Optimal Fleet Size When National Quotas Can Be Traded

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Abstract Assuming stochastic quotas for a fish stock that is shared between two nations, we find the optimal fleet size for one of them by maximizing expected profit under the assumption that national quotas can be traded and that stable national quotas is a political goal. As an example we use the Norwegian purse seiner fleet and the summer capelin fishery in the Barents Sea.

Introduction

There exists a substantial literature on questions concerning quotas in fisheries, most of which is based on deterministic models. But as pointed out by many authors [see, e.g., Sissenwine (1984)], the environment of fisheries is heavily influenced by uncertainties, in particular, uncertainties related to recruitment and thereby quotas.

Several questions concerning quotas can be posed. We mention how to settle the total quota if the resource is managed by only one country (Clark, 1980; Spulber, 1982) and if it is managed by

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several countries (Munro, 1979). It is also important to know how to distribute the total quota among the participating vessels and enforce the regulations (Andersen and Sutinen, 1983; Clark, 1980), and how to split the total quota among countries if the stock is a shared resource.

Gulland (1980) describes the problems facing countries that must manage stocks of fish that cross the boundaries between them. This is a verbal description. Several authors have also modeled problems connected to shared resources. We have already mentioned Munro (1979), who considers the optimal management of a transboundary resource where the two participating countries cooperate. Levhari and Mirman (1980), on the other hand, investigate the case of non-cooperative management. Hannesson (1984) shows how the catch capacities become too large if two countries, having identical fish stocks except for the probability distribution of their abundances, do not cooperate. Beddington and Clark (1984) treat the question of allowing foreign fleets to take part in the fishing of a stock that is managed by only one country, that is, whether it can be beneficial to a country to let other nations fish on a stock that is solely its own. These two last papers both assume stochastic recruitment.

Consider a shared resource where questions about the total quota and the division of it among the countries are settled. Our question is the following: Provided that a political goal for one of the participating countries (country A) is to keep the (stochastic) quotas stable by selling and buying quotas, and that the other country (country B) under certain conditions is willing to take part in such a trade, what is the optimal fleet size for country A, given different trading prices? We shall look upon the fishery as if it were run by one firm (the state). We find such an approach appropriate from the society's point of view; see also Flåm and Storøy (1982).

Questions concerning the optimal fleet size have also been addressed by others [see, e.g., Clark and Kirkwood (1979)]. They do not consider shared resources and they assume a fixed stock-independent recruitment. As they suggest in their paper, we have replaced this by a stochastic recruitment.

Which prices are actually used will be a result of negotiations. Our goal here is not to predict the outcome of such negotiations, but to show the optimal solution for different trading prices. These optimal solutions are useful from two viewpoints. First, if country A and country B manage to agree on trading prices, such that country A always can sell or buy as much as it wishes at those prices, the solutions presented in this paper show what country A's optimal fleet will look like as a result of the negotiations.

It is, however, probably rather unrealistic to assume that such a treaty can be agreed upon. It is perhaps more reasonable to assume that the negotiations will not only result in trading prices, but also a quota $\mathbf{R}$ which is country A's stable quota. Hence if R is the quota allotted to country A in a specific year, it will sell $R - \mathbf{R}$ if $R > \mathbf{R}$ and buy $\mathbf{R} - R$ if $\mathbf{R} > R$ at the agreed prices. In this case the model is a useful input to the negotiations, since it shows country A what is optimal from its viewpoint. Note that none of the situations we have described above imply that country A will wish $\mathbf{R}$ as large as possible. There is an optimal value for $\mathbf{R}$. Above this value, the country will start losing money.

If country B accepts the treaty, it acts as a kind of insurance company for country A. It is therefore reasonable to assume that only trading prices that result in a net average (or expected) gain for country B are interesting. Typically, country B will be much larger than country A, so that its economy more easily absorbs variation in the activity level of its fishing fleet.

Our objective is to maximize expected profit for country A given the above-mentioned goal. In the long run the question of maximized expected profit is a question of resource management and the structure of the fleet and the processing industry. We shall assume that the processing industry is given and that the resource is properly managed (and therefore that the total quota has a stable distribution), such that maximizing expected profit is equivalent to finding the optimal fleet structure.

The assumption that the processing industry is given is clearly rather restrictive in the general case. We have chosen this approach, however, because we have found earlier [see Wallace (1982)] that the processing industry in the Norwegian industrial fisheries is much closer to its optimal size than the fleet is, and we wanted to highlight the situation in the fleet for these fisheries. Therefore, at this point, the model formulation depends on the application it is intended for. Also, for political reasons, closing plants is much more difficult than taking vessels out of the fisheries. The question to answer is therefore: For different trading prices, what is the optimal fleet, and in these cases, how much will country A catch?

The Capelin Fisheries and the Purse Seiner Fleet

The quotas allotted to the Norwegian purse seiner fleet vary considerably from one year to the next. This variation results in difficulties when the structure of the fleet is to be planned. Flåm and Storøy (1982) have shown a method to settle the fleet size when the quotas are assumed deterministic. Assuming that the quotas are stochastic but that they have a stable distribution, Wallace and Flåm (1982) have shown how the optimal fleet size can be found when we take into consideration that a given fleet will behave differently with different quotas. The latter approach is based on a formulation of a nonlinear two-stage stochastic optimization problem with recourse, where the long-run (first stage) decision is the size of the fleet and the short-run (second stage) decision is how to choose speed to catch a given quota with a given fleet. For a review of two-stage stochastic optimization problems, see Wets (1983).

The Norwegian purse seiner fleet takes part in several fisheries in the North Sea and the Barents Sea. The two major fisheries are the summer capelin fishery and the winter capelin fishery. The total catch of capelin in 1982 was 16.7 million hectoliters, out of which most of the 67% allotted to the Norwegians was caught by the purse seiners. The remaining 33% was caught by vessels from the USSR. The catch in 1982 was below average. In these fisheries the catch is always equal to the quota.

The capelin (*Mallotus villosus*) is a small pelagic fish belonging to the family Osmeridae. The spawning stock consists of 3- and 4-year-old fish, and the fish dies after spawning. Because of the short life of the capelin, it is not important to distinguish among the different year classes. It is therefore allowable to talk about stochastic quotas instead of stochastic recruitment as we do in this article. The fishing pattern is of no importance. The only problem for the managers of the fish stock is therefore to make sure that the escapement is of a reasonable size. So far this has been successful. For more information about the capelin, see Jangaard (1974).

Clearly, aspects of the fishery other than the quota are also stochastic, such as the position of the fishing ground and the size of each catch. We have chosen to concentrate on the quota, however, since we believe that this is the major uncertainty.

Although the amount of fish caught is approximately the same in the two capelin fisheries, the summer capelin fishery requires many more vessels than does the winter capelin fishery. The reason is that whereas the winter capelin fishery takes place along the coast of northern Norway, the summer capelin fishery takes place off the coast of Spitzbergen (Svalbard), far north in the Barents Sea. The need for transportation is therefore very large. Also, preservation of the capelin is more difficult in the light summer months, far north of the Arctic Circle.

The main problem of the Norwegian purse seiner fleet, as we see it, is its enormous overcapacity. The fleet consists of approximately 160 vessels with cargo capacities between 2000 and 12,000 hectoliters. We show in this paper [see also Flåm (1981); Flåm and Storøy (1982); and Wallace and Flåm (1982)] that a reduction to between 40 and 50 large vessels would be more appropriate. Such a fleet would be very profitable.

There are two main problems connected to the overcapacity of the fleet. First, it represents an enormous waste of capital. The fixed costs of a large vessel is about 4.9 million Norwegian kroner per year (between 0.6 and 0.7 million U.S. dollars). To calculate the fixed costs we have used 7% rate of return on capital and numbers from the official Norwegian fisheries statistics, see Budsjettnemda (1983).

The second problem, however, is also very important. It is connected to the fact that too many vessels take part in the fishery simultaneously. Therefore, large queues occur at the fishmeal plants and some vessels have to go all the way to southern Norway to deliver the cargo. Also, the time available is not fully utilized, as many vessels catch their individual quotas very early in the season. Both the queues and the long trips could be avoided with a smaller fleet, since it would lengthen the fishery in time and avoid the peak in the first weeks of the fishery. The economic gain of such an extension is substantial.

To understand that queues and long trips can be avoided by decreasing the number of vessels, it is important to remember the geography of the capelin fisheries. The fisheries take place north of the Norwegian mainland, and the plants are spread southward along the coast in an almost straight line. Furthermore, there are several plants in northern Norway, very few in the middle part, and many in the southern part. The extra costs of a trip to southern Norway in the first weeks of the fishery cannot be offset by short trips later in the season. Therefore, it is important to keep the capelin in the northern part of the country. It should be more obvious that the queues decrease when the number of vessels fishing simultaneously decreases.

Further background information on the fisheries in which the Norwegian purse seiner fleet takes part can be found in Flåm (1981). As mentioned above, the fishery that is most intensive is the summer capelin fishery, so we shall concentrate on that fishery. The reason is that the optimal fleet is found by checking for which fleet size marginal costs equals marginal income. Therefore, the most intensive fishery will be of greatest importance, since that is the fishery where the marginal vessel is mostly needed and therefore the fishery where it creates most of its income. Hence we reformulate our problem a little. Earlier we said that a goal of country A (in this case, Norway) was to keep the quotas stable. We now only require the quota in the summer capelin fishery to be stable.

The capelin stock in the Barents Sea is, as mentioned, a resource shared between Norway and the USSR. Therefore, this is a stock for which our formulation can be used. If the stock had been purely Norwegian, we could of course sell quotas but not buy. As of today, no trading in quotas is taking place.

The Model

In this section we give the model for the problem presented in the preceding sections. The model is a linear stochastic optimization model with simple recourse [see Wets (1975)].

The main idea behind a stochastic program with simple recourse is as follows. The decision maker is confronted with one long-run decision, uncertainty, and several short-run decisions. In our problem the long-run decision is the fleet structure, the uncertainty is related to the quota, and the short-run decisions are how much to sell/buy when the fleet size and the quota for a specific year is known (i.e., when the uncertainty is revealed to the decision maker). The trading is done in order to keep the fleet busy (i.e., in order to get the national quota equal to the capacity of the fleet). These two types of decision are of course not independent. Since we assume that a political goal is to keep national quotas stable (and have a fleet with capacity equal to this quota), it should be clear that the larger the fleet, the more probable it is that we have to buy quotas.

Assume that we have a set of plants, indexed by f, and a set of vessel groups, indexed by v. The aim is to maximize total expected profit with respect to some constraints. The total expected profit is equal to the net value of the fish minus the variable and fixed costs of the vessels and finally, minus the expected value of the fish bought in order to keep the quota stable. (Clearly, if we on average sell fish, we have to add the expected value of fish sold instead.) Let R_i, $i = 1, \ldots, n$, be the possible values for the quota R and let p_i be the probability that $R = R_i$. The total expected profit θ is then given by

$$\theta = \sum_v \sum_f (g_v P - c_{vf}) X_{vf} - \sum_v F_v Z_v - \mathbf{Q}(X) \tag{1}$$

where

$$\mathbf{Q}(X) = \sum Q(X, R_i) p_i \tag{2}$$

and

$$Q(X, R_i) = \operatorname{Min}\{-q^+ y^+ + q^- y^- \| y^+ - y^- = R_i - \sum_v \sum_f X_{vf} g_v\} \tag{3}$$

The parameters are:

- g_v: Average catch per trip for a vessel in group v. This number is based on empirical studies and it equals approximately 70% of the cargo capacity.
- P: Net value of 1 hectoliter (hl) capelin.
- c_{vf}: Cost of one trip from fishing ground to plant f and back, including all variable costs for a vessel in group v.
- F_v: Fixed costs for a vessel in group v that must be covered from this fishery. The fixed costs include a return on capital plus maintenence and depreciation.

q^+: Selling price for 1 hl of capelin in the sea.
q^-: Buying price for the same.
R_i: Outcome for stochastic quota R.
p_i: Probability that $R = R_i$.

and the variables are:

X_{vf}: Total number of times vessels in group v deliver cargo at plant f.
Z_v: Number of vessels in group v.

The variables X_{vf} and Z_v are the so-called first-stage variables. They therefore represent the policy decision we want to make. In addition, we have the second-stage variables y^+ and y^-, which for a given X and R_i show how much we sell or buy, respectively, in order to keep the national quota stable.

Note that it is trivial to solve Equation (3), which represents the *recourse* action. It shows how we in a given year have to buy quota (y^-) if the quota allotted to us (R_i) is less than what we had planned to catch ($\sum\sum X_{vf}g_v$) and how we wish to sell (y^+) if our quota is larger than what we had planned for. If we then take the expectation of (3) for a given X, we get the expected value of traded quotas $\mathbf{Q}(X)$. We see from Equation (1) that we must measure these indirect (or second-stage) costs against the direct (or first-stage) costs and the income.

Hence the goal in a stochastic optimization problem with recourse is to find the first-stage variables (in our case, X_{vf} and Z_v). The second-stage variables (y^+ and y^-) are *not* a part of the solution. In fact, there are as many y^+ and y^- variables as there are possible outcomes for R.

Our constraints are

- Plant f must not be overemployed.

$$\sum_v g_v X_{vf} \leqslant \text{Cap}_f \qquad \text{for all } f \tag{4}$$

where Cap_f is the production capacity of plant f during the season.

- The vessels must not be overemployed.

$$\sum_f t_{vf} X_{vf} \leqslant Z_v T \qquad \text{for all } v \tag{5}$$

where t_{vf} is the time needed to catch the fish, deliver it at plant f, and return to the fishing ground for a vessel in group v, and T is the total length of the fishing season.

- Do not use more vessels than are available.

$$Z_v \leqslant \text{Max}_v \tag{6}$$

where Max_v is the total number of vessels available in group v.

Constraint (6) is used since we are considering an existing fleet. Thus we do not allow an increase in the number of vessels of a certain type even if the total number is decreased. If we had considered building a totally new fleet, constraint (6) would not have been used.

As explained above, this is again a two-stage stochastic optimization problem with simple recourse. Equations (1) to (6) are in standard format for such problems. They can be solved either iteratively using a variant of Benders' decomposition developed by Van Slyke and Wets (1969) or as large linear programs as explained by Wets (1975). We have solved ours as a large linear program.

To highlight the two-stage nature of these problems, let us reformulate Equations (1) to (6). The goal is to maximize θ, where

$$\theta = \sum_v \sum_f (g_v P - c_{vf}) X_{vf} - \sum_v F_v Z_v + \sum (q^+ y_i^+ - q^- y_i^-) p_i$$

subject to

$$y_i^+ - y_i^- = R_i - \sum\sum X_{vf} g_v \qquad i = 1, \ldots, n$$

and Equations (4) to (6). This should clarify that Equations (1) to (6) comprise simply a large linear program, and that there are as many y^+ and y^- variables as there are possible values for the quota R.

Table 1
Assumed Distribution of the Norwegian Part of the Quota in the Summer Capelin Fishery (Millions of Hectoliters)[a]

Quota	Probability	Quota	Probability
3.5	0.15	5.5	0.15
4	0.15	6	0.15
4.5	0.15	6.5	0.05
5	0.15	7	0.05

[a] The expected value is 4.95 million hectoliters.

Results

Table 1 shows our assumption of the distribution of the Norwegian part of the quota in the summer capelin fishery. Furthermore, we let the cost of labor be zero to reflect that alternative jobs do not exist in rural Norway. Using the information above and well-established data about the Norwegian purse seiner fleet, we get Tables 2 to 4.

In Table 2 we show the capacity of different fleet sizes, all measured in millions of hectoliters. Since we assume that quotas are kept stable via trade, we shall naturally get a fleet that operates on the margin of its capacity every year. Therefore, when we find a fleet size in Table 3, we can immediately see from Table 2 what amount that fleet will catch and thereby also how much we will sell on average each year. The catch capacities in Table 2 correspond to what we earlier called **R**.

Table 2
Catch Capacity and Average Amount of Quota Sold for Different Fleet Sizes (Millions of Hectoliters)[a]

Vessels	Catch Capacity	Average Amount Sold
30	3.5	1.45
34	3.8	1.05
36	4.0	0.95
40	4.4	0.55
43	4.7	0.25

[a] All vessels have cargo capacity above 8000 hl.

Table 3
Optimal Fleet Size for Different Values of Selling Price (q^+) and Buying Price (q^-) (Norwegian Kroner)[a]

	q^+			
q^-	0	2	4	10
0	43			
6	43		43	
15	43		42	
20	42	42	42	40
40	40			
50			40	40
60	40			
150	36			
250	36		34	
∞	30			

[a] All vessels have cargo capacity above 8000 hl.

Table 4
Average Value of Quotas Sold (millions of Norwegian Kroner) for Different Values of Selling Price (q^+) and Buying Price (q^-) (Norwegian Kroner)

	q^+			
q^-	0	2	4	10
0	0.0			
6	−1.8		0.9	
15	−3.7		−0.7	
20	−5.0	−3.1	−1.7	−3.7
40	−7.7			
50			−6.6	−2.0
60	−14.7			
150	−11.9			
250	−19.9		−8.4	
∞	0.0			

The fixed costs that enter the model are not the total fixed costs for a vessel, but rather the part of it that on average must be covered from this fishery. Since that value will vary with fleet size, we had to calibrate the model. This was done when Tables 3 and 4 were created. The part of the fixed costs that is covered from other fisheries was found by simulation on a model developed at Chr. Michelsen Institute. A short description can be found in Hilstad (1982).

In the upper left corner of Table 3 we see that with $q^+ = q^- = 0$, we will use only 43 vessels. (We solved the model with several vessel groups, but ended up only with vessels with cargo capacity above 8000 hl.) This fleet structure is rather surprising, since it means that with no quotas whatsoever ($q^- = 0$ means that any quota can be bought at zero cost), we will only use 43 vessels and catch 4.7 million hectoliters of capelin. This is less than the average catch today, and means that if the fishery was run by one firm, and that the firm did not consider recruitment problems at all, it would only catch 4.7 million hectoliters using 43 vessels. The forty-fourth vessel would incur a net loss for the firm.

The results do not confirm with today's situation at all. There are several reasons. First, we have used 7% rate of return (which is commonly used in Norway) on all capital when calculating the fixed costs of a vessel. Today, the rate is kept above zero only because of government subsidies. Second, we maximize profit for the fleet as a whole, whereas the political goals today do not even require the fishing fleet to be in balance. Because of the externalities there is, of course, a considerable difference even between profit maximization and just balance.

In Tables 3 and 4 we have considered only situations where $q^+ < q^-$, except for the case $q^+ = q^- = 0$. The reason is, as we mentioned earlier, that since we wish to buy national quotas when total quotas are small and sell when total quotas are large, it is reasonable to assume that the other countries will require some compensation for absorbing all the variations.

As we move from the upper left corner of Table 3, we see how the optimal fleet decreases as the buying price increases (the cost of keeping the quota at a certain level goes up) or as the selling price goes up (it becomes more profitable to sell the marginal reserves).

When it is no longer possible to buy quotas ($q^- = \infty$) we get an optimal fleet with 30 vessels. This is the number of vessels necessary to catch the minimum possible quota 3.5 million hectoliters.

Table 4 shows the expected value of traded quotas in connection with the different solutions in Table 3. Note that we have an expected gain only when $q^- = 6$ and $q^+ = 4$. We consider that combination of trading prices rather improbable, however, since the difference is so small (the compensation for absorbing all the risk is low). Thus for all reasonable trading prices we will on average sell quotas, but still have an expected economic loss due to the difference between selling and buying prices. It is important to note, however, that the other country will also gain from the fact that it on average will catch more fish than today. (This is, of course, not a general result.) The value of this gain will depend on the cost structure of its fishing fleet.

It is worth noting that the fishmeal and fish-oil production from the North Sea and the Barents Sea is not large enough to have any major influence on the world market prices. Therefore, a year with high quotas in the Barents Sea might easily be a year with high prices on the world market. This is why we have assumed that the value of 1 hl of capelin is independent of the quota.

There are different ways of reducing the fleet size. To take part in the capelin fisheries today, a vessel needs a license. The license states the official cargo capacity of the vessel. Based on the cargo capacity the vessel will be given a certain part of the total quota. The formula used to calculate this portion is such that the value of marginal capacity decreases rapidly with the size of the licensed cargo capacity.

Today, there is a market for licenses. But if someone buys a license, the cargo capacity attached to the new license is added to the cargo capacity attached to the buyer's old license. Since, as mentioned, the marginal value of capacity decreases rapidly with the total cargo capacity, this extra capacity will be of little value to the buyer. And even more important, it will be worth much less for the seller. Clearly, in a market where the commodity is worth much less for the buyer than for the seller, not much trading takes place.

Our suggestion is that the rules are changed so as to add not licensed cargo capacities, but rather the resulting portions of the total quota. Thereby the license gets the same value for both the seller and the buyer. Hopefully, this will reduce the number of vessels in the fisheries on a voluntary basis. It is also possible for the government to buy back licenses. This can be a good investment for the government since it will reduce the needs for subsidies.

Conclusions

The main conclusion of this article is that the number of vessels should be reduced from 160 to between 40 and 50. The model also suggests that only the largest vessels should be kept. The reason is that the vessels spend most of their time transporting and not fishing, and the large vessels are best suited for transportation.

We have also shown the rather surprising result that with no restrictions on quotas in the summer capelin fishery, it is optimal to use 43 vessels and catch 4.7 million hectoliters. This means that with the current plant structure the forty-fourth vessel will incur a net loss for the fleet even when allowed to catch as much as it possibly can.

It is worth noting that this drastic cut in catch capacity will not have any major effect on employment, since the remaining vessels will need several crews instead of only one, as today. The reduction is therefore beneficial to everybody except the shipowner not allowed to continue.

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