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EXPLOITATION AND CONSERVATION OF NORWEGIAN SPRING-SPAWNING HERRING: OPEN ACCESS VERSUS OPTIMAL HARVESTING STRATEGIES

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Abstract

In this report we study a three-fleet bioeconomic model of the Norwegian spring-spawning (or Atlanto-Scandian) herring fishery. The biological model is described by a discrete time age structured model. The economic model is based on constant price and log-linear costs. We study the optimal mix between the three fleets from the viewpoint of a single exploiter of the herring stock. In addition, we study several adaptive strategies of the fleets. We show that adaptive strategies based on spawning-stock biomass (SSB) produce largest economic rents for the fishery. Further, we show that open access leads to stock extinction and zero profits after a period of 60 years.

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Contents

1 Introduction

The Norwegian spring-spawning herring (*Clupea harengus*) is the largest fish stock in the North Atlantic [1]. It is an important source of food and revenue in adjacent coastal area, especially in Norway which has largest annaual catches. In addition, Iceland, Russia, the Faroe Islands and the EU take significant catches. The purse-seiner fleets overfished the formerly fairly healthy stock almost to extinction during the 1960's after the tremendous development in their fishing equipment and technique. It took about 20 years for the stock to recover to the Minimum Biological Acceptable Level (MBL) and only in the 1990's it has reached the level where Total Allowable Catch (TAC) quotas can be increased.

In this work, we study harvesting of the stock with a case where one state has three types of fleets fishing the Norwegian spring-spawning herring: purse seine, coastal vessel and trawler fleets. These fleets have different properties in the capability to select the catch and different cost structures. We assume that purse seiners are the largest vessels with a big capacity to carry yield and thus they have rather small average costs per kg harvested. On the other hand, the coastal vessels have only a small capacity and large costs. However, they are more selective and thus good for the quality of the harvesting. The capacity of the trawlers is close to coastal vessels, but they are less selective and thus have lower costs. The state can restrict the harvest with limiting the effort of the fleets on the fishing or with limiting the number of vessels.

The state optimizes the total profit along time. Optimal harvesting strategy contains optimal effort (optimal number of vessels) and optimal possibility to select the catch. Thus, we study the sensitivity of the annual catch and the size of population on the rate of fishing mortality and selectivity. The fleets are able to adjust the effort, and even the rate of selectivity, to the current situation with some lag and constraints which are due to the investments on the vessels and gear and to the possibility to convert the selectivity. Even in an open access situation the share of the harvest is partly limited because of the reaction capability of the fleets. Especially, the fleets tend to be able to react rapidly when it comes to increasing effort, while it exit tends to be much slower (see [2]).

In this report, we first introduce the notation and the biological and economic models of the population and the harvest in section 2. In section 3, we concentrate on studying the sensitivity of the size of population and the profit on changes in the fishing mortality and selectivity. In section 4, we study the optimal strategies with adjustable properties of fleets and different criteria on the optimization. An open acces situation is shown in subsection 4.1, and another possible profit based strategy in subsection 4.2. Sustainable strategy which is based on the size of population is discussed in subsection 4.3. The results in total are gathered to Conclusions in section 5.

2 Model

The model describing the population dynamics here stems from PATTERSON's report [3]. In the current report, we expose only the elementary features of the biologigal model (for further information see [4]) and concentrate on the economic model. The model for harvest given in [4] is modified to match the three fleet case, where each fleet has their own fishing methods. The cost function is also modified and contains different fishing method dependent parameters for each fleet.

To ease the reading of this report, we first introduce most of the notations in subsection 2.1 the values and units of which are more accurately shown in the following subsections. Subsection 2.2 contains the brief summary of the biological model, and subsection 2.4 introduces the models attached to harvest and profit.

This model is implemented as Matlab routine. The simulation period is set as 100 years where the boundary years are $[y_1,\ y_2] = [1997,\ 2096]$. The implementation is discussed more thoroughly in [4].

2.1 Notations

Table 1 summarizes the notations used in this report. First we present some general remarks of the model:

- The population is distributed in 17 age classes, beginning from recruitment age class 0.
- The time step is considered to be one year.
- The flow into the first age class, a classical stock-recruitment relationship is used linking the number of recruits R to the spawning stock biomass SSB. Here we use BEVERTON-HOLT [5] function, other possibility would be RICKER [6] relationship, cf. [4].

2.2 Population dynamics

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

$$\begin{aligned} N_{0,y} &= R_y \\ N_{a+1,y+1} &= N_{a,y} e^{-m_a - \sum_{i=1}^{3} s_{a,y,i} f_{y,i}} \\ N_{a,0} & \quad \text{known.} \end{aligned} \tag{1}$$

Subscripts	definition	range	
a	age	$\{0, 1, 2, \cdots, 16\}$ years	
y	time	current year	
i	fleet index	fleet $\{1, 2, 3\}$	
Variables	**definition**	**unit**	**subscripts**
N	abundance	numbers	a, y
B	biomass	kg	a, y
SSB	spawning stock biomass	kg	y
R	recruitment	numbers	y
TY	total yield, catch in weight	kg	a, y, i
CW	individual weight at age in the catch	kg/numbers	a
SW	individual weight at age in the stock	kg/numbers	a
MO	maturity ogive	percentage	a
f	fishing mortality	none	y, i
S	selectivity	none	a, y, i
Nv	number of vessels	numbers	y, i
a_1	first fishing age	numbers	y, i
Parameters	**definition**	**value and unit**	**subscripts**
m	natural mortality	cf. table 2	a
h	fish price per kg	cf. table 3	i
$q_1,\ q_2,\ Q_4$	cost function parameters	cf. table 3	i

Table 1: Notations.

Here $N_{a,y}$ is the number of fish of each age class in each year and the input R_y to the stock is called the recruitment. For further information about recruitment see [4]. The initial numbers of fish $N_{a,0}$ are estimated as averages from the historical data.

All age classes are submitted to natural mortality m_a (Table 2) which is significantly higher for juveniles than for mature fish. The age classes are also submitted to rate of harvest. It is defined by the means of a fishing mortality term $f_{y,i}$, related to the effort applied by the fleets to the stock each year, and a selectivity rate $S_{a,y,i}$ that describes the vulnerability of each age class. These variables are discussed more in subsection 2.4.

Parameter	value	subscripts	unit
m	0.9	$a \in \{0, 1, 2\}$	none
m	0.15	$a \in \{3, 4, \cdots, 16\}$	none

Table 2: Natural mortality parameter.

In this work, we use the simple density-independent model, which means using the annually constant averages from the historical data in certain age class dependent variables. As a contrast, the density-dependent growth of the population is described using the annual individual weights at age $SW_{a,y}$. In the density-independent model these weights are estimated as constant averages SW_a from the historical data. Thus, the total population biomass in year y is expressed by

$$B_y = \sum_{a=0}^{16} SW_a N_{a,y}. \tag{2}$$

It is assumed that only 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 only partially mature. In the density-independent model we estimate the maturity ogive which defines the proportion of the mature individuals among the age class as constant averages MO_a for each age class. The annual *spawning stock biomass* is given by:

$$SSB_y = \sum_{a=0}^{16} MO_a SW_a N_{a,y}. \tag{3}$$

The term SSB defines the spawning stock biomass as kilograms of the proportion of the annual number of fish.

2.3 Model calibration

In this subsection we study whether our biological model predicts the actual developments in the herring stock with actual harvesting levels. We use the actual fishing mortalities (for each age class), starting from 1950 and attempt to reproduce the actual stock and spawning stock values. We see from figure 1 that the model predicts quite well the development for the next 20 years approximately, but fails to predict the rise of the stock from 1980's. However, if we take year 1977 as the initial condition year then the model will predict an increase in the stock level. This is seen in figure 2. Note that the spawning stock level rises more rapidly than it has actually risen. The initial condition year 1977 includes the choice of weights for each age class of herring which remains the same throughout the simulation. To verify this we present a third simulation starting from 1987. Figure 3 shows how the size of stock at 1997 is lower for the third simulation, and thus much closer to the actual value.

One explanation for the incorrect predictions of our model would be the density-dependence phenomenon. It seems that our density-independent model is only capable of predicting a fall in the stock size since the weights of the individual fish are then small in the beginning of the simulation. Another reason for the inability of our model to predict biomass changes correctly is the large variances of the herring stock which could be captured by the stochastic model. Some realisations of the simulations would indeed give results close to the actual values.

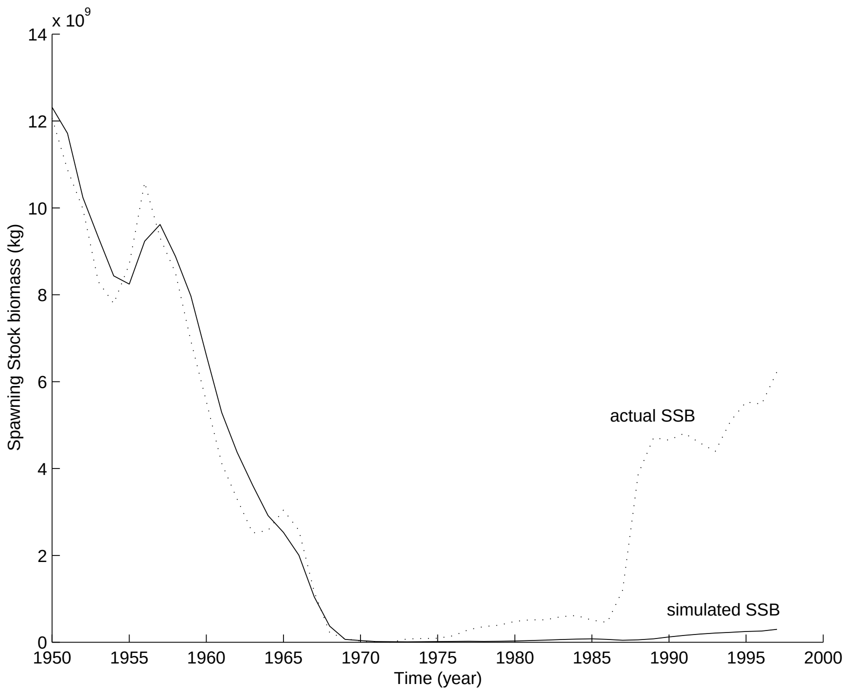

Figure 1: Actual and simulated spawning stock biomass 1950-1997

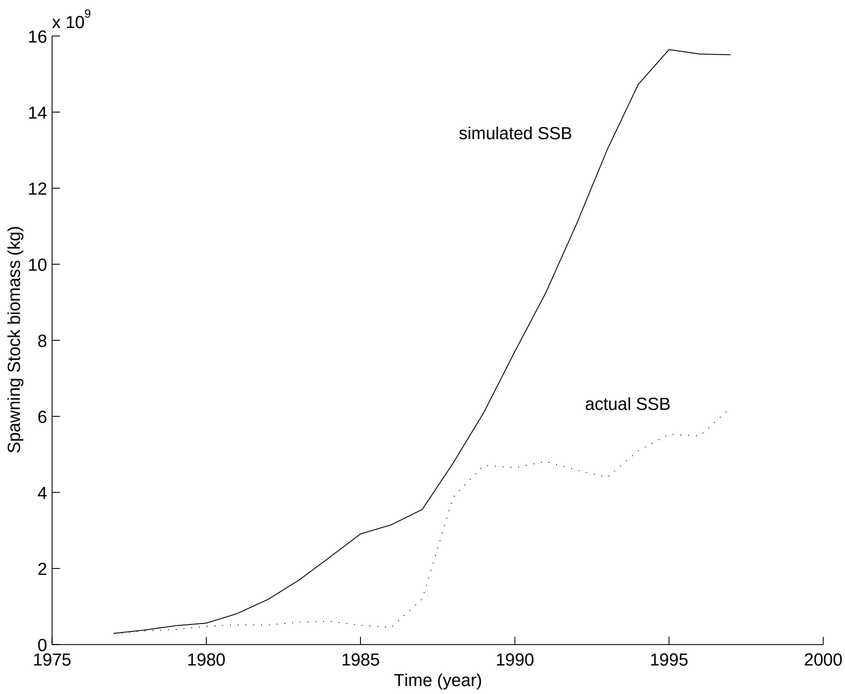

Figure 2: Actual and simulated spawning stock biomass 1977-1997

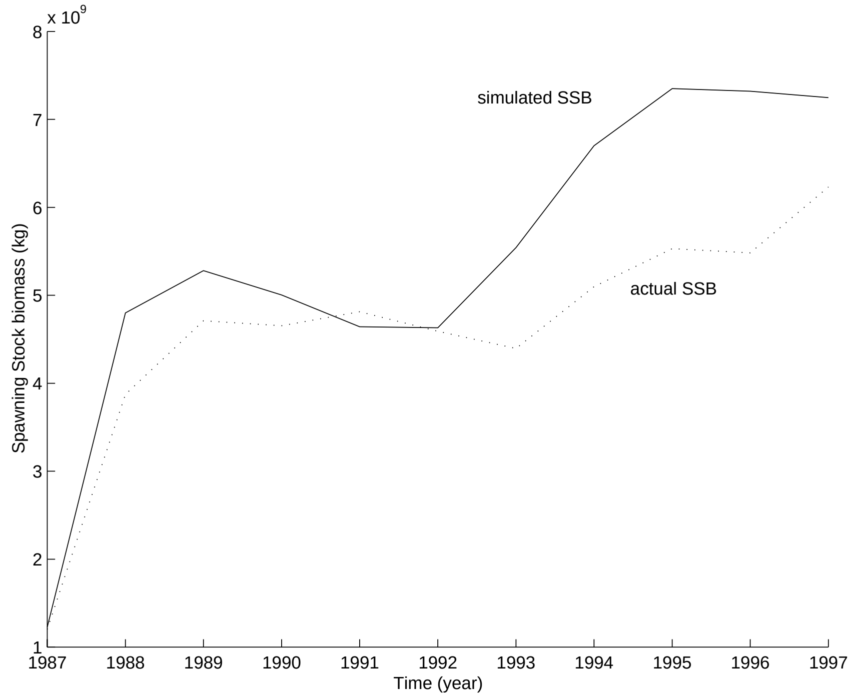

Figure 3: Actual and simulated spawning stock biomass 1987-1997

2.4 Catch and profit

If we consider the proportion of fish died because of harvesting and compare it to the total mortality during the year y, we obtain the following *catch* for fleet i in numbers:

$$C_{a,y,i} = \frac{S_{a,y,i} f_{y,i}}{m_a + \sum_{i=1}^{3} S_{a,y,i} f_{y,i}} \left(N_{a,y} - N_{a+1,y+1}\right). \tag{4}$$

Here the catch weights at each age, which differ from the stock weight, are estimated as constant averages CW_a from the historical data. Inserting them into equation 1 we obtain the annual total yield $TY_{y,i}$ for fleet i:

$$TY_{y,i} = \sum_{a=0}^{a=16} CW_a N_{a,y} \frac{S_{a,y,i} f_{y,i}}{m_a + \sum_{i=1}^{3} S_{a,y,i} f_{y,i}} \left(1 - e^{-m_a - \sum_{i=1}^{3} S_{a,y,i} f_{y,i}}\right) \tag{5}$$

Here the rate of catch for each fleet i is controlled via two parameters, *fishing mortality* $f_{y,i}$ and *selectivity* $S_{a,y,i}$.

The fishing mortality is related to the effort applied by fishermen on the stock and is considered as a *control term.* The realistic range for the total fishing mortality would be, after the historical data: $\sum_{i=1}^{3} f_{y,i} \in [0, 2]$. Here we assume that the individual components of it can be modified to reflect the realistic capability for each fleet i within this restriction.

The latter parameter, selectivity, depends on the interaction between fish and gear of vessels of each fleet. All age classes are not as vulnerable and each gear is more or less efficient towards the age classes. Here the *selection pattern* would be for each fleet i:

- age classes that are not yet harvested by fleet i: $S_{a,y,i} = 0 \; \forall a < a_{1,y,i}$
- age classes that are harvested by fleet i: $S_{a,y,i} = 1 \; \forall a \geq a_{1,y,i}$

For control purposes, we assume that the first fishing age $a_{1,y,i}$ and thus the selectivity can be modified to reflect the realistic gear of fleet i.

Since the maximum capacity for each vessel of fleet i is restricted, the number of vessels in the fleet must increase proportionally to the increase of the effort applied on the stock $f_{y,i}$. Using a rough estimation and a linear model of the initial dependence of fishing mortality $f_0 = (0.6\ 0.3\ 0.1)0.2$ and number of vessels $Nv_{0,i}$ (Table 3) we have the number of vessels at each year as

$$vNv_{y,i} = \frac{Nv_{0,i}}{f_{0,i}} f_{y,i}. \tag{6}$$

Thus, the effort each fleet has to the stock is defined also in terms of its number of vessels.

The annual profit each fleet makes depends on the total annual yield $TY_{y,i}$ and the total annual costs $Q_{y,i}$. For each fleet i the total costs are

$$Q_{y,i} = Nv_{y,i} e^{q_{1,i}} \left(\frac{TY_{y,i}}{Q4_i Nv_{y,i}} \right)^{q_{2,i}}. \tag{7}$$

The cost parameters for each fleet are shown in table 3. Parameters q_1 and Q_4 are attached to the proportional costs versus the number of the vessels and yield. Parameter q_2 is the cost elasticity which defines the percentage change in the costs proportional to one percent change in the total yield.

Parameter	Fleet 1 purse seine	Fleet 2 coastal	Fleet 3 trawler
$q_{1,i}$	**15.04469**	16	15
$q_{2,i}$	**0.56**	**0.137**	**0.635**
$Q_{4,i}$	$\mathbf{1.2449 \cdot 10^6}$	$0.4 \cdot 10^6$	$0.6 \cdot 10^6$
$Nv_{0,i}$	40	50	30
h_i	1.6 NOK/kg	1.35 NOK/kg	0.95 NOK/kg

Table 3: Fleet parameters. The unit of parameter q_1 is $ln(NOK)$. The accurate parameter values estimated from historical data are shown with bold font, other values are selected to represent the differencies in the fleets.

Henceforth, we state the fleets with following indices:

- purse seiners are Fleet 1,

- coastal vessels are Fleet 2
- and trawlers are Fleet 3.

If the harvesting strategy is planned in advance for the whole time horizon, also the discount rate must be taken into account:

$$\rho_y = (1+r)^{y-y1}. \tag{8}$$

Here $r = 0.02$ is the annual discount rate. If the harvesting strategy is planned annually $\rho_y = 1, r = 0$. The total discounted annual profit for fleet i is

$$P_{y,i} = \frac{h_i TY_{y,i} - Q_{y,i}}{\rho_y}. \tag{9}$$

3 Effect of changes in selectivity and fishing mortality

The optimal harvesting strategy for the state with three types of fleets requires control of the effort of each fleet. The allowed effort must be planned with respect to the costs and quality of the effort of the fleet. A more selective fleet, such as the coastals vessels, may fish with stronger effort than the less selective fleets and not alarmingly diminish the population. But high selectivity demands high costs and is not necessary within reasonable effort. However, a strong effort without selectivity is destructive for the population. Thus, it is needed to study the optimal share of the effort (number of vessels) and selectivity to create a constant riskless optimal harvesting strategy.

The rate of the total annual effort to the catch of herring is defined with fishing mortality parameter for each fleet i, $f = (f_1 \ f_2 \ f_3)$. The profit and state of the population which is here considered in terms of the size of spawning stock biomass depend on f and selectivity patterns $S = (S_1 \ S_2 \ S_3)$. The risk of destroying the population during the simulation period is proportional to the minimum observed average SSB of the period; the risk is high if it sinks under the critical level $SSB_{crit} = 2.5 \cdot 10^9 kg$ (cf. [4] and [7]).

We begin from the situation, where each fleet fishes with the same constant effort such that the total effort $\sum_{i=1}^{3} f_{y,i} = 0.2$ for all y. The gear of fleet 2 is more selective so that the constant first fishing age for fleet 2 is $a_{1,2} = 7$, as it for fleets 1 and 3 is $a_{1,1} = a_{1,3} = 3$. To study the best possible share of individual efforts of fleets considering also their flexibility in the sense of selectivity, we test how sensitive the average population is to individual changes in these parameters. First we study the risk of extinction during the simulation period and the average discounted profit when the parameters f_3 and $a_{1,3}$ are changing such that for each $a_{1,3}$ f_3 goes from 0.01 to $2 - f_1 - f_2 = 1.81$.

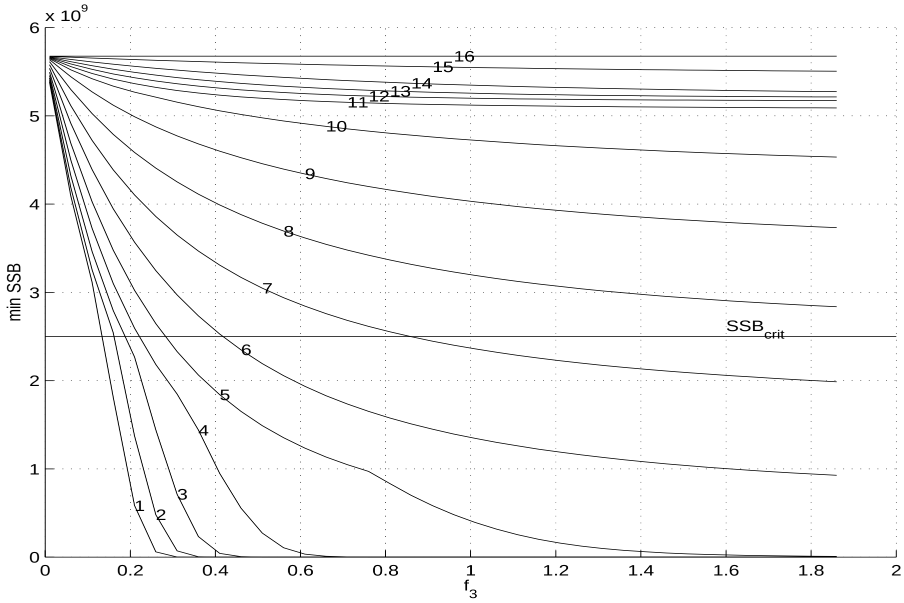

Figure 4: The minimum spawning stock biomass during the simulation period as functions of f_3 and $a_{1,3} = 1, 2, \cdots, 16$. Each line represents different selectivities in terms of $a_{1,3}$.

In figure 4 the minimum spawning stock biomass during the simulation period is shown as a function of the fishing mortality parameter of fleet 3. We attempt to study how the SSB and profits to the fleets are affected by unilateral changes in the fishing mortality and selectivity of fleet 3. The effect of the selectivity is shown as separate minimum SSB lines for each first fishing age $a_{i,1} = 1, 2, \cdots, 16$. If there is no selection ($a_{1,3} = 1$), the population is fished to extinction even with low effort. The higher the first fishing age, the better the spawning stock biomass remains above the critical level SSB_{crit} despite the strength of the effort.

The effects of the individual effort on fishing are seen in the discounted ($r = 0.02$) average profit of each fleet during the simulation period. The range of the profit for Fleet 1 (Figure 5) resembles the curves of the spawning stock biomass when the variables are attached to Fleet 3. The profits for Fleets 1 and 2 are at highest level when Fleet 3 fishes with zero effort. The costs for the more selective Fleet 2 tend to be always high, and thus it is difficult to gain any profit (Figure 6). In total, the fishing mortality parameter affects most the profit for Fleet 3 (Figure 7). For this fleet, the best possible choice would be keeping the value of f_3 at about 0.12 and no selection. However, this is unprofitable in the view of total profit as the size of the average spawning stock biomass tends to go below the critical level. Fleet 3 gains almost the same sum of profit with $a_{1,3} \in \{3, 4, 5, 6\}$ and the average SSB remains in the safe range while $f_3 \leq 0.2$. The total profit for the fleets of the state is shown in Figure 8. The maximum of the average profit is gained with $f_3 \leq 0.2$ and $a_{1,3} \in \{6, 7, \cdots, 16\}$. However, Fleet 3 is not capable to the high selectivity and the first fishing age is tied to $a_{1,3} = 3$.

Furthermore, from figure 8 it is clear to see that it is never optimal to raise the harvest of fleet 3 since total profits generally decrease as f_3 increases.

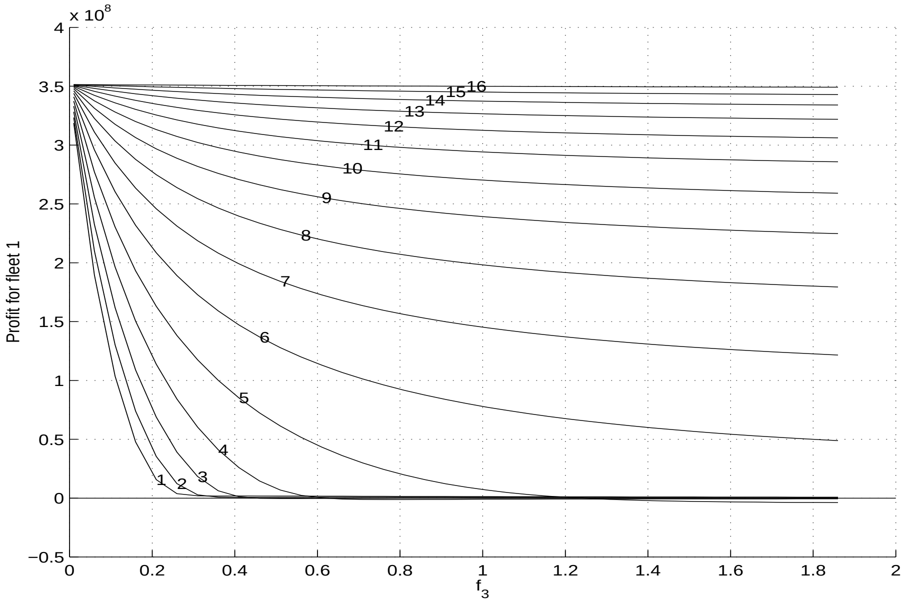

Figure 5: Average annual profit for the fleet 1 as fuctions of f_3 and $a_{1,3}$.

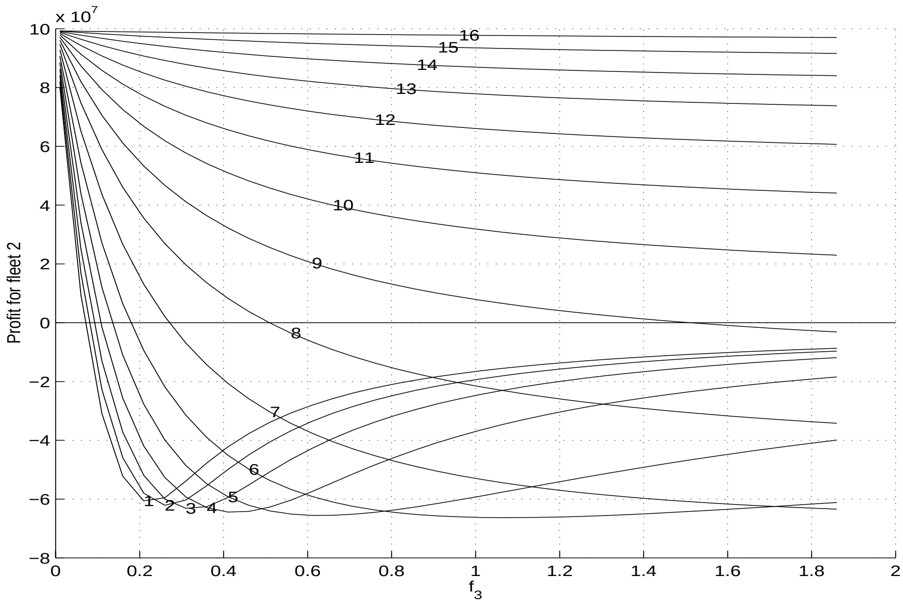

Figure 6: Average annual profit for the fleet 2 as fuctions of f_3 and $a_{1,3}$.

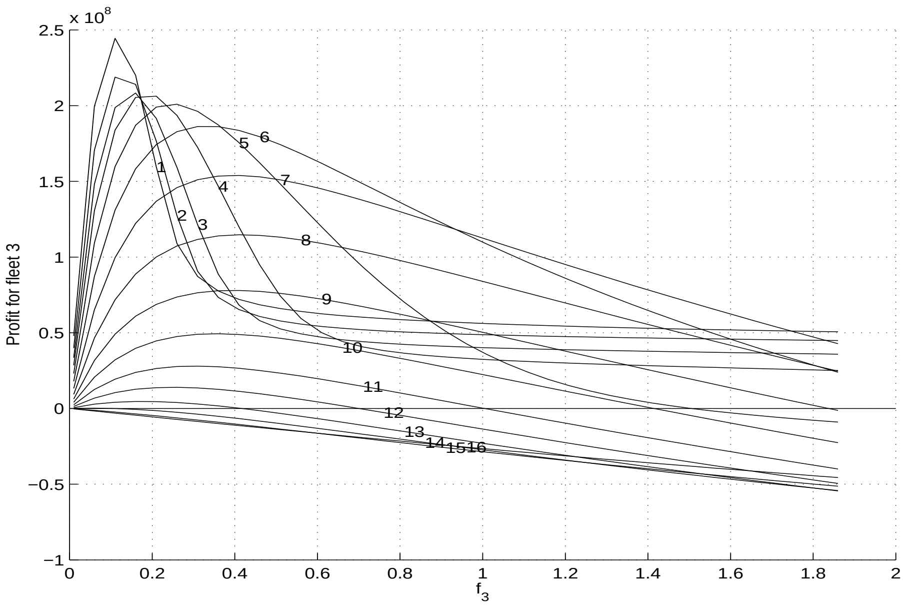

Figure 7: Average annual profit for the fleet 3 as fuctions of f_3 and $a_{1,3}$.

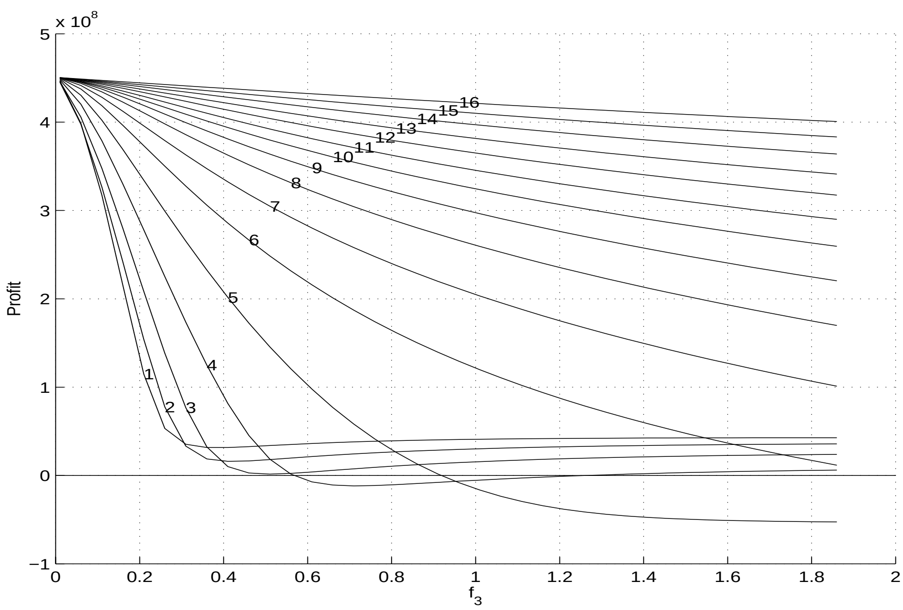

Figure 8: Total average annual profit as fuctions of f_3 and $a_{1,3}$.

Quite similar results can be obtained using the parameters of fleets 2 and 1 as variables. The total profit tends to go negative with fishing mortality $f_2 > 0.2$ and small fishing age $a_{1,2}$ since the fishing of Fleet 2 is unprofitable (Figure 9). Also more selective fishing of Fleet 2 results in a reduction of the total profit, but is riskless for the stock (Figure 10). However, the total profit does not benefit from the fishing of Fleet 2 with any constant efforts and first fishing ages. On the contrary, Fleet 1 causes increase in the total profit with rather small first fishing ages and fishing mortality parameter $f_1 < 0.2$ (Figure 11). Within this fishing mortality range also the risk of too low spawning stock biomass is small (with $a_1 > 4$) and the resulting curves are similar to the ones in figure 4. Thus, using a constant strategy during the whole time horizon it is profitable for the state to fish mostly with fleets 1 and 3 with fishing parameters $f_1, f_3 < 0.2$ and some selection.

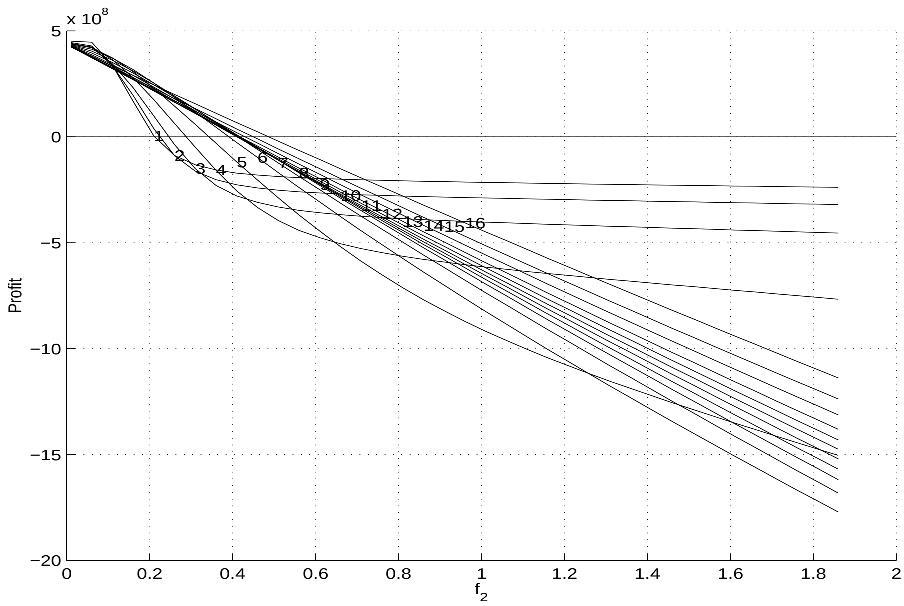

Figure 9: Total average annual profit as fuctions of f_2 and $a_{1,2}$.

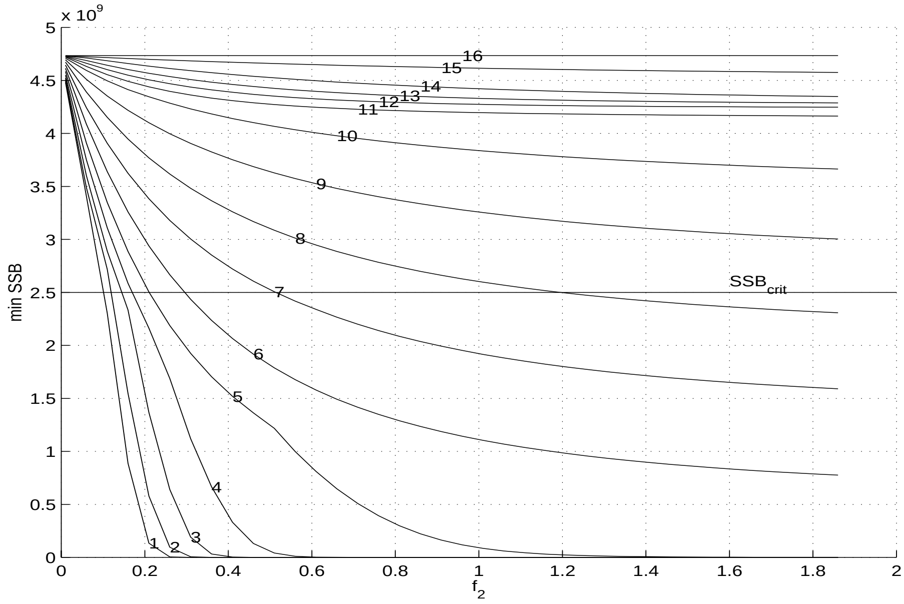

Figure 10: The minimum spawning stock biomass during the simulation period as functions of f_2 and $a_{1,2} = 1, 2, \cdots, 16$. Each line represents different selectivities in terms of $a_{1,2}$.

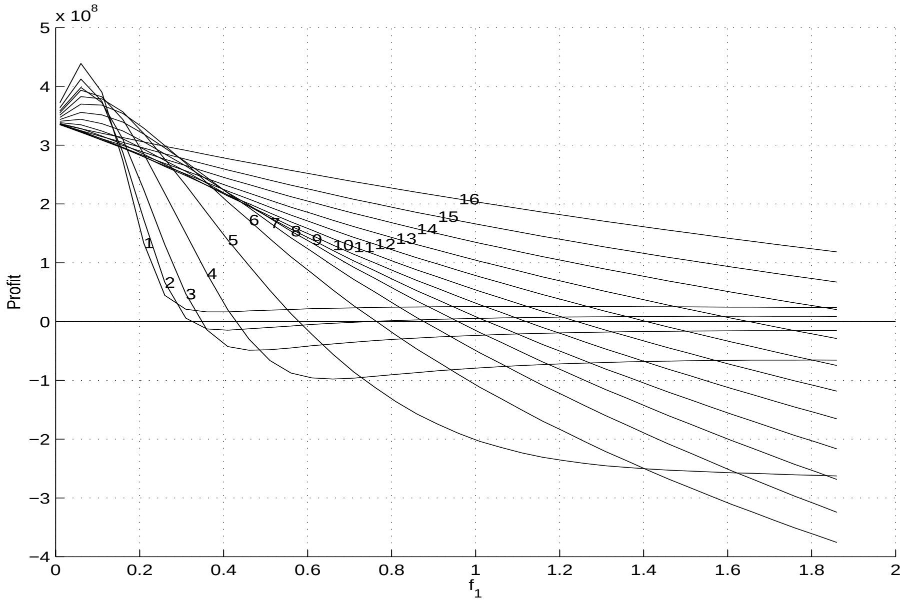

Figure 11: Total average annual profit as fuctions of f_1 and $a_{1,1}$.

4 Adaptive harvesting strategies

To gain the best possible profit and stable healthy fish stock, the effort and selectivity must vary according to the current situation. However, in reality instant changes are not obtainable, as the realization of the investments occurs always with some delay. In this section we present three different market mechanisms according to which the fleets react. Subsections 4.1 and 4.2 deal with reactions based on the profitability of the herring fishery. Subection 4.3 studies sustainable strategies which are based on reactions to the size of the population rather than to the profit. The sustainable strategies are shown to be a good solution also in economic point of view. In this section, we study strategies which are annually planned ($\rho = 1, r = 0$).

4.1 Open access

First we study an open access situation where there are no restrictions for the fishing, and each fleet is assumed to constitute its effort to the catch so that its profit would be as high as possible. The reaction to the change in profit is not instant but has a lag of one or two years. In open access situation the fleets react according to the sign of the profit (for a similar approach see [8]), thus the annual fishing mortality parameter is:

$$f_{y,i} = \beta_i sign(P_{y,i-dy}) f_{y,i-dy} + f_{y,i-1}, \tag{10}$$

where β is the arbitrary reaction multiplier of the fleet:

$$\beta = (0.02,\ 0.1,\ 0.04).$$

Further, we have $dy = 2$ as the rate of lag. Thus, we have two measures how the fleets react to changes in economic conditions. We begin again from the situation, where each fleet harvests with the same effort such that the total effort $\sum_{i=1}^{3} f_{i,0} = 0.2$. The first fishing age parameters are assumed to be constant $a_1 = (3\ 7\ 3)$.

As the simulation begins from a rather healthy stock condition situation, all the fleets gain profit in the first years (Figure 12). However, this situation is not sustaining, as the fleets constantly increase their effort (Figure 13). Thus, the stock gets more and more harvested (Figure 14) and after an adjustment period of about 60 years the result of an open access situation is extinction of the population and zero profit. As there is a lag in the change of effort, the fleets fish even the extinct stock. Similar results would be derived even with faster adjustment capability (with smaller delay), since the profits stay positive rather long and when the collapse to the negative profits occurs, the population is already fished very close to extinction. Surprisingly, fleet 3 is able to make the highest profit. This is probably due to lower costs as compared to fleet 2 and more intensive reaction (β) as compared to fleet 1.

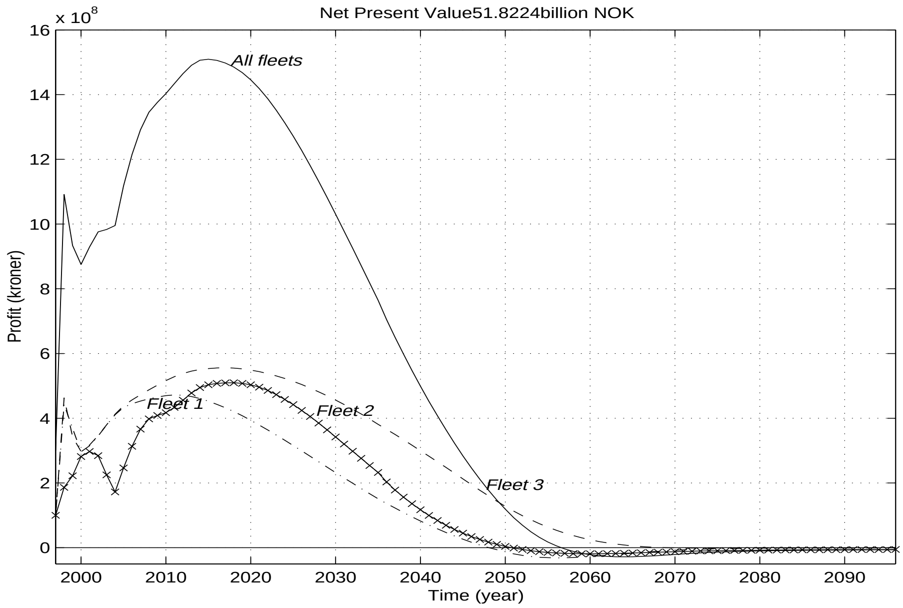

Figure 12: The annual profit for the fleets in open access situation.

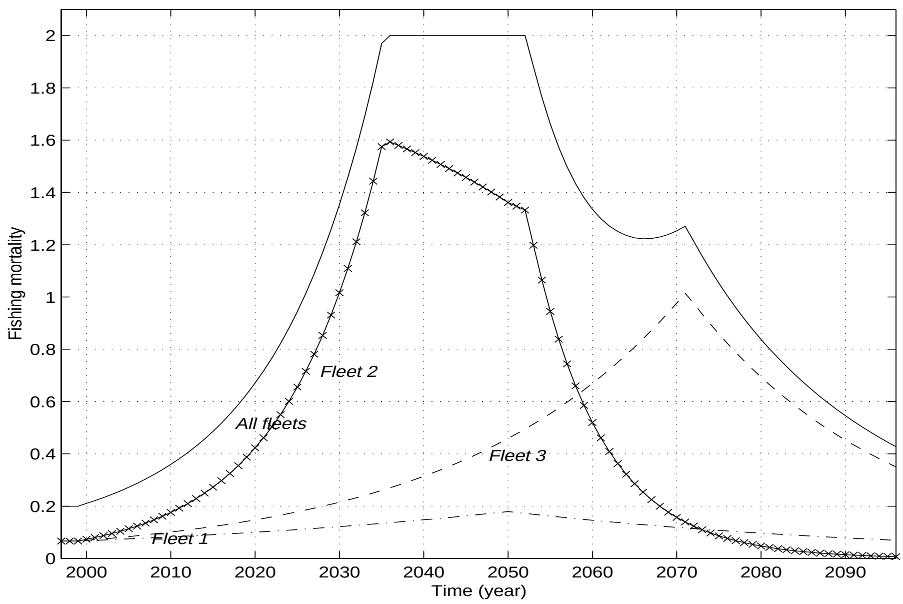

Figure 13: The behaviour of the fishing mortality parameters in open access situation.

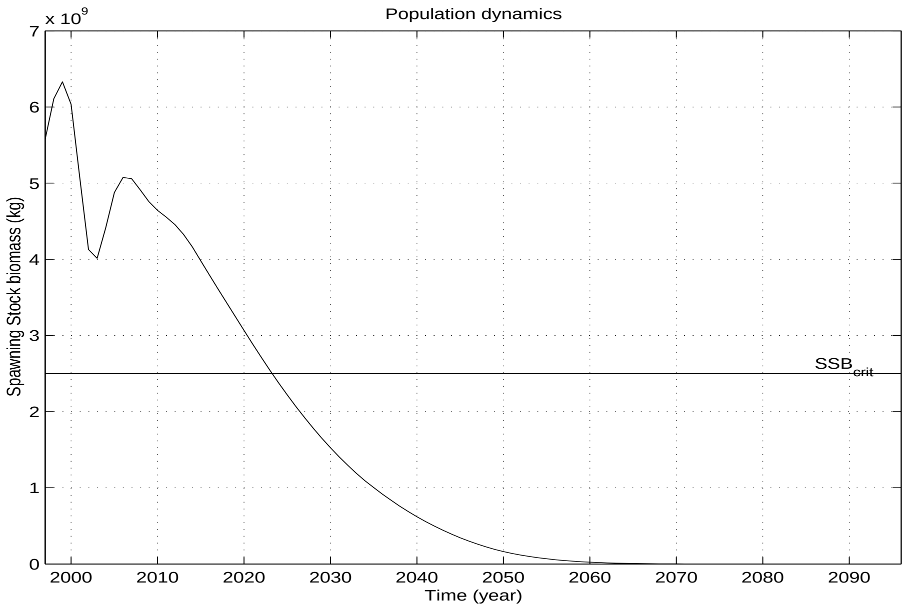

Figure 14: Spawning stock biomass during the simulation period in open access situation.

4.2 Strategy based on the direction of change in the profit

A slightly improved situation, where the fleets react according to the direction of the change of the profit is given as

$$f_{y,i} = \beta_i sign(P_{y,i-dy} - P_{y,i-dy-1}) f_{y,i-dy} + f_{y,i-1} \quad (11)$$

This form of adaptive strategy considerably changes the final average situation. Fleet 2, which reacts the strongest to the changes is also most in danger to gain losses because of its costs and its higher first fishing age, decreases its harvesting rapidly to zero effort. Also Fleet 1 which is weak in the reactions, ends almost to zero effort, and Fleet 3 overcomes at the end of the simulation the profit from the other fleets. However, carefully studying the results we observe that even in a situation, where the stock is rather healthy, the fishing mortality parameters are decreased and the profit tends smaller. That means that the profit function is completelly disconnected from the population behavior until the critical limits are reached. A small depression caused by the natural change in the profit can lead to a spin, where the smaller effort on fishing causes smaller profits and thus even smaller effort. So, in fact, the profit sustaining strategy may end up to zero harvesting and healthy population. (See Appendix 6.1 for the stochastic simulation of the same strategy.)

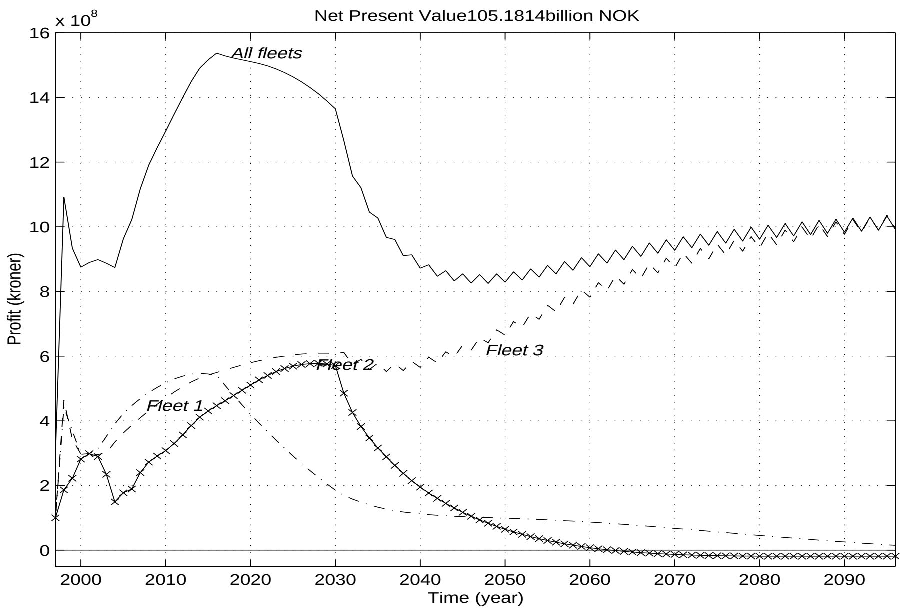

Figure 15: The annual profit for the fleets using the strategy based on the direction of change in profit.

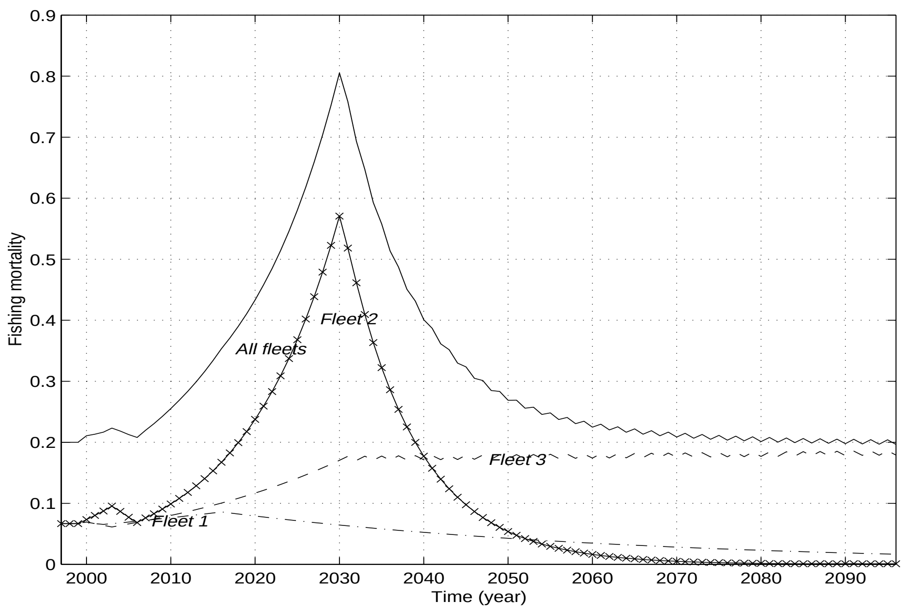

Figure 16: The behaviour of the fishing mortality parameters using the strategy based on the direction of change in profit.

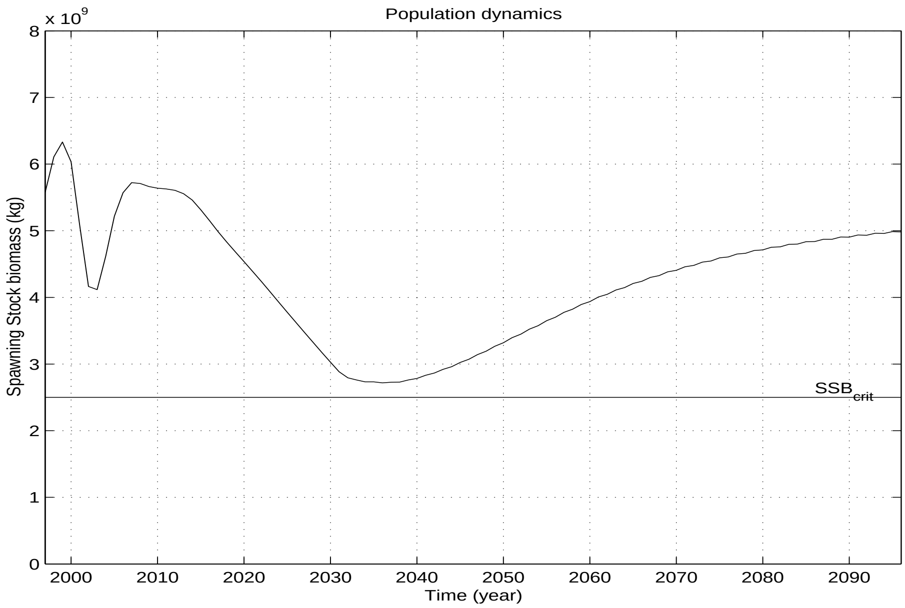

Figure 17: Spawning stock biomass during the simulation period using the strategy based on the direction of change in profit.

4.3 Sustainable harvesting strategies

As the open access situation is endurable in the terms of sustainable development, and even the modified profit-based thinking leads to unreasonable behavior of the fleets, some other approach to the effort reaction needs to be established.

In the profit based strategies the cost functions cause misleading decisions. The sensitivity to end up to a spin of decreasing profit and effort regardless of the state of the stock, refers that the behavior of the size of the population must be taken into account. Thus, in the long run, another aspect to the benefit of the fleets is the size of the spawning stock biomass, i.e., the future yield. We study the case where fleets react according to the change in SSB:

$$f_{y,i} = \beta_i sign(SSB_{y-dy} - SSB_{y-dy-1}) f_{y,i-dy} + f_{y,i-1}. \tag{12}$$

Here the total profit is in fact higher than in the merely profit based strategy (Figure 18). The annual profit reaches a steady level where it oscillates only a little because of the lag in the reactions. Thus also the fishing mortality approaches a steady state (Figure 19), which is reasonable since the spawning stock biomass does not fluctuate very much (Figure 20).

However, the trend in SSB is increasing. The reaction capability of the fleets is not flexible enough to observe this, and thus the annual yield and the profit the fleets receive could possibly be even higher within the framework of sustainable development.

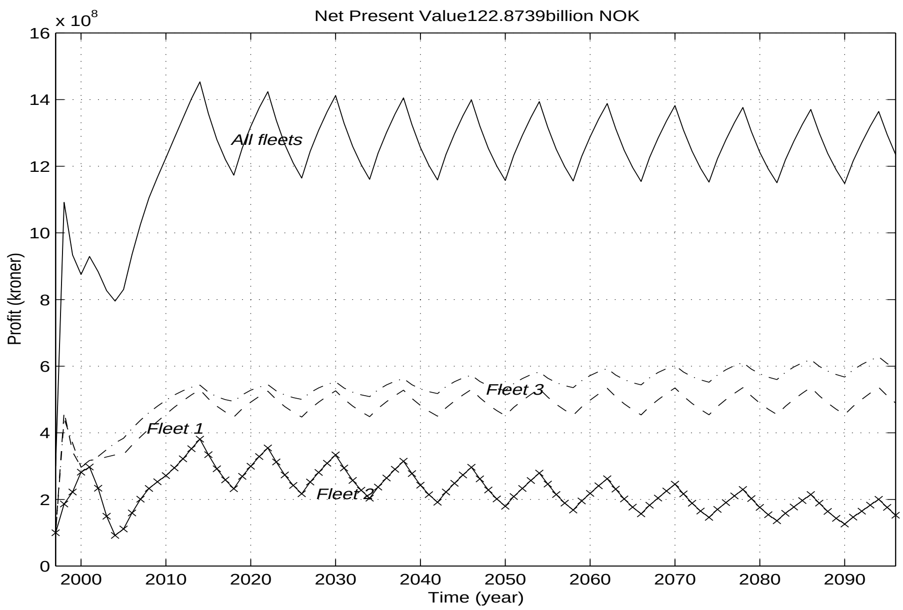

Figure 18: The annual profit for the fleets in situation where the fleets react to the sign of the change in SSB.

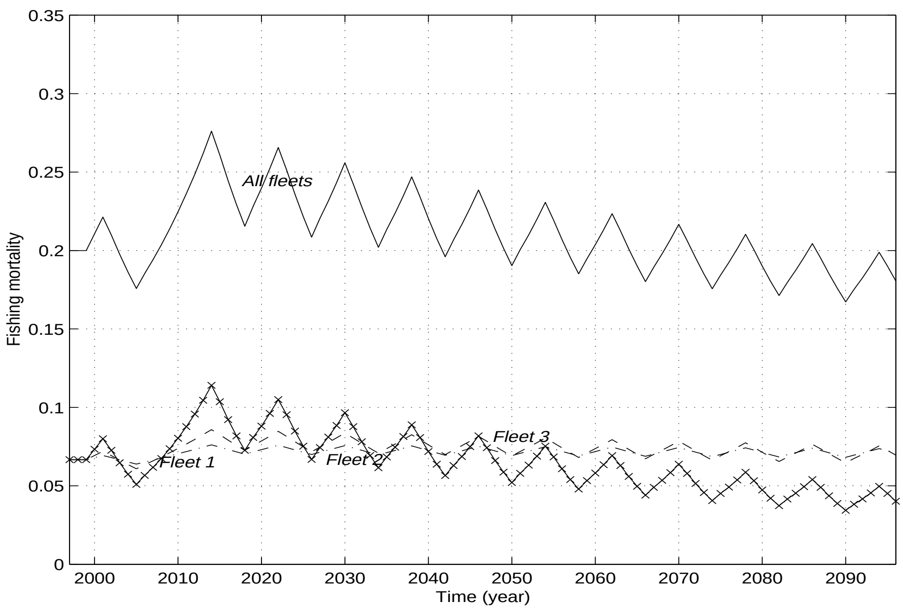

Figure 19: The behaviour of the fishing mortality parameters in situation where the fleets react to the sign of the change in SSB.

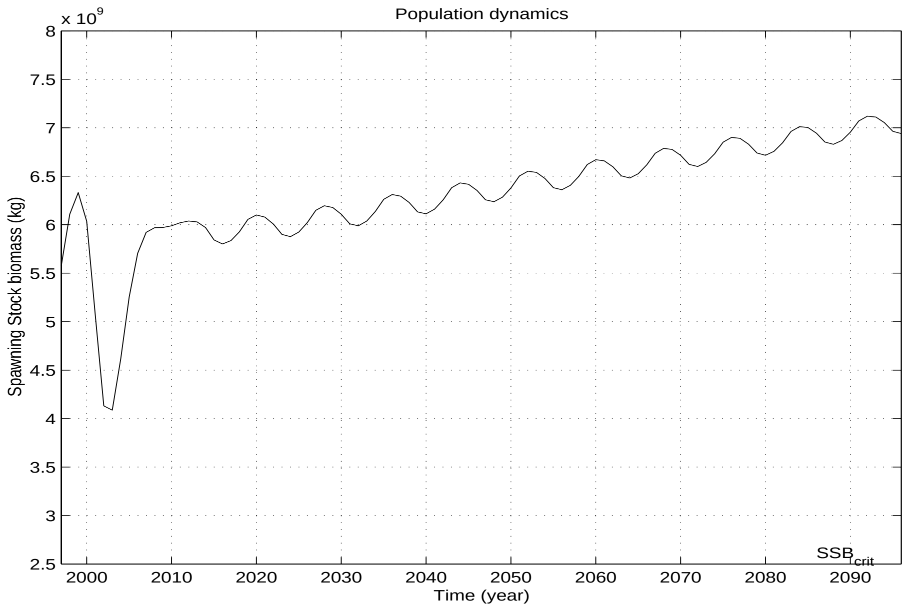

Figure 20: Spawning stock biomass during the simulation period in situation where the fleets react to the sign of the change in the SSB.

Thus, we also add the possibility to change the selectivity according to the criterium of steady and sustainable SSB for fleet 2. After a harsh estimation of the range and behavior of SSB from figure 20, we end up changing the first fishing age $a_{1,y,2}$ each time when crossing the limit of $2.5, 3, 3.5, 4, \cdots, 9 \cdot 10^9 kg$ in the size of spawning stock biomass. The initial fishing age $a_{1,0,2} = 7$ is linked to $5.6 \cdot 10^9 kg$. If the change is in the positive direction, the spawning stock biomass is growing and thus it is safer to catch even the smaller fishes, i.e., increase the first fishing age $a_{1,y,2}$. The resulting total profit is higher (Figure 21) since the profit for Fleet 2 oscillates on a higher steady state level. However, as the costs for Fleet 2 are high, the change in the total profit is not tremendous. The fishing mortality parameter for Fleet 2 has still a slightly decreasing trend (Figure 22), but the fleet has compensated the loss in effort with the selectivity. The size of the spawning stock biomass is stabilized onto a level which is close to the level where Fleet 2 would diminish its selectivity again and catch even smaller fish (Figure 23). (See Appendix 6.2 for the stochastic simulation of the same strategy.)

The change in the first fishing age in the strategy of fleet 2 (or even other fleets) could be even more adjustable to make better profits. However, in reality the change in selectivity is rigid, and the reflection of the current situation is better accomplished through the fishing mortality parameter. The reaction multipliers β used here are arbitrary and must be more accurately adjusted to the realistic reaction capability. Too elastic reaction capability leads to highly oscillating fishing mortality parameter which causes investment and adjustment costs which may not be desirable. However, in the current model investment decisions are not explicitly modelled and therefore, it is difficult to draw specific conclusions within this framework.

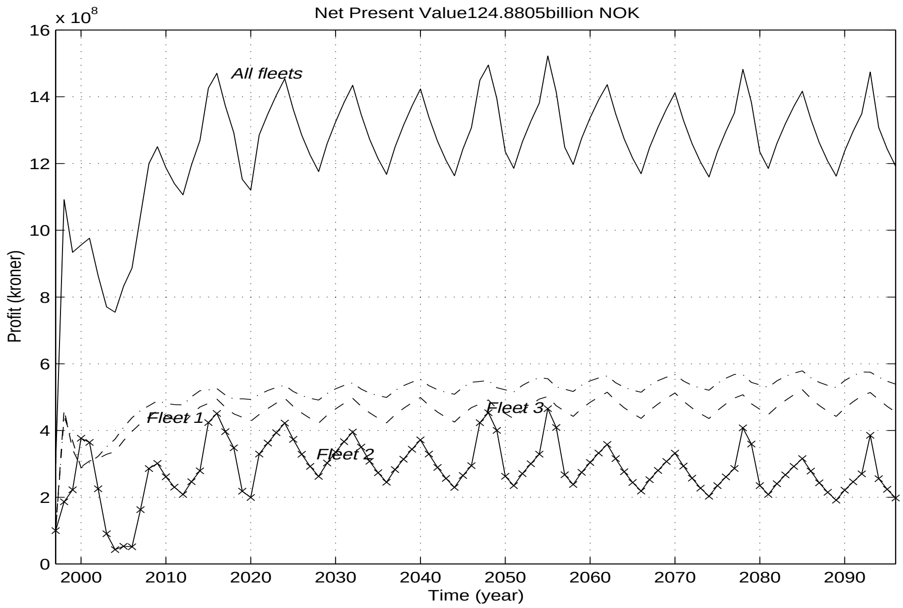

Figure 21: The annual profit for the fleets in situation where the fleets react after the sign and rate of the change in SSB.

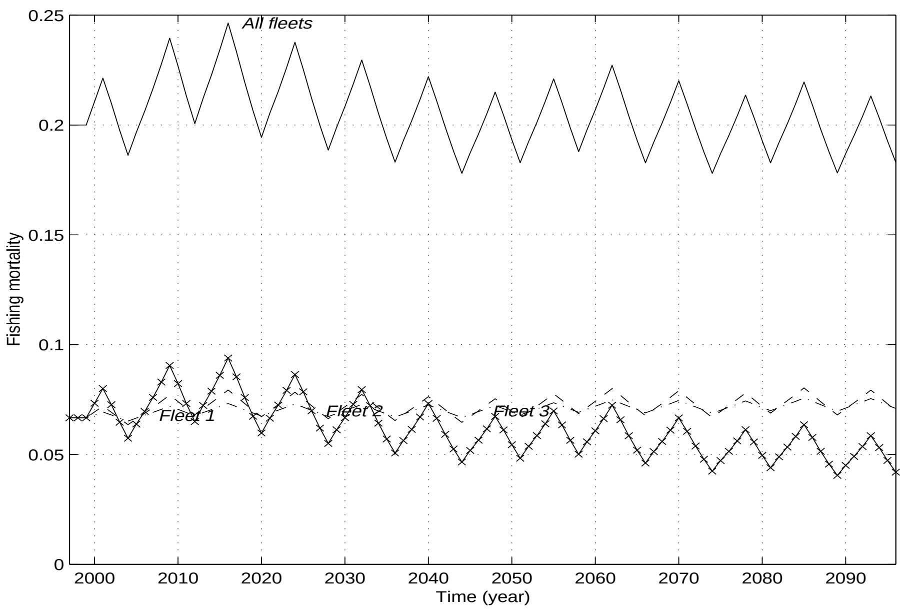

Figure 22: The behaviour of the fishing mortality parameters in situation where the fleets react after the sign and rate of the change in SSB.

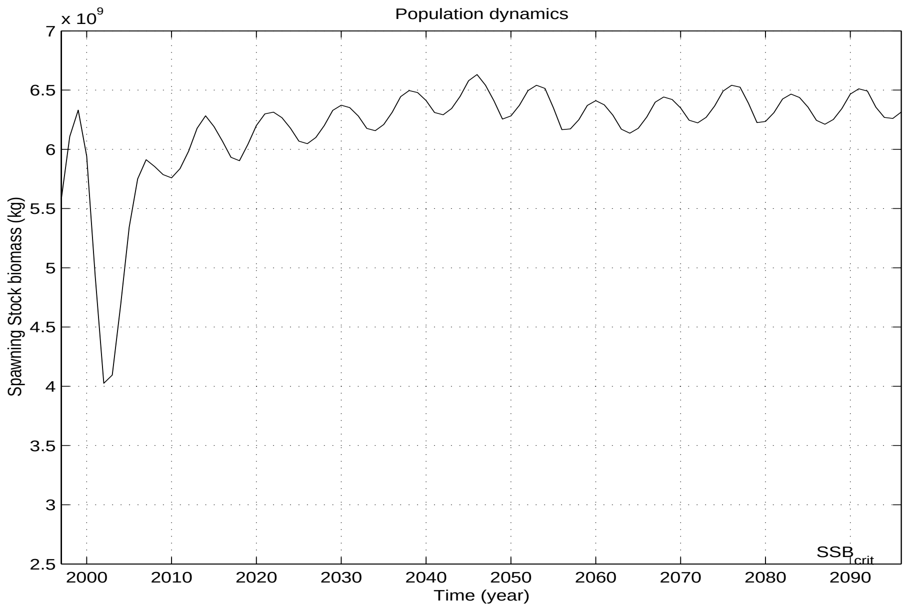

Figure 23: Spawning stock biomass during the simulation period in situation where the fleets react after the sign and rate of the change in the SSB.

5 Conclusions

In this report, we have studied the sensitivity of the herring population and the size of catch on the changes in fishing mortality and selectivity. The discounted profits for fleets and the size of the spawning stock biomass were presented using in advance planned constant strategy. This strategy did not yield any optimal solutions in both economic and biological sense. Thus, we introduced annually planned harvesting strategies. We studied strategies attached both to economic and to biological criteria and that were controlled with altering fishing mortality and first fishing age parameters.

The Norwegian spring spawning herring population is sensitive to the rate of fishing, especially if all of the age classes are harvested. Even one heavily fishing fleet may cause its extinction within some decades. This is not profitable for any of the fleets nor for the state since the gained high profit is only a short term solution. By improving the selectivity of the fleets the size of the population becomes selfsupporting and even a harsh fishing cannot destroy it, since there is always some young spawning herring left.

If the fleets are able to react to the current situation with adjustable fishing mortality parameters, the state must restrict the fishing. In the case of open access to the stock, each fleet aims to the best possible individual profit. The stock is harvested constantly more and more, and in some decades (depending on the reactions), it is harvested to extinction. If the fleets adjust their effort on the stock by reacting to the size of the stock via the size of the change in the profit, they may, in average situation, end to zero effort even when fishing healthy stock. The profit is tied to the effort, and a small depression in the size of the stock causes smaller effort, which leads into a spin of smaller effort and profit where the stock remains large. Thus, a strategy, where the effort, and if possible, the selectivity are proportional to the size of the spawning stock biomass, is more sustainable even in an economic sense.

The capability to carry the yield of the vessels is taken into account in this model only roughly, since the connection between the number of vessels and the effort on the stock is not based on empirical data. Also the investments on the new vessels or reduction of the vessels and thus the number of employees are hardly as flexible in reality as they are in this model, where the proportional adjustment term is an arbitrary parameter. The cost function is still incomplete, not including any investment costs, for example. Also the parameters in the cost functions are partly arbitrary and must still be studied more closely.

The model of sustainable optimal strategy is purely based on the size of the spawning stock biomass. However, in reality economic thinking is stronger, and thus a model which contains both these criteria should be established in the sense of multicriteria optimization and game theory. In total, all the results in this report are only average results, an idea of the realistic situations can be achieved from the stochastic simulations of the same strategies in the Appendix. However, even the average results drawn from the simplified model show the basic advantages and drawbacks of the strategies.

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6 Appendix

6.1 Stochastic simulations of the change in profit related strategy

In the stochastic simulations we use Beverton–Holt's *recruitment* with log-normal error:

$$R_y = \frac{aSSB_y}{1 + SSB_y/b}\, e^{\varepsilon_y}. \tag{13}$$

The error term reflects the high variability in recruitment due to numerous external factors (e.g. cod predation, environmental fluctuations). Random variable ε_y is normally distributed with mean 0 and variance σ. For paramaters see [3].

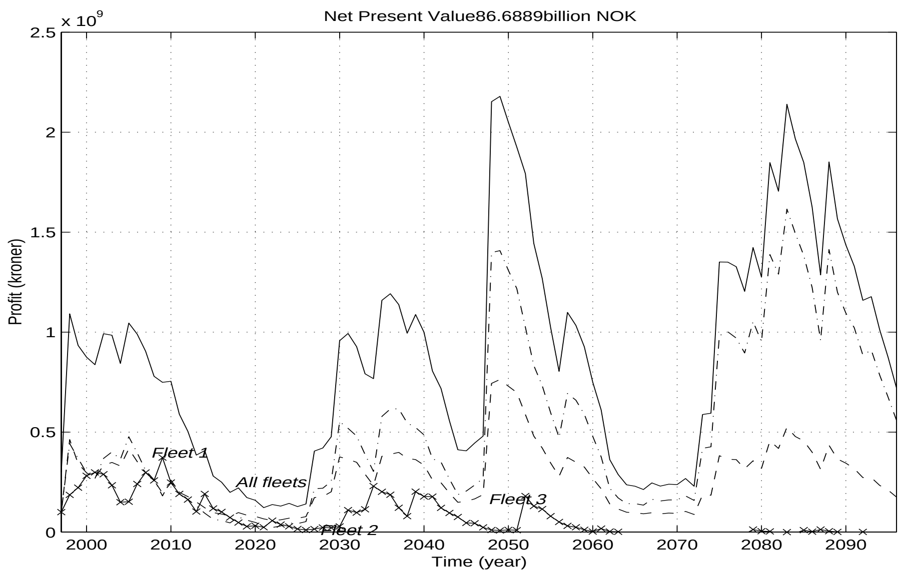

Figure 24: The annual profit for the fleets in stochastic simulation using the direction in the change of the profit based strategy.

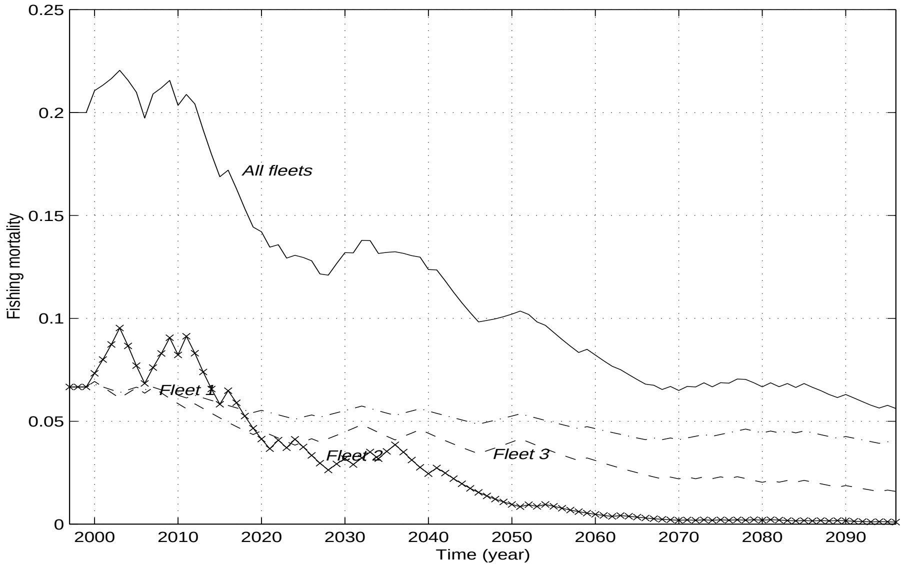

Figure 25: The behaviour of the fishing mortality parameters in stochastic simulation using the direction in the change of the profit based strategy.

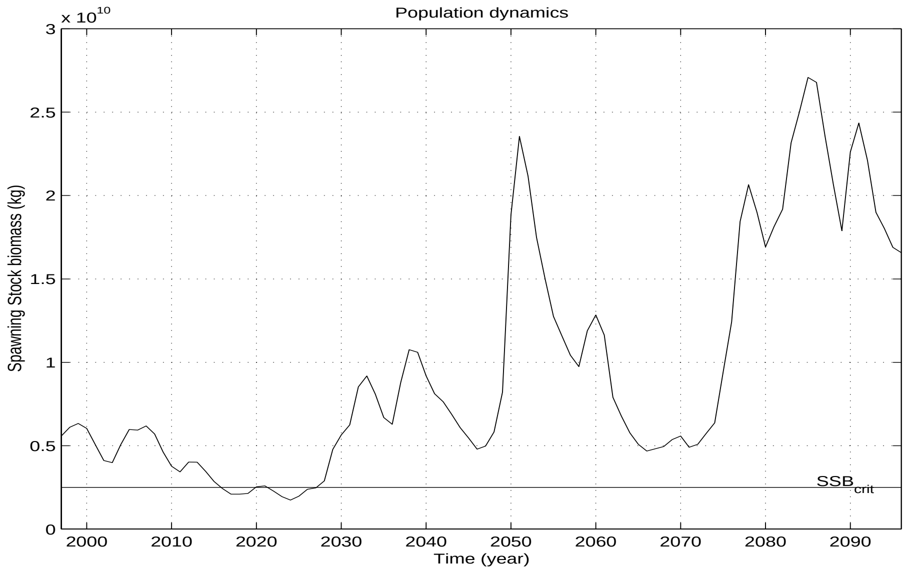

Figure 26: Spawning stock biomass during the stocastic simulation using the direction in the change of the profit based strategy.

6.2 Stochastic simulations of the change in SSB related strategy

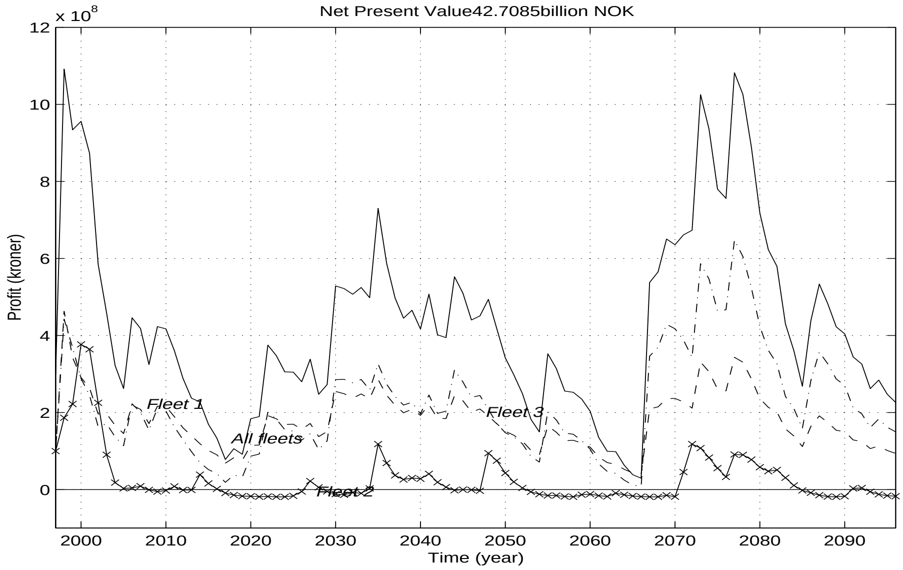

Figure 27: The annual profit for the fleets in stochastic simulation of SSB-related strategy.

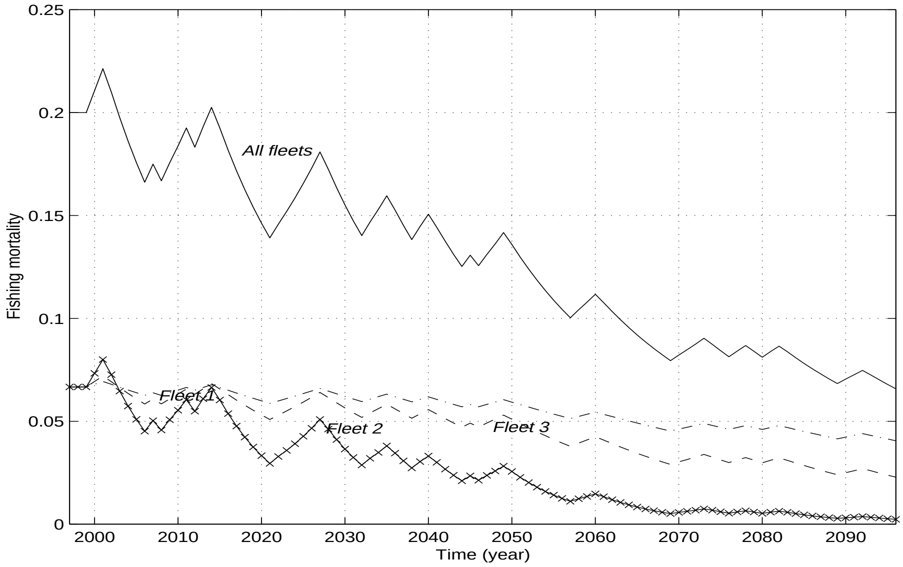

Figure 28: The behaviour of the fishing mortality parameters in stochastic simulation of SSB-related strategy.

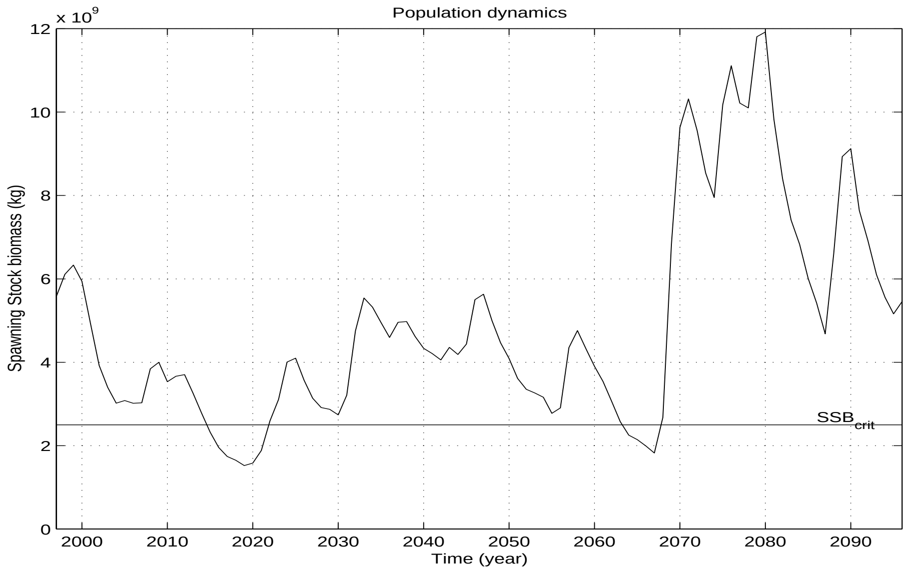

Figure 29: Spawning stock biomass during the stochastic simulation of SSB-related strategy.

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