text{if } SSB(y) > B_{high}$$

$$p_{a,y,q,i} = \phi\frac{\pi_{a,q,i,1950} + \pi_{a,q,i,1959} + \pi_{a,q,i,1983}}{3} + (1-\phi)\pi_{a,q,i,1972} \qquad \text{if } B_{low} \leqslant SSB(y) \leqslant B_{high}$$

$$p_{a,y,q,i} = \pi_{a,q,i,1972} \qquad if SSB(y) < B_{low}$$

$$\text{with: } \phi = \frac{SSB(y) - B_{low}}{B_{high} - B_{low}}$$

The spatial and seasonal year class data $\pi_{a,q,i,yc}$ are available in PATTERSON's report [7], appendix E. The other parameters are presented in table 6.

Parameter	value	unit
B_{crit}	500	10^6kg
B_{low}	360	10^6kg
B_{high}	500	10^6kg

Table 6: Spatial distribution parameters

B MATLAB M-files

```
%****************************************
% NSS HERRING POPULATION DYNAMICS (HER1.M)
%****************************************
%
% DENSITY-INDEPENDENT BIOECONOMIC MODEL
%
%Age-structured model, discrete time, one year time step.
%Stock-recruitement: Beverton-Holt (SR=0) or Ricker (SR=1)
%                    determinitic (RD=0) or + noise (RD=1)
%                    with (AC=1) or without (AC=0) autocorrelation.
%Natural mortality: constant (along time) and age-dependent.
%Fishing mortality: constant or fluctuating and age-independent.
%Selectivity: constant and age-dependent.
%Economic yield: constant price/kg, fixed and proportionnal harvesting costs.
%Maturity rates (MO), stock/catch weights-at-age (SW/CW), selectivities (S)
%and initial abundances (NO) are estimated as the mean values of the data
%corresponding to the initial condition years (IC).
%DATA = *.dat : 1st row=years, 1st year=1950
%               1st column=age classes, 1st class=0
%-> OUTPUT:  N = abundance (age and year)
%            B = biomass (age and year)
%            Y = yield, i.e. catch in weight (age and year)
%          SSB = spawning stock biomass (year)
%            Q = costs (year)
%            P = profit (year)
%NB: column->year, row->age class
%    Weights at age in kg/unit
%    Numbers        in units
%    Biomasses      in kg
%    Prices, Costs  in Norwegian kroner(/kg)
%
%References (number) correspond to equation numbers in the report.

% SIMULATION PARAMETERS
y1=1997; y2=2017;                %Simulation period [y1 y2]
IC=[1993:1996];                  %Initial condition years (vector)
SR=0;                            %Stock-recruitment (SR): 0=B-H, 1=Ricker
RD=1;                            %  1=stochastic error, 0=none
AC=0;                            %  1=autocorrelation,  0=none
amin=0;                          %Ages: minimum
amax=16;                         %      maximum

% ECONOMIC PARAMETERS
%f=ones(1,y2-y1+1)*0.35;         %Fishing mortality: constant
f=abs(.2*randn(1,y2-y1+1)+.35);  %                   fluctuating
a1=3;                            %1st fishing age for simple selectivities
                                 %    a1<0 => data selectivities
q1=1E7;                          %Costs: fixed
```

```
q2=5E6;                          %       proportional
h=1.45;          %Average price [1995, Norges Sildesalgslag, rsmeldinger)

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;      %Natural mortality
%m(1:3)=ones(3,1)*0.9;           %(high juvenile mortality)
arec=0;                          %Recruitment age
if SR==0 & AC==0                 %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                  %  variance of the SR fitting
   g=0;                          %  no autocorrelation
elseif SR==0 & AC==1
   a=31.637;
   b=3284060E3;
   sigma=1.666;
   g=-0.2553;                    %  1st order autocorrelation in SR
elseif SR==1 & AC==0
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
   g=0;
elseif SR==1 & AC==1
   a=25.760;
   b=1.094E-10;
   sigma=1.694;
   g=-0.2655;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                   %Simple selectivities:
   S=ones(amax+1-amin,1);              % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);      % 0 before recruitment
end
load mo.dat;load sw.dat;               %Data loading:
load cw.dat;load n.dat;
MO=mo(2:amax+2-amin,IC-1950+2);        % maturity ogives
SW=sw(2:amax+2-amin,IC-1950+2);        % stock weights at age
CW=cw(2:amax+2-amin,IC-1950+2);        % catch weights at age
N0= n(2:amax+2-amin,IC-1950+2);        % initial abundances (in millions)
if length(IC)>1
   MO=mean(MO')';SW=mean(SW')';        %Mean data over IC:
   CW=mean(CW')';N0=mean(N0')';
end
```

```
N=zeros(amax-amin+1,length(y1:y2));
B=zeros(size(N));
Y=zeros(size(N));
SSB=zeros(size(y1:y2));
N(:,1)=N0*1E6;                          %Initial abundances in units
B(:,1)=SW.*N0*1E6;                      %        biomasses
SSB(1)=MO'*B(:,1);                      %        spawning stock biomass
E1=sqrt(sigma)*randn*RD;                %SR autocorrelation initialization

% POPULATION DYNAMICS SIMULATION
for t=2:y2-y1+1
   E=sqrt(sigma)*randn*RD;                            %SR error generation
   for i=arec+2-amin:amax+1-amin
      N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f(t-1)*S(i-1)); %Population ageing (1)
   end
   SSB(t)=MO'*(SW.*N(:,t));                          %SSB (6)
   if SR==0                                           %SR: Beverton-Holt (7)
      N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(g*E1+E);
   else                                               %SR: Ricker (8)
      N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(g*E1+E);
   end
   B(:,t)=SW.*N(:,t);                                 %Biomasses at age (4)
   E1=E;                                              %SR error autocorrelation
end

% YIELD
for t=1:y2-y1+1
   z=m+f(t)*S;                                        %Total mortality at time t
   Y(:,t)=CW.*(1-exp(-z)).*(f(t)*S./z).*N(:,t);     %Yield at age
end
TY=sum(Y);                                            %Total yield (9)
Q=q1+q2.*f;                                           %Costs
P=h.*TY-Q;                                            %Profit (10)

% PLOTS
figure
plot(y1:y2,sum(B(arec+1-amin:amax+1-amin,:)))       %Stock biomass along time
xlabel('Time (year)');
ylabel('Stock biomass (kg)');
title('Population dynamics');

figure
plot(y1:y2,TY)                                        %Yield along time
xlabel('Time (year)');
ylabel('Yield (kg)');
title('Harvest');

figure
plot(SSB,N(1,:),'o')                                  %SR
xlabel('SSB (kg)');
```

```
ylabel('Number of recruits (age class 0)');
title('Stock-recruitment');

figure
plot(y1:y2,P)                                           %Profit along time
xlabel('Time (year)');
ylabel('Profit (kroner)');
title('Economic yield');

figure
plot(TY,Q,'o')                                          %Cost function
xlabel('Yield (kg)');
ylabel('Costs (kroner)');
title('Cost function');



%********************************************
% NSS HERRING POPULATION DYNAMICS (HER1EQ.M)
%********************************************
%
% DENSITY-INDEPENDENT BIOECONOMIC MODEL:
% EQUILIBRIUM STUDY
%
%Cf HER1, but constant fishing mortality along time.
%-> OUTPUT: L = total biomass (fishing mortality and year)
%           Z = total yield (fishing mortality and year)
%NB: column->year, row->fishing mortality (among F)

% SIMULATION PARAMETERS
y1=1997; y2=2097;                %Simulation period [y1 y2]
IC=[1993:1996];                  %Initial condition years (vector)
SR=0;                            %Stock-recruitment (SR): 0=B-H, 1=Ricker
PLO=1;                           %1=plot equilibrium curves, 2=all
amin=0;                          %Ages: minimum
amax=16;                         %      maximum

% HARVESTING PARAMETERS
F=[0:.05:1];                     %Fishing mortalities
a1=3;                            %1st fishing age for simple selectivities
                                 %    a1<0 => data selectivities

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;      %Natural mortality
%m(1:3)=ones(3,1)*0.9;           %(high juvenile mortality)
arec=0;                          %Recruitment age
if SR==0                         %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                  %  bias of the SR fitting
elseif SR==1
```

```
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                    %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                       %Simple selectivities:
   S=ones(amax+1-amin,1);                  % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);          % 0 before recruitment
end
load mo.dat;load sw.dat;                   %Data loading:
load cw.dat;load n.dat;
MO=mo(2:amax+2-amin,IC-1950+2);            % maturity ogives
SW=sw(2:amax+2-amin,IC-1950+2);            % stock weights at age
CW=cw(2:amax+2-amin,IC-1950+2);            % catch weights at age
N0= n(2:amax+2-amin,IC-1950+2);            % initial abundances (in millions)
if length(IC)>1
   MO=mean(MO')';SW=mean(SW')';            %Mean data over IC:
   CW=mean(CW')';N0=mean(N0')';
end
N=zeros(amax+1,length(y1:y2));             %Initializations
B=zeros(size(N));
Y=zeros(size(N));
SSB=zeros(size(y1:y2));
Z=zeros(length(F),length(y1:y2));
L=zeros(length(F),length(y1:y2));
N(:,1)=N0*1E6;                             %Initial abundances (in units)
B(:,1)=SW.*N0*1E6;                         %        biomasses
SSB(1)=MO'*B(:,1);                         %        spawning stock biomass

% POPULATION DYNAMICS SIMULATION
j=1;
for f=F
   z=m+f*S;                                          %Total mortality for f
   Y(:,1)=CW.*(1-exp(-z)).*(f*S./z).*N(:,1);         %Initial yield at age
   for t=2:y2-y1+1
      for i=arec+2-amin:amax+1-amin
         N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f*S(i-1));%Population ageing (1)
      end
      SSB(t)=MO'*(SW.*N(:,t));                       %Spawning stock biomass (6)
      if SR==0                                       %SR: Beverton-Holt (7)
         N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(sigma/2);
      else                                           %SR: Ricker (8)
         N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(sigma/2);
```

```
      end
      B(:,t)=SW.*N(:,t);                             %Biomasses at age (4)
      Y(:,t)=CW.*(1-exp(-z)).*(f*S./z).*N(:,t);  %Yield at age (9)
   end
   L(j,:)=sum(B);                                    %Biomasses at f
   Z(j,:)=sum(Y);                                    %Yields at f
   j=j+1;
end

% PLOTS
if PLO==1 | PLO==2
figure                                   %Equilibrium biomass & yield
clf reset
plot(F,Z(:,y2-y1+1),F,L(:,y2-y1+1)/10,'--')
xlabel('Fishing mortality');
ylabel('Biomass/10 (dashed) and Yield (kg)');
if SR==0
   title('Equilibrium (DI - Beverton-Holt recruitment)');
elseif SR==1
   title('Equilibrium (DI - Ricker recruitment)');
end

if PLO==2
figure                                   %Biomasses along time for small f
clf reset
plot(y1:y2,L(1:5,:))
xlabel('Time (year)');
ylabel('Biomass (kg)');
if SR==0
   title(['Fishing mortality=',mat2str(F(1:5)),' (Beverton-Holt)']);
elseif SR==1
   title(['Fishing mortality=',mat2str(F(1:5)),' (Ricker)']);
end

figure                                   %Biomasses along time for large f
clf reset
plot(y1:y2,L(length(F)-4:length(F),:))
xlabel('Time (year)');
ylabel('Biomass (kg)');
if SR==0
   title(['Fishing mortality=',mat2str(F(length(F)-4:length(F))),...
   ' (Beverton-Holt)']);
elseif SR==1
   title(['Fishing mortality=',mat2str(F(length(F)-4:length(F))),...
   ' (Ricker)']);
end
end
end
```

```
%******************************************
% NSS HERRING POPULATION DYNAMICS (HER1DI.M)
%******************************************
%
% DENSITY-INDEPENDENT BIOECONOMIC MODEL:
% RISK ANALYSIS & RISK DISTRIBUTION
%
%Cf HER1, HER1RI.
%-> OUTPUT: R*  = Risk (F fishing mortalities and SIM simulations)
%           T1* = First year beyond the critical level (F and SIM)
%           TN* = Number of years beyond the critical level (F and SIM)
%                 column SIM+1 : mean value (probability for R)
%                 column SIM+2 : standard deviation
%           M*  = Mean value (F and year)
%           D*  = Risk distribution (F and year)
%           *=B : for the total biomass
%           *=S : for the spawning stock biomass
%           *=Y : for the yield (catch in weight)
%           *=P : for the profit
%           Results file: hdi"SR""AC""period".mat
%NB: row->fishing mortality (among F)
%    column->simulation (SIM)

% SIMULATION PARAMETERS
SIM=100;                        %Simulations number
Bcrit=0.5E10;                   %Critical biomass
SSBcrit=0.25E10;                %         SSB
Ycrit=0.05E10;                  %         yield
Pcrit=0;                        %         profit
y1=1997; y2=2097;               %Simulation period [y1 y2]
IC=[1993:1996];                 %Initial condition years (vector)
SR=0;                           %Stock-recruitment (SR): 0=B-H, 1=Ricker
RD=1;                           %  1=stochastic error, 0=none
AC=0;                           %  1=autocorrelation,  0=none
PLO=1;                          %1=plot the curves
PRI=1;                          %1=save results in mat-file
amin=0;                         %Ages: minimum
amax=16;                        %      maximum

% ECONOMIC PARAMETERS
F=[0:.05:1.3,1.4:.1:2];         %Fishing mortalities
a1=3;                           %1st fishing age for simple selectivities
                                %    a1<0 => data selectivities
q1=1E7;                         %Costs: fixed
q2=5E6;                         %       proportional
h=1.45;         %Average price [1995, Norges Sildesalgslag, rsmeldinger)

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;     %Natural mortality
%m(1:3)=ones(3,1)*0.9;          %(high juvenile mortality)
```

```
arec=0;                                %Recruitment age
if SR==0 & AC==0                       %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                        %  variance of the SR fitting
   g=0;                                %  no autocorrelation
elseif SR==0 & AC==1
   a=31.637;
   b=3284060E3;
   sigma=1.666;
   g=-0.2553;                          %  1st order autocorrelation in SR
elseif SR==1 & AC==0
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
   g=0;
elseif SR==1 & AC==1
   a=25.760;
   b=1.094E-10;
   sigma=1.694;
   g=-0.2655;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                      %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                         %Simple selectivities:
   S=ones(amax+1-amin,1);                    % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);            % 0 before recruitment
end
load mo.dat;load sw.dat;                     %Data loading:
load cw.dat;load n.dat;
MO=mo(2:amax+2-amin,IC-1950+2);              % maturity ogives
SW=sw(2:amax+2-amin,IC-1950+2);              % stock weights-at-age
CW=cw(2:amax+2-amin,IC-1950+2);              % catch weights-at-age
N0= n(2:amax+2-amin,IC-1950+2);              % initial abundances (in millions)
if length(IC)>1
   MO=mean(MO')';SW=mean(SW')';              %Mean data over IC:
   CW=mean(CW')';N0=mean(N0')';
end
N=zeros(amax-amin+1,length(y1:y2));          %Initializations
B=zeros(size(N));
Y=zeros(size(N));
RB=zeros(length(F),2+SIM); T1B=zeros(size(RB)); TNB=zeros(size(RB));
RS=zeros(size(RB));        T1S=zeros(size(RB)); TNS=zeros(size(RB));
RY=zeros(size(RB));        T1Y=zeros(size(RB)); TNY=zeros(size(RB));
```

```
RP=zeros(size(RB));        T1P=zeros(size(RB)); TNP=zeros(size(RB));
MB=zeros(length(F),length(y1:y2)); DB=zeros(size(MB));
MS=zeros(size(MB));                DS=zeros(size(MB));
MY=zeros(size(MB));                DY=zeros(size(MB));
MP=zeros(size(MB));                DP=zeros(size(MB));
SSB=zeros(size(y1:y2));
N(:,1)=N0*1E6;                         %Initial abundances in units
B(:,1)=SW.*N0*1E6;                     %        biomasses
SSB(1)=MO'*B(:,1);                     %        spawning stock biomass
E1=sqrt(sigma)*randn*RD;               %SR autocorrelation initialization
fis=1;

% POPULATION DYNAMICS SIMULATIONS
for f=F                                                %F fishing mortalities
   z=m+f*S;                                            %Total mortality for f
   Y(:,1)=CW.*(1-exp(-z)).*(f*S./z).*N(:,1);           %Initial yield at age (9)
   for j=1:SIM                                         %SIM simulations
      for t=2:y2-y1+1
         E=sqrt(sigma)*randn*RD;                       %SR error generation
         for i=arec+2-amin:amax+1-amin
            N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f*S(i-1));%Population ageing (1)
         end
         SSB(t)=MO'*(SW.*N(:,t));                      %SSB (6)
         if SR==0                                      %SR: Beverton-Holt (7)
            N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(g*E1+E);
         else                                          %SR: Ricker (8)
            N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(g*E1+E);
         end
         B(:,t)=SW.*N(:,t);                            %Biomasses at age (4)
         Y(:,t)=CW.*(1-exp(-z)).*(f*S./z).*N(:,t);  %Yield at age (9)
         E1=E;                                         %SR error autocorrelation
      end
      P=h*sum(Y)-(q1+q2*f);                            %Profit (10)
      % MEAN VALUES  (fishing mort. & year)
      MB(fis,:)=MB(fis,:)+sum(B)/SIM;                  %Mean biomass
      MS(fis,:)=MS(fis,:)+SSB/SIM;                     %     SSB
      MY(fis,:)=MY(fis,:)+sum(Y)/SIM;                  %     yield
      MP(fis,:)=MP(fis,:)+P/SIM;                       %     profit
      % RISK (fishing mort. & simulation)
      if min(sum(B))<Bcrit
         RB(fis,j)=1;                                  %BIOMASS risk
         ind=find(sum(B)<Bcrit);
         T1B(fis,j)=min(ind)+y1-1;                     %First year < Bcrit
         TNB(fis,j)=length(ind);                       %Number of years < Bcrit
      end
      if min(SSB)<SSBcrit
         RS(fis,j)=1;                                  %SSB risk
         ind=find(SSB<SSBcrit);
         T1S(fis,j)=min(ind)+y1-1;                     %First year < SSBcrit
         TNS(fis,j)=length(ind);                       %Nb of years < SSBcrit
```

```
      end
      if min(sum(Y))<Ycrit
         RY(fis,j)=1 ;                                  %YIELD risk
         ind=find(sum(Y)<Ycrit);
         T1Y(fis,j)=min(ind)+y1-1;                      %First year < Ycrit
         TNY(fis,j)=length(ind);                        %Number of years < Ycrit
      end
      if min(P)<Pcrit
         RP(fis,j)=1;                                   %PROFIT risk
         ind=find(P<Pcrit);
         T1P(fis,j)=min(ind)+y1-1;                      %First year < Pcrit
         TNP(fis,j)=length(ind);                        %Number of years < Pcrit
      end
   end
   fis=fis+1;
end

% RISK ANALYSIS (fishing mort.)
ind=find(MB<Bcrit);                                     %BIOMASS:
DB(ind)=ones(size(ind));                                %Risk distribution (year)
RB(:,SIM+1)=mean(RB(:,1:SIM)')';                        %Risk probability
RB(:,SIM+2)=std(RB(:,1:SIM)')';                         % standard deviation
f1b=find(RB(:,SIM+1));
for i=[f1b]'
   si=find(T1B(i,1:SIM));
   T1B(i,SIM+1)=mean(T1B(i,si));                        %Mean first year < Bcrit
   T1B(i,SIM+2)=std(T1B(i,si));                         % standard deviation
end
TNB(:,SIM+1)=mean(TNB(:,1:SIM)')';                      %Mean nb of years < Bcrit
TNB(:,SIM+2)=std(TNB(:,1:SIM)')';                       % standard deviation
%
ind=find(MS<SSBcrit);                                   %SSB:
DS(ind)=ones(size(ind));                                %Risk distribution (year)
RS(:,SIM+1)=mean(RS(:,1:SIM)')';                        %Risk probability
RS(:,SIM+2)=std(RS(:,1:SIM)')';                         % standard deviation
f1s=find(RS(:,SIM+1));
for i=[f1s]'
   si=find(T1S(i,1:SIM));
   T1S(i,SIM+1)=mean(T1S(i,si));                        %Mean first year < SSBcrit
   T1S(i,SIM+2)=std(T1S(i,si));                         % standard deviation
end
TNS(:,SIM+1)=mean(TNS(:,1:SIM)')';                      %Mean nb of years < SSBcrit
TNS(:,SIM+2)=std(TNS(:,1:SIM)')';                       % standard deviation
%
ind=find(MY<Ycrit);                                     %YIELD:
DY(ind)=ones(size(ind));                                %Risk distribution (year)
RY(:,SIM+1)=mean(RY(:,1:SIM)')';                        %Risk probability
RY(:,SIM+2)=std(RY(:,1:SIM)')';                         % standard deviation
f1y=find(RY(:,SIM+1));
for i=[f1y]'
```

```
   si=find(T1Y(i,1:SIM));
   T1Y(i,SIM+1)=mean(T1Y(i,si));                     %Mean first year < Ycrit
   T1Y(i,SIM+2)=std(T1Y(i,si));                      % standard deviation
end
TNY(:,SIM+1)=mean(TNY(:,1:SIM)')';                   %Mean nb of years < Ycrit
TNY(:,SIM+2)=std(TNY(:,1:SIM)')';                    % standard deviation
%
ind=find(MP<Pcrit);                                  %PROFIT:
DP(ind)=ones(size(ind));                             %Risk distribution (year)
RP(:,SIM+1)=mean(RP(:,1:SIM)')';                     %Risk probability
RP(:,SIM+2)=std(RP(:,1:SIM)')';                      % standard deviation
f1p=find(RP(:,SIM+1));
for i=[f1p]'
   si=find(T1P(i,1:SIM));
   T1P(i,SIM+1)=mean(T1P(i,si));                     %Mean first year < Pcrit
   T1P(i,SIM+2)=std(T1P(i,si));                      % standard deviation
end
TNP(:,SIM+1)=mean(TNP(:,1:SIM)')';                   %Mean nb of years < Pcrit
TNP(:,SIM+2)=std(TNP(:,1:SIM)')';                    % standard deviation

% RISK PLOTS
if PLO==1
%
figure                                       %TOTAL BIOMASS:
clf reset
subplot(3,1,1)
plot(F,RB(:,SIM+1),'mo:')                    %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for biomass');
subplot(3,1,2)
plot(F(f1b),T1B(f1b,SIM+1),'mo:')            %First year < Bcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Bcrit');
subplot(3,1,3)
plot(F,TNB(:,SIM+1),'mo:')                   %Number of years < Bcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Bcrit');
```

```
%
figure                                    %Biomass risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MB);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean total biomass');
subplot(2,1,2)
mesh(y1:y2,F,DB);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Biomass risk distribution');

figure                                    %SPAWNING STOCK BIOMASS:
clf reset
subplot(3,1,1)
plot(F,RS(:,SIM+1),'mo:')                 %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for SSB');
subplot(3,1,2)
plot(F(f1s),T1S(f1s,SIM+1),'mo:')         %First year < SSBcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond SSBcrit');
```

```
subplot(3,1,3)
plot(F,TNS(:,SIM+1),'mo:')                    %Number of years < SSBcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond SSBcrit');
%
figure                                        %SSB risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MS);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean SSB');
subplot(2,1,2)
mesh(y1:y2,F,DS);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('SSB risk distribution');

figure                                        %YIELD:
clf reset
subplot(3,1,1)
plot(F,RY(:,SIM+1),'mo:')                     %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for yield');
```

```
subplot(3,1,2)
plot(F(f1y),T1Y(f1y,SIM+1),'mo:')           %First year < Ycrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Ycrit');
subplot(3,1,3)
plot(F,TNY(:,SIM+1),'mo:')                  %Number of years < Ycrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Ycrit');
%
figure                                      %Yield risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MY);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean yield');
subplot(2,1,2)
mesh(y1:y2,F,DY);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Yield risk distribution');

figure                                      %PROFIT:
clf reset
subplot(3,1,1)
plot(F,RP(:,SIM+1),'mo:')                   %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',nXSum2str(Pcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SxsIM),' simulations (',...
```

```
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for profit');
subplot(3,1,2)
plot(F(f1p),T1P(f1p,SIM+1),'mo:')           %First year < Pcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Pcrit');
subplot(3,1,3)
plot(F,TNP(:,SIM+1),'mo:')                  %Number of years < Pcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Pcrit');
%
figure                                      %Profit risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MP);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean profit');
subplot(2,1,2)
mesh(y1:y2,F,DP);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Profit risk distribution');
end

if PRI==1
   file=['hdi',int2str(SR),int2str(AC),int2str(y2-y1+1)];
   save(file,'AC','Bcrit','CW','Ycrit','DB','DY','DS','MB','MY','MS',...
      'F','IC','MO','NO','RB','RY','RD','RS','SIM','SR','SSBcrit',...
      'SW','T1B','TNB','T1Y','TNY','T1S','TNS','a1','amax','amin',...
      'arec','b','g','f1b','f1y','f1s','m','S','sigma','y1','y2',...
      'DP','Pcrit','MP','RP','T1P','TNP','f1p')
end
```

```
%***************************************
% NSS HERRING POPULATION DYNAMICS (HER2.M)
%***************************************
%
% DENSITY-DEPENDENT BIOECONOMIC MODEL
%
%Age-structured model, discrete time, one year time step.
%Stock-recruitement: Beverton-Holt (SR=0) or Ricker (SR=1)
%                    determinitic (RD=0) or + noise (RD=1)
%                    with (AC=1) or without (AC=0) autocorrelation.
%Natural mortality: constant (along time) and age-dependent.
%Fishing mortality: constant or fluctuating and age-independent.
%Selectivity: constant and age-dependent.
%Economic yield: constant price/kg, fixed and proportionnal harvesting costs.
%Density-dependent maturity ogive (MO), stock/catch weight at age (SW/CW)
%functions.
%Selectivities (S) and initial abundances (N0) are estimated as the mean
%values of the data corresponding to the initial condition years (IC).
%DATA = *.dat : 1st row=years, 1st year=1950
%               1st column=age classes, 1st class=0
%-> OUTPUT:  N = abundance (age and year)
%            B = biomass (age and year)
%            Y = yield, i.e. catch in weight (age and year)
%          SSB = spawning stock biomass (year)
%            Q = costs (year)
%            P = profit (year)
%NB: column->year, row->age class (1st class = 0)
%    Weights at age in kg/unit
%    Numbers        in units
%    Biomasses      in kg
%    Prices, Costs  in Norwegian kroner(/kg)
%
%References (number) correspond to equation numbers in the report.

% SIMULATION PARAMETERS
y1=1997; y2=2100;                %Simulation period [y1 y2]
IC=[1993:1996];                  %Initial condition years (vector)
SR=0;                            %Stock-recruitment (SR): 0=B-H, 1=Ricker
RD=1;                            %    1=stochastic error, 0=none
AC=0;                            %    1=autocorrelation,  0=none
amin=0;                          %Ages: minimum
amax=16;                         %      maximum

% ECONOMIC PARAMETERS
f=ones(1,y2-y1+1)*0.35;          %Fishing mortality: constant
%f=abs(.2*randn(1,y2-y1+1)+.5);  %Fishing mortality: fluctuating
a1=3;                            %1st fishing age for simple selectivities
                                 %    a1<0 => data selectivities
q1=1E7;                          %Costs: fixed
q2=5E6;                          %       proportional
```

```
h=1.45;          %Average price [1995, Norges Sildesalgslag, rsmeldinger]

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;       %Natural mortality
%m(1:3)=ones(3,1)*0.9;            %(high juvenile mortality)
c=[0.006759;1.356;2.686;3.977];   %Maturity parameters
d=-0.2744;
alpha=-0.299;                     %Stock weights at age parameters
Bmax=16218E6;
w0=0.203;
k0=0.703;
winf=0.447;
alpha1=-0.368;                    %Catch weights at age parameters
w01=0.217;
k01=0.650;
winf1=0.430;
arec=0;                           %Recruitment age
if SR==0 & AC==0                  %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                   %  variance of the SR fitting
   g=0;                           %  no autocorrelation
elseif SR==0 & AC==1
   a=31.637;
   b=3284060E3;
   sigma=1.666;
   g=-0.2553;                     % 1st order autocorrelation in SR
elseif SR==1 & AC==0
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
   g=0;
elseif SR==1 & AC==1
   a=25.760;
   b=1.094E-10;
   sigma=1.694;
   g=-0.2655;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                 %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                    %Simple selectivities:
   S=ones(amax+1-amin,1);               % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);       % 0 before recruitment
end
```

```
load('n.dat');                          %Data loading:
N0= n(2:amax+2-amin,IC-1950+2);         % initial abundances (in millions)
if length(IC)>1
   N0=mean(N0')';                       %Mean data over IC
end
N=zeros(amax+1-amin,length(y1:y2));
B=zeros(size(N));
Y=zeros(size(N));
SW=zeros(size(N));
CW=zeros(size(N));
MO=zeros(size(N));
MO(8-amin:amax+1-amin,:)=ones(size(MO(8:amax+1,:)));   %Fully mature ages
SSB=zeros(size(y1:y2));
N(:,1)=N0*1E6;                          %Initial abundances (in units)
SW(:,1)=ones(size(SW(:,1)))*w0;         %        stock weights at age (2)
CW(:,1)=ones(size(CW(:,1)))*w01;        %        catch weights at age (3)
B(:,1) =SW(:,1).*N0*1E6;                %        biomasses
B4=sum(B(5-amin:amax+1-amin,1))*1E-3;   %        stock biomass (in tonnes)
MO(4-amin:7-amin,1)=1./(1+exp(-c)*B4^(-d));%    maturity ogives (5)
SSB(1) =MO(:,1)'*B(:,1);                %        spawning stock biomass
E1=sqrt(sigma)*randn*RD;                %SR autocorrelation initialization

% POPULATION DYNAMICS SIMULATION
for t=2:y2-y1+1
   E=sqrt(sigma)*randn*RD;                            %SR error generation
   for i=arec+2-amin:amax+1-amin
      N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f(t-1)*S(i-1)); %Population ageing (1)
      k=k0*exp(-alpha*sum(B(:,t-1))/Bmax);          %Stock weights at age (2)
      SW(i,t)=abs((1-k)*winf^(1/3)+k*SW(i-1,t-1)^(1/3))^3;
      k1=k01*exp(-alpha1*sum(B(:,t-1))/Bmax);        %Catch weights at age (3)
      CW(i,t)=abs((1-k1)*winf1^(1/3)+k1*CW(i-1,t-1)^(1/3))^3;
   end
   B4=SW(5-amin:amax+1-amin,t)'*N(5-amin:amax+1-amin,t); %Maturity ogives:
   MO(4-amin:7-amin,t)=1./abs(1+exp(-c)*B4^(-d));   %partially mature ages (5)
   SSB(t)=SW(:,t)'*(MO(:,t).*N(:,t));               %SSB (6)
   if SR==0                                         %SR: Beverton-Holt (7)
      N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(g*E1+E);
   else                                             %SR: Ricker (8)
      N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(g*E1+E);
   end
   B(:,t)=SW(:,t).*N(:,t);                          %Biomasses at age (4)
   E1=E;                                            %SR error autocorrelation
end

% YIELD
for t=1:y2-y1+1
   z=m+f(t)*S;                                      %Total mortality at time t
   Y(:,t)=CW(:,t).*(1-exp(-z)).*(f(t)*S./z).*N(:,t);%Yield at age
end
TY=sum(Y);                                          %Total yield (9)
```

```
Q=q1+q2.*f;                                         %Costs
P=h.*TY-Q;                                          %Profit (10)

% PLOTS
figure
plot(y1:y2,sum(B(arec+1-amin:amax+1-amin,:)))       %Stock biomass along time
xlabel('Time (year)');
ylabel('Stock biomass (kg)');
title('Population dynamics');

figure
plot(y1:y2,TY)                                      %Yield along time
xlabel('Time (year)');
ylabel('Yield (kg)');
title('Harvest');

figure
clf reset
plot(SSB,N(1,:),'o')                                %SR
xlabel('SSB (kg)');
ylabel('Number of recruits (age class 0)');
title('Stock-recruitment');

figure
plot(y1:y2,P)                                       %Profit along time
xlabel('Time (year)');
ylabel('Profit (kroner)');
title('Economic yield');

figure
plot(TY,Q,'o')                                      %Cost function
xlabel('Yield (kg)');
ylabel('Costs (kroner)');
title('Cost function');



%*******************************************
% NSS HERRING POPULATION DYNAMICS (HER2EQ.M)
%*******************************************
%
% DENSITY-DEPENDENT BIOECONOMIC MODEL:
% EQUILIBRIUM STUDY
%
%Cf HER2, but constant fishing mortality along time.
%-> OUTPUT: L = total biomass (fishing mortality and year)
%           Z = total yield (fishing mortality and year)
%NB: column->year, row->fishing mortality (among F)

% SIMULATION PARAMETERS
y1=1997; y2=2057;                  %Simulation period [y1 y2]
```

```
IC=[1993:1996];                    %Initial condition years (vector)
SR=0;                              %Stock-recruitment (SR): 0=B-H, 1=Ricker
PLO=1;                             %1=plot equilibrium curves, 2=all
amin=0;                            %Ages: minimum
amax=16;                           %      maximum

% HARVESTING PARAMETERS
F=[0:.05:1];                       %Fishing mortalities
a1=3;                              %1st fishing age for simple selectivities
                                   %    a1<0 => data selectivities

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;        %Natural mortality
%m(1:3)=ones(3,1)*0.9;             %(high juvenile mortality)
c=[0.006759;1.356;2.686;3.977];    %Maturity parameters
d=-0.2744;
alpha=-0.299;                      %Stock weights at age parameters
Bmax=16218E6;
w0=0.203;
k0=0.703;
winf=0.447;
alpha1=-0.368;                     %Catch weights at age parameters
w01=0.217;
k01=0.650;
winf1=0.430;
arec=0;                            %Recruitment age
if SR==0                           %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                    %  bias of the SR fitting
elseif SR==1
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                   %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                      %Simple selectivities:
   S=ones(amax+1-amin,1);                 % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);         % 0 before recruitment
end
load('n.dat');                            %Data loading:
N0= n(2:amax+2-amin,IC-1950+2);           % initial abundances (in millions)
if length(IC)>1
```

```
   N0=mean(N0')';                        %Mean data over IC
end
N=zeros(amax+1,length(y1:y2));           %Initializations
B=zeros(size(N));
Y=zeros(size(N));
SW=zeros(size(N));
CW=zeros(size(N));
MO=zeros(size(N));
MO(8-amin:amax+1-amin,:)=ones(size(MO(8:amax+1,:))); %Fully mature ages
Z=zeros(length(F),length(y1:y2));
L=zeros(length(F),length(y1:y2));
SSB=zeros(size(y1:y2));
N(:,1)=N0*1E6;                            %Initial abundances (in units)
SW(:,1)=ones(size(SW(:,1)))*w0;           %        stock weights at age (2)
CW(:,1)=ones(size(CW(:,1)))*w01;          %        catch weights at age (3)
B(:,1)=SW(:,1).*N0*1E6;                   %        biomasses
B4=sum(B(5-amin:amax+1-amin,1))*1E-3;     %        stock biomass (in tonnes)
MO(4-amin:7-amin,1)=1./(1+exp(-c)*B4^(-d));%       maturity ogives (5)
SSB(1) =MO(:,1)'*B(:,1);                  %        spawning stock biomass

% POPULATION DYNAMICS SIMULATION
j=1;
for f=F
   z=m+f*S;                                            %Total mortality for f
   Y(:,1)=CW(:,1).*(1-exp(-z)).*(f*S./z).*N(:,1);     %Initial yield at age
   for t=2:y2-y1+1
      for i=arec+2-amin:amax+1-amin
         N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f*S(i-1));     %Population ageing (1)
         k=k0*exp(-alpha*sum(B(:,t-1))/Bmax);          %Stock weights at age (2)
         SW(i,t)=abs((1-k)*winf^(1/3)+k*SW(i-1,t-1)^(1/3))^3;
         k1=k01*exp(-alpha1*sum(B(:,t-1))/Bmax);       %Catch weights at age (3)
         CW(i,t)=abs((1-k1)*winf1^(1/3)+k1*CW(i-1,t-1)^(1/3))^3;
      end
      B4=SW(5-amin:amax+1-amin,t)'*N(5-amin:amax+1-amin,t);
      MO(4-amin:7-amin,t)=1./abs(1+exp(-c)*B4^(-d)); %Maturity ogives (5)
      SSB(t)=MO(:,t)'*(SW(:,t).*N(:,t));              %SSB (6)
      if SR==0                                         %SR: Beverton-Holt (7)
         N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(sigma/2);
      else                                             %SR: Ricker (8)
         N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(sigma/2);
      end
      B(:,t)=SW(:,t).*N(:,t);                          %Biomasses at age (4)
      Y(:,t)=CW(:,t).*(1-exp(-z)).*(f*S./z).*N(:,t); %Yield at age (9)
   end
   L(j,:)=sum(B);                                      %Biomasses at f
   Z(j,:)=sum(Y);                                      %Yields at f
   j=j+1;
end

% PLOTS
```

```
if PLO==1 | PLO==2
figure                                  %Equilibrium biomass & yield
clf reset
plot(F,Z(:,y2-y1+1),F,L(:,y2-y1+1)/10,'--')
xlabel('Fishing mortality');
ylabel('Biomass/10 (dashed) and Yield (kg)');
if SR==0
   title('Equilibrium (DD - Beverton-Holt recruitment)');
elseif SR==1
   title('Equilibrium (DD - Ricker recruitment)');
end

if PLO==2
figure                                  %Biomasses along time for small f
clf reset
plot(y1:y2,L(1:5,:))
xlabel('Time (year)');
ylabel('Biomass (kg)');
if SR==0
   title(['Fishing mortality=',mat2str(F(1:5)),' (Beverton-Holt)']);
elseif SR==1
   title(['Fishing mortality=',mat2str(F(1:5)),' (Ricker)']);
end

figure                                  %Biomasses along time for large f
clf reset
plot(y1:y2,L(length(F)-4:length(F),:))
xlabel('Time (year)');
ylabel('Biomass (kg)');
if SR==0
   title(['Fishing mortality=',mat2str(F(length(F)-4:length(F))),...
   ' (Beverton-Holt)']);
elseif SR==1
   title(['Fishing mortality=',mat2str(F(length(F)-4:length(F))),...
   ' (Ricker)']);
end
end
end



%*******************************************
% NSS HERRING POPULATION DYNAMICS (HER2DI.M)
%*******************************************
%
% DENSITY-DEPENDENT BIOECONOMIC MODEL:
% RISK ANALYSIS & RISK DISTRIBUTION
%
%Cf HER2, but constant fishing mortality along time..
%-> OUTPUT: R*  = Risk (F fishing mortalities and SIM simulations)
%           T1* = First year beyond the critical level (F and SIM)
```

```
%           TN* = Number of years beyond the critical level (F and SIM)
%                 column SIM+1 : mean value (probability for R)
%                 column SIM+2 : standard deviation
%           M*  = Mean value (F and year)
%           D*  = Risk distribution (F and year)
%           *=B : for the total biomass
%           *=S : for the spawning stock biomass
%           *=Y : for the yield (catch in weight)
%           *=P : for the profit
%           Results file: hdd"SR""AC""period".mat
%NB: row->fishing mortality (among F)
%    column->simulation (SIM)

% SIMULATION PARAMETERS
SIM=100;                        %Simulations number
Bcrit=0.5E10;                   %Critical biomass
SSBcrit=0.25E10;                %         SSB
Ycrit=0.10E10;                  %         yield
Pcrit=0;                        %         profit
y1=1997; y2=2097;               %Simulation period [y1 y2]
IC=[1993:1996];                 %Initial condition years (vector)
SR=0;                           %Stock-recruitment (SR): 0=B-H, 1=Ricker
RD=1;                           %  1=stochastic error, 0=none
AC=0;                           %  1=autocorrelation,  0=none
PLO=1;                          %1=plot the curves
PRI=0;                          %1=save results in mat-file
amin=0;                         %Ages: minimum
amax=16;                        %      maximum

% ECONOMIC PARAMETERS
F=[0:.05:.8,.9:.1:2];           %Fishing mortalities
a1=3;                           %1st fishing age for simple selectivities
                                %    a1<0 => data selectivities
q1=1E7;                         %Costs: fixed
q2=5E6;                         %       proportional
h=1.45;         %Average price [1995, Norges Sildesalgslag, rsmeldinger)

% BIOLOGICAL PARAMETERS
m=ones(amax-amin+1,1)*0.15;     %Natural mortality
%m(1:3)=ones(3,1)*0.9;          %(high juvenile mortality)
c=[0.006759;1.356;2.686;3.977]; %Maturity parameters
d=-0.2744;
alpha=-0.299;                   %Stock weights at age parameters
Bmax=16218E6;
w0=0.203;
k0=0.703;
winf=0.447;
alpha1=-0.368;                  %Catch weights at age parameters
w01=0.217;
k01=0.650;
```

```
winf1=0.430;
arec=0;                             %Recruitment age
if SR==0 & AC==0                    %SR parameters:
   a=32.459;
   b=3044867E3;
   sigma=1.763;                     %  variance of the SR fitting
   g=0;                             %  no autocorrelation
elseif SR==0 & AC==1
   a=31.637;
   b=3284060E3;
   sigma=1.666;
   g=-0.2553;                       %  1st order autocorrelation in SR
elseif SR==1 & AC==0
   a=26.753;
   b=1.2105E-10;
   sigma=1.802;
   g=0;
elseif SR==1 & AC==1
   a=25.760;
   b=1.094E-10;
   sigma=1.694;
   g=-0.2655;
end

% DATA LOADING & INITIAL CONDITION
if a1<0                                   %Data selectivities
   load('s.dat');
   S = s(2:amax+2-amin,IC-1950+2);
   if length(IC)>1
      S=mean(S')';
   end
else                                      %Simple selectivities:
   S=ones(amax+1-amin,1);                 % 1 for the stock
   S(1:a1-amin)=zeros(a1-amin,1);         % 0 before recruitment
end
load('n.dat');                            %Data loading:
N0= n(2:amax+2-amin,IC-1950+2);           % initial abundances (in millions)
if length(IC)>1
   N0=mean(N0')';                         %Mean data over IC
end
N=zeros(amax-amin+1,length(y1:y2));       %Initializations
B=zeros(size(N));
Y=zeros(size(N));
RB=zeros(length(F),2+SIM); T1B=zeros(size(RB)); TNB=zeros(size(RB));
RS=zeros(size(RB));        T1S=zeros(size(RB)); TNS=zeros(size(RB));
RY=zeros(size(RB));        T1Y=zeros(size(RB)); TNY=zeros(size(RB));
RP=zeros(size(RB));        T1P=zeros(size(RB)); TNP=zeros(size(RB));
MB=zeros(length(F),length(y1:y2)); DB=zeros(size(MB));
MS=zeros(size(MB));                DS=zeros(size(MB));
MY=zeros(size(MB));                DY=zeros(size(MB));
```

```
MP=zeros(size(MB));                DP=zeros(size(MB));
SW=zeros(size(N));
CW=zeros(size(N));
MO=zeros(size(N));
MO(8-amin:amax+1-amin,:)=ones(size(MO(8:amax+1,:))); %Fully mature ages
SSB=zeros(size(y1:y2));
N(:,1)=N0*1E6;                         %Initial abundances in units
SW(:,1)=ones(size(SW(:,1)))*w0;        %        stock weight at age (2)
CW(:,1)=ones(size(CW(:,1)))*w01;       %        catch weight at age (3)
B(:,1)=SW(:,1).*N0*1E6;                %        biomasses
B4=sum(B(5-amin:amax+1-amin,1))*1E-3;  %        stock biomass in tonnes
MO(4-amin:7-amin,1)=1./(1+exp(-c)*B4^(-d));%    maturity ogives (5)
SSB(1)=MO(:,1)'*B(:,1);                %        spawning stock biomass
E1=sqrt(sigma)*randn*RD;               %SR autocorrelation initialization
fis=1;

% POPULATION DYNAMICS SIMULATIONS
for f=F                                              %F fishing mortalities
   z=m+f*S;                                          %Total mortality for f
   Y(:,1)=CW(:,1).*(1-exp(-z)).*(f*S./z).*N(:,1);   %Initial yield at age (9)
   for j=1:SIM                                       %SIM simulations
      for t=2:y2-y1+1
         E=sqrt(sigma)*randn*RD;                     %SR error generation
         for i=arec+2-amin:amax+1-amin
            N(i,t)=N(i-1,t-1)*exp(-m(i-1)-f*S(i-1));%Population ageing (1)
            k=k0*exp(-alpha*sum(B(:,t-1))/Bmax);    %Stock weights at age (2)
            SW(i,t)=abs((1-k)*winf^(1/3)+k*SW(i-1,t-1)^(1/3))^3;
            k1=k01*exp(-alpha1*sum(B(:,t-1))/Bmax); %Catch weights at age (3)
            CW(i,t)=abs((1-k1)*winf1^(1/3)+k1*CW(i-1,t-1)^(1/3))^3;
         end
         B4=SW(5-amin:amax+1-amin,t)'*N(5-amin:amax+1-amin,t);
         MO(4-amin:7-amin,t)=1./abs(1+exp(-c)*B4^(-d)); %Maturity ogives (5)
         SSB(t)=SW(:,t)'*(MO(:,t).*N(:,t));         %SSB (6)
         if SR==0                                    %SR: Beverton-Holt (7)
            N(arec+1-amin,t)=a*SSB(t)/(1+SSB(t)/b)*exp(g*E1+E);
         else                                        %SR: Ricker (8)
            N(arec+1-amin,t)=a*SSB(t)*exp(-b*SSB(t))*exp(g*E1+E);
         end
         B(:,t)=SW(:,t).*N(:,t);                     %Biomasses at age (4)
         Y(:,t)=CW(:,t).*(1-exp(-z)).*(f*S./z).*N(:,t); %Yield at age (9)
         E1=E;                                       %SR error autocorrelation
      end
      P=h*sum(Y)-(q1+q2*f);                          %Profit (10)
      % MEAN VALUES (fishing mort. & year)
      MB(fis,:)=MB(fis,:)+sum(B)/SIM;                %Mean biomass
      MS(fis,:)=MS(fis,:)+SSB/SIM;                   %     SSB
      MY(fis,:)=MY(fis,:)+sum(Y)/SIM;                %     yield
      MP(fis,:)=MP(fis,:)+P/SIM;                     %     profit
      % RISK (fishing mort. & simulation)
      if min(sum(B))<Bcrit
```

```
            RB(fis,j)=1;                                      %BIOMASS risk
            ind=find(sum(B)<Bcrit);
            T1B(fis,j)=min(ind)+y1-1;                         %First year < Bcrit
            TNB(fis,j)=length(ind);                           %Number of years < Bcrit
         end
         if min(SSB)<SSBcrit
            RS(fis,j)=1;                                      %SSB risk
            ind=find(SSB<SSBcrit);
            T1S(fis,j)=min(ind)+y1-1;                         %First year < SSBcrit
            TNS(fis,j)=length(ind);                           %Nb of years < SSBcrit
         end
         if min(sum(Y))<Ycrit
            RY(fis,j)=1   ;                                   %YIELD risk
            ind=find(sum(Y)<Ycrit);
            T1Y(fis,j)=min(ind)+y1-1;                         %First year < Ycrit
            TNY(fis,j)=length(ind);                           %Number of years < Ycrit
         end
         if min(P)<Pcrit
            RP(fis,j)=1;                                      %PROFIT risk
            ind=find(P<Pcrit);
            T1P(fis,j)=min(ind)+y1-1;                         %First year < Pcrit
            TNP(fis,j)=length(ind);                           %Nb of years < Pcrit
         end
      end
      fis=fis+1;
   end

   %RISK ANALYSIS (fishing mort.)
   ind=find(MB<Bcrit);                                        %BIOMASS:
   DB(ind)=ones(size(ind));                                   %Risk distribution (year)
   RB(:,SIM+1)=mean(RB(:,1:SIM)')';                           %Risk probability
   RB(:,SIM+2)=std(RB(:,1:SIM)')';                            % standard deviation
   f1b=find(RB(:,SIM+1));
   f1b=find(RB(:,SIM+1));
   for i=[f1b]'
      si=find(T1B(i,1:SIM));
      T1B(i,SIM+1)=mean(T1B(i,si));                           %Mean first year < Bcrit
      T1B(i,SIM+2)=std(T1B(i,si));                            % standard deviation
   end
   TNB(:,SIM+1)=mean(TNB(:,1:SIM)')';                         %Mean nb of years < Bcrit
   TNB(:,SIM+2)=std(TNB(:,1:SIM)')';                          % standard deviation
   %
   ind=find(MS<SSBcrit);                                      %SSB:
   DS(ind)=ones(size(ind));                                   %Risk distribution (year)
   RS(:,SIM+1)=mean(RS(:,1:SIM)')';                           %Risk probability
   RS(:,SIM+2)=std(RS(:,1:SIM)')';                            % standard deviation
   f1s=find(RS(:,SIM+1));
   for i=[f1s]'
      si=find(T1S(i,1:SIM));
      T1S(i,SIM+1)=mean(T1S(i,si));                           %Mean first year < SSBcrit
```

```
   T1S(i,SIM+2)=std(T1S(i,si));                            % standard deviation
end
TNS(:,SIM+1)=mean(TNS(:,1:SIM)')';                         %Mean nb of years < SSBcrit
TNS(:,SIM+2)=std(TNS(:,1:SIM)')';                          % standard deviation
%
ind=find(MY<Ycrit);                                        %YIELD:
DY(ind)=ones(size(ind));                                   %Risk distribution (year)
RY(:,SIM+1)=mean(RY(:,1:SIM)')';                           %Risk probability
RY(:,SIM+2)=std(RY(:,1:SIM)')';                            % standard deviation
f1y=find(RY(:,SIM+1));
for i=[f1y]'
   si=find(T1Y(i,1:SIM));
   T1Y(i,SIM+1)=mean(T1Y(i,si));                           %Mean first year < Ycrit
   T1Y(i,SIM+2)=std(T1Y(i,si));                            % standard deviation
end
TNY(:,SIM+1)=mean(TNY(:,1:SIM)')';                         %Mean nb of years < Ycrit
TNY(:,SIM+2)=std(TNY(:,1:SIM)')';                          % standard deviation
%
ind=find(MP<Pcrit);                                        %PROFIT:
DP(ind)=ones(size(ind));                                   %Risk distribution (year)
RP(:,SIM+1)=mean(RP(:,1:SIM)')';                           %Risk probability
RP(:,SIM+2)=std(RP(:,1:SIM)')';                            % standard deviation
f1p=find(RP(:,SIM+1));
for i=[f1p]'
   si=find(T1P(i,1:SIM));
   T1P(i,SIM+1)=mean(T1P(i,si));                           %Mean first year < Pcrit
   T1P(i,SIM+2)=std(T1P(i,si));                            % standard deviation
end
TNP(:,SIM+1)=mean(TNP(:,1:SIM)')';                         %Mean nb of years < Pcrit
TNP(:,SIM+2)=std(TNP(:,1:SIM)')';                          % standard deviation

% RISK PLOTS
if PLO==1
%
figure                                              %TOTAL BIOMASS:
clf reset
subplot(3,1,1)
plot(F,RB(:,SIM+1),'mo:')                           %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
```

```
end
xlabel('Fishing mortality');
ylabel('Risk probability for biomass');
subplot(3,1,2)
plot(F(f1b),T1B(f1b,SIM+1),'mo:')            %First year < Bcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Bcrit');
subplot(3,1,3)
plot(F,TNB(:,SIM+1),'mo:')                   %Number of years < Bcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Bcrit');
%
figure                                       %Biomass risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MB);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Bcrit=',num2str(Bcrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean total biomass');
subplot(2,1,2)
mesh(y1:y2,F,DB);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Biomass risk distribution');

figure                                       %SPAWNING STOCK BIOMASS:
clf reset
subplot(3,1,1)
plot(F,RS(:,SIM+1),'mo:')                    %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
```

```
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for SSB');
subplot(3,1,2)
plot(F(f1s),T1S(f1s,SIM+1),'mo:')           %First year < SSBcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond SSBcrit');
subplot(3,1,3)
plot(F,TNS(:,SIM+1),'mo:')                  %Number of years < SSBcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond SSBcrit');
%
figure                                      %SSB risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MS);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  SSBcrit=',num2str(SSBcrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean SSB');
subplot(2,1,2)
mesh(y1:y2,F,DS);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('SSB risk distribution');

figure                                      %YIELD:
clf reset
subplot(3,1,1)
plot(F,RY(:,SIM+1),'mo:')                   %Risk probability / F
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
```

```
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for yield');
subplot(3,1,2)
plot(F(f1y),T1Y(f1y,SIM+1),'mo:')           %First year < Ycrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Ycrit');
subplot(3,1,3)
plot(F,TNY(:,SIM+1),'mo:')                  %Number of years < Ycrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Ycrit');
%
figure                                      %Yield risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MY);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Ycrit=',num2str(Ycrit/1e10),'E10 kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean yield');
subplot(2,1,2)
mesh(y1:y2,F,DY);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Yield risk distribution');

figure                                      %PROFIT:
clf reset
subplot(3,1,1)
plot(F,RP(:,SIM+1),'mo:')                   %Risk probability / F
```

```
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',nXSum2str(Pcrit/1e10),'E10 kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SxsIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit/1e10),'E10 kg']);
end
xlabel('Fishing mortality');
ylabel('Risk probability for profit');
subplot(3,1,2)
plot(F(f1p),T1P(f1p,SIM+1),'mo:')           %First year < Pcrit / F
xlabel('Fishing mortality');
ylabel('First year beyond Pcrit');
subplot(3,1,3)
plot(F,TNP(:,SIM+1),'mo:')                  %Number of years < Pcrit / F
xlabel('Fishing mortality');
ylabel('Number of years beyond Pcrit');
%
figure                                      %Profit risk distribution
clf reset
subplot(2,1,1)
mesh(y1:y2,F,MP);
if SR==0 & AC==0
   title(['Beverton-Holt - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==0 & AC==1
   title(['Beverton-Holt AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==1 & AC==0
   title(['Ricker - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
elseif SR==1 & AC==1
   title(['Ricker AC - ',int2str(SIM),' simulations (',...
   int2str(y2-y1+1),' years),  Pcrit=',num2str(Pcrit),' kg']);
end
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Mean profit');
subplot(2,1,2)
mesh(y1:y2,F,DP);
xlabel('Year');
ylabel('Fishing mortality');
zlabel('Profit risk distribution');
end
```

```
if PRI==1
   file=['hdd',int2str(SR),int2str(AC),int2str(y2-y1+1)];
   save(file,'AC','Bcrit','CW','Ycrit','DB','DY','DS','MB','MY','MS',...
      'F','IC','MO','NO','RB','RY','RD','RS','SIM','SR','SSBcrit',...
      'SW','T1B','TNB','T1Y','TNY','T1S','TNS','a1','amax','amin',...
      'arec','b','g','f1b','f1y','f1s','m','s','sigma','y1','y2',...
      'DP','Pcrit','MP','RP','T1P','TNP','f1p'))
end
```