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Discarding Fish at Sea

Report to the Ministry of Fisheries

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Foreword

As a part of the OECD Committee's Study on the Economic Impact of Responsible Fisheries, the Directorate for Food, Agriculture and Fisheries Committee invited the member countries to inform about the implications of responsible post harvesting practices on responsible fishing in their country. The report presented here, the Issue Report, is prepared by the request of Ministry of Fisheries by the Institute of Economic Studies (IoES).

The Issue Report on the other hand focuses on the discarding of fish. After the implementation of the individual transferable quota system (ITQ) in Iceland, many concerns rose about whether the adoption of this system induced excessive discarding of fish. This Issue Paper explores the theoretical and empirical research done on this issue. The first part exhibits the discarding theory. The existence of discarding is analysed under different fishery regimes namely the free access regime and ITQ. The theory is expanded with the inclusion of the gear selectivity and the capacity constraints of the vessels. In the second part, the empirical research done on discarding is presented.

Ayse Sabuncu is the author of the report.

IoES in June 1999

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1. Introduction

After the implementation of the individual transferable quota system (ITQ) in Iceland, many concerns rose about whether the adoption of this system induced excessive discarding of fish. This Issue Paper explores the theoretical and empirical research done on this issue.

The theory of catch discarding presented in the first chapter is due to Arnason 1994, 1996(a) and 1996(b). The theoretical work attempts to examine the economics of catch discarding in fisheries. In order to study this issue a dynamic fisheries model is used.

The first part includes the introduction of the basic model, the identification of the socially optimal discarding rule and the exploration of this rule under competitive fishery and individual transferable quota fisheries management system. It is shown that discarding can be socially optimal in a differentiated fishery. Moreover, the competitive fishery is found to employ the socially optimal discarding rule. It is further investigated in this first part whether there is an increased tendency toward discarding in an ITQ fisheries management system compared to the free access alternative. In fact, an ITQ managed system is found to generate an excessive incentive for discarding catch compared to a competitive fishery. The factors responsible for this deviation and the potential remedies are also discussed.

The second part of the paper extends the theory allowing for selectivity in harvesting technology. The question is how the introduction of selectivity effects the discarding value under the free access regime and ITQ managed system. It is found that a switch from free access to an ITQ system can both increase or decrease the volume of discards, depending on the shapes of the discarding and selectivity cost functions.

The last part analyses the effects of capacity constraints on discarding. A more general formula including capacity constraints is derived, and the results obtained in the first part are shown to be a special case of the ones derived in this last part. On the other hand, the selectivity possibilities are not explicitly included in this section but this analysis can easily be extended to include selectivity as well.

2. Catch Discarding Theory: A Comparison of Catch Discards under the Free Access Regime and ITQ Managed Fisheries

2.1 Basic Model

In this analysis a differentiated fishery model is used as discarding makes economic sense only in this kind of fishery as shown later. A differentiated fishery is a fishery characterised by more than one economic grade of the catch. These grades reflect different landing prices of individual fish, different handling costs aboard the vessel etc. The grades are detectable by fishermen; they are associated with physical appearance of individual fish such as its size, skin damage, colour, etc.

Let the index i refer to economics grades in the catch and let there be I economic grades of fish. Refer to catch grade i as $y(i)$, $i = 1,2,\ldots I$. Aggregation over catch grades yields total catch as $y \equiv \Sigma_i\, y(i)$.

Let instantaneous harvesting be determined by the following strictly increasing, jointly concave harvesting function:

$$y \equiv \Sigma_i\, y(i) = \Sigma_i Y(e,x,i), \text{ for all } i \text{ and } e,x \geq 0,\;\; Y(0,x,i) = Y(e,0,i) = 0 \qquad (1)$$

where the variable x represents aggregate biomass and e fishing effort. The fishing effort is assumed to be the same for all grades.

Aggregate biomass develops according to the usual rule in aggregate fisheries models:

$$\dot{x} = G(x) - y, \text{ for } e,x \geq 0, \qquad (2)$$

where the natural biomass function $G(x)$, is assumed to have the usual shape with, $G(0) = G(x_1) = G(x_2) = 0$ for $0 \leq x_1 < x_2$ and $G_{XX} < 0$.

Harvesting costs are given by the strictly increasing convex cost function:

$$CE(e), \text{ for } e \geq 0,\; CE(0) \geq 0. \qquad (3)$$

Landings of fish of grade i is defined as the difference between harvest and discards:

$$l(i) \equiv Y(e,x,i) - d(i), \qquad (4)$$

where $Y(e,x,i)$ represents the harvest of grade i as specified above, $l(i)$ retained or landed harvest and $d(i)$ the discarded harvest of grade i. A negative level of discarding would be harvesting. Therefore we assume that $d(i) \geq 0$, all i. Also, since fisheries are characterised by nonnegative landings, we impose the restriction $l(i) \geq 0$, all i.

There would generally be economic costs associated with landings and discarding. Let us represent these costs by the nondecreasing, convex cost functions:

$$CL(l(i),i), \text{ for } l(i) \geq 0, \text{ all } i,\; CL(0) \geq 0, \qquad (5)$$

$$CD(d(i),i), \text{ for } d(i) \geq 0, \text{ all } i,\; CD(0) \geq 0. \qquad (6)$$

The $CL(\;)$ functions represent various costs associated with retaining catch of grade i and landing it. These costs include the cost of preliminary fish processing aboard the vessel, handling, gutting, storing, preserving etc., as well as the actual landing costs.

The $CD(\;)$ functions represent the costs associated with discarding of fish of grade i. As discarding is generally relatively easy, these costs would in most cases be small. Notice, however, that if discarding were illegal or socially frowned upon, discarding costs would tend to be correspondingly higher.

Given the specifications in (1) to (6) we can write the instantaneous profit function of a given firm in the fishery as:

$$\pi(e,\boldsymbol{d},x;\boldsymbol{p}) = \Sigma_i\, p(i) \cdot l(i) - CE(e) - \Sigma_i CL(l(i),i)) - \Sigma_i CD(d(i),i), \qquad (7)$$

where $p(i)$ denotes the price of one unit of landings. The (1 x I) vectors $\boldsymbol{d}$ and $\boldsymbol{p}$ represent discarding and quay prices of different grades of fish, respectively. In this profit function, fishing effort, e, and discarding, $\boldsymbol{d}$, are natural control variables. Biomass, x, is a state variable and the fish prices, $p(i)$, are parameters.

2.2 Optimal Discarding

The social problem is to adjust fishing effort and the vector of discards so as to maximise present value of profits from the fishery. More precisely:

$$\underset{e,d}{Max} \int_0^\infty \pi(e,\mathbf{d},x;\mathbf{p}) \, . \, exp(-r \cdot t)dt \qquad \text{(I)}$$

Subject to: $\dot{x} = G(x) - \Sigma_i \, y(i),$

$e,\mathbf{d} \geq 0,$

where r denotes the rate of discount.

A solution to this problem includes the socially optimal discarding rule[1]:

$$d(i) > 0 \;\text{ if }\; p(i) + CD_d(0,i) < CL_l(Y(e,x,i) - 0,i) \qquad (8)$$

The left-hand-side of the second inequality of the discarding rule, $p(i) + CD_d(0,i)$, represents the marginal costs of discarding. This cost consists of two parts; the unit price of landed catch foregone by discarding, $p(i)$, and the direct marginal costs of discarding evaluated at zero discarding, i.e., $CD_d(0)$. The right-hand-side of (8), $CL_l(Y(e,x,i)-0,i)$, represents the marginal benefits of discarding (or marginal costs of retaining) catch also evaluated at zero discarding. Thus, the discarding rule expressed in (8) states that the catch of grade *i* should be discarded, i.e., $d(i) > 0$, if the marginal benefits of discarding exceed the costs.

To facilitate the analysis it is convenient to define the discarding function for fish of grade *i*:

$$\Gamma(i) = CL_l(y(i)-0,i) - p(i) - CD_d(0,i) \qquad (9)$$

The left-hand-side of (9), $\Gamma(i)$, is the discarding value for fish of grade *i*. If the discarding value for a particular grade is positive, marginal catch of that grade is discarded. If $\Gamma(i)$ is negative, catch of grade *i* is retained. The discarding function is not equivalent to the quantity discarded, but it can be interpreted as the tendency to discard.

The discarding function shows that the optimal decision to discard depends directly on (a) the quay price, (b) the marginal landing costs and (c) the marginal discarding costs of the grade in question. It seems empirically likely that $CL_l(y(i) - 0)$ is increasing in the catch rate, $y(i)$, at least for $y(i)$ above a certain level. In that case, the discarding function implies that the tendency to discard increases with the catch rate. Moreover, as catch increases monotonously with biomass and fishing effort, the tendency to discard also generally increases with these variables, *ceteris paribus*. On the other hand, the tendency to discard a particular grade diminishes with the price of catch, $p(i)$, and the marginal cost of discarding, $CD_d(0)$.

The analysis so far suggests three seemingly interesting propositions concerning socially optimal discarding[2]:

Proposition 1

In an undifferentiated fishery discarding of catch is not optimal.

[1] See Appendix 1 for the first-order conditions.
[2] See Appendix 1 for the proofs of the propositions.

Proposition 2

Discarding of catch may be socially optimal.

Proposition 3

In a differentiated fishery no discarding may be optimal.

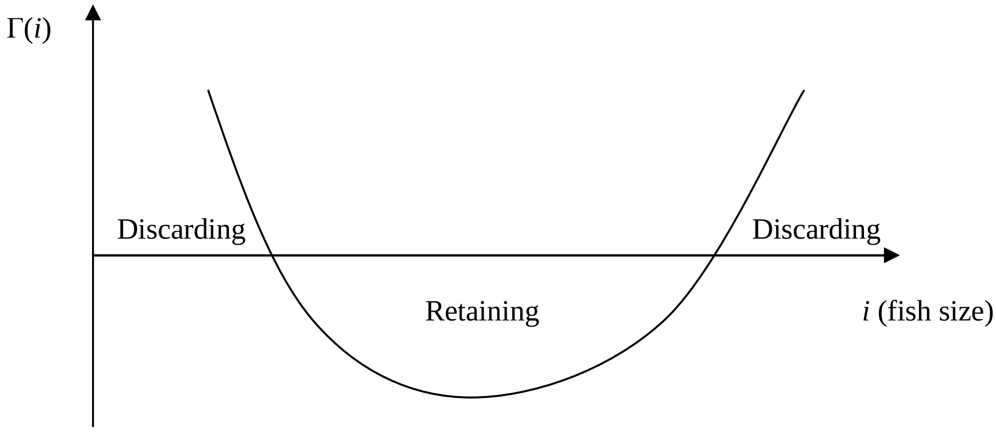

Fig. 1 An example of a discarding function

2.3 Free Access, Competitive Fisheries

Under competitive fishery, an arbitrary firm, *j*, will solve the following problem:

$$\underset{e(j),d(j)}{Max} \int_0^\infty \pi(e(j),\mathbf{d}(j),x;\mathbf{p})\cdot exp(-r\cdot t)dt \tag{II}$$

Subject to: $\dot{x} = G(x) - \Sigma_k \Sigma_i Y(e,x,i)$

$$e(j), \mathbf{d}(j) \geq 0,$$

where $e(j)$ is the firm j's fishing effort and $\pi(e(j),\mathbf{d}(j),x;\mathbf{p})$ its profit function corresponding to equation (7) above. The summation, Σ_k, is over all firms in the industry.

A solution to this problem includes the discarding rule:

$$d(i,j) > 0 \text{ if } p(i) + CD_d(0,i,j) < CL_l(Y(e(i),x,i,j)-0,i,j), \text{ all } i, \tag{10}$$

where $d(i,j)$ is firm j's discarding of catch of grade i.

A comparison of the competitive discarding rule, (10), with the socially optimal one, (8), shows that the two are formally identical. In fact, formulating the social problem in terms of the same number of fishing firms yields the same discarding rule.

This result can be explained as follows. Competitive utilisation of fish stocks deviates only from the optimal one due to the stock externality. The discarding activity, at least as formulated here, does not generate any external effects.[3] Hence, competitive profit maximising discarding rule should be optimal. It is important to realise, however, that this

[3] Discarding would, however, produce an externality (presumably a positive one) if some fraction of discarded catch survived and thus constituted additions to the biomass.

does not mean that the level of competitive discarding is socially optimal. Competitive discarding is only socially optimal conditional upon the existing competitive catch and biomass levels. These, however, are generally sub-optimal.

2.4 Individual Transferable Quotas

Now, we will analyse catch discarding under ITQ fisheries management systems. Consider a continuous ITQ system. The essentials of this system are as follows. The fishing firms hold a stock of permanent ITQs. These aggregate ITQs refer to aggregate catch volumes and are not differentiated according to grades. Let $q(j)$ denote firm j's quota holding by firm j at time t. At each point of time quota holdings must at least equal the firm's rate of catch. However, if discards are not counted against quota, as in fact generally is the case, the firm's j instantaneous quota constraint is:

$$q(j) \geq \Sigma_i\, l(i,j) \equiv \Sigma_i[y(i,j) - d(i,j)], \qquad (11)$$

where $l(i,j)$ denotes the instantaneous landings of catch of grade i by firm j, $y(i,j)$ the instantaneous catch and $d(i,j)$ the corresponding discard.

Quota holdings can be adjusted by trading, z, at a market price, s. Thus, quota holdings move over time according to the equation:

$$\dot{q} = z. \qquad (12)$$

Now, under quite unrestrictive assumptions, in particular that the quota price is positive, the total quota (TAC) determined by the quota authority is equal to total landings. The actual development of biomass, however, depends on natural growth and total catches including discards. I.e.,

$$\dot{x} = G(x) - \mathrm{Q} - \Sigma_i\, \Sigma_j\, d(i,j), \qquad (13)$$

where Q represents the total quota issued and, as before, Σ_j denotes summation over all firms in the fishery.

Within this management framework fishing firm j attempts to solve the following problem:

$$\underset{e(j),z(j),d(j)}{Max} \quad \mathrm{V} = \int_0^\infty [\pi(e(j),\boldsymbol{d}(j),x;\boldsymbol{p}) - s \cdot z]\cdot exp(-r\cdot t)dt \qquad (\mathrm{III})$$

$$\text{Subject to:} \quad \dot{q} = z,$$

$$\dot{x} = G(x) - \mathrm{Q} - \Sigma_i\, \Sigma_j\, d(i,j),$$

$$q \geq \Sigma_i[Y(e,x,i) = d(i,j)] \equiv \Sigma_i l(i,j),$$

$$e(j),\boldsymbol{d}(j) \geq 0.$$

A solution to this problem (III) includes the discarding rule for firm j:

$$d(i,j) > 0 \text{ if } \; p(i) + CD_d(0,i,j) < CL_l(Y(e(i),x,i,j) - 0,i,j) + \sigma(j) - \delta(j), \text{ all } i. \qquad (14)$$

This discarding rule is similar to the socially optimal and competitive discarding rule, except two Lagrange multipliers, $\sigma(j)$ and $\delta(j)$. The Lagrange multiplier $\sigma(j)$ represents the marginal value of quotas to firm *j*. Since quotas can be freely left unused, maximisation of profits requires this term to be nonnegative. Thus, landing of catch represents a cost to the firm amounting to $\sigma(j)$. Hence, $\sigma(j)$ normally encourages discarding of catch.

The other Lagrange multiplier, $\delta(j)$ represents firm *j*'s shadow value of biomass. The appearance of this multiplier in the discarding rule reflects the fact that in spite of the quota restriction, firm *j* can influence the path of the biomass via discarding of catch. Since higher biomass is normally economically beneficial to the firm, $\delta(j)$ is usually positive. Hence, $\delta(j)$ represents a disincentive to discarding. In a fishery composed of many firms, however, $\delta(j)$ is comparatively small.

Let $\Omega(j) \equiv \sigma(j) - \delta(j)$. The difference $\Omega(j)$ represents the deviation of the discarding rule under an ITQ system from the optimal one. A positive $\Omega(j)$ represents an excessive incentive for discarding under ITQ system and vice versa. In most commercial fisheries, $\Omega(j)$ would be expected to be nonnegative. $\Omega(j)$ is the user cost of quota for the species in question. It is closely related to the instantaneous quota price provided that there is reasonably large number of firms in the industry. In fact, in equilibrium, $\Omega(j)$ is approximately equal to the present value of this price.

The ITQ discarding function for the ITQ-managed fishery is:

$$\Gamma^{\circ}(i) = CL_l(y(i) - 0,i) + \Omega(j) - p(i) - CD_d(0,i) = \Gamma(i) + \Omega(j), \qquad (15)$$

where $\Gamma(i)$ is the discarding value for the unmanaged fishery as defined in (9) above.

Proposition 4

Under the ITQ system described above and when there is more than one fishing firm there is generally an excessive incentive for discarding the catch.

The result expressed in Proposition 4 is economically intuitive. Under a competitive fisheries management regime, a fisherman contemplating whether or not to retain a particular fish will elect to do so if the net return (measured as the sum of its quay price and discarding costs less the landings costs) is positive. Under an ITQ system, this net return must be compared to the alternative benefits of discarding the fish and selling the corresponding quota. More precisely, the net return of landing the fish must exceed the quota price. Provided that the quota price is positive in an ITQ system the discarding value is always larger compared to an unmanaged fishery.

Notice, however, that the result expressed in Proposition 4 does not necessarily mean that there will be excessive discarding under an ITQ system. There may be corner solutions. This means that if there is no discarding under competitive fisheries management regime, there may possibly be no discarding under an ITQ system as well. On the other hand, if there is discarding under a competitive regime, there will almost certainly be excessive discarding under an ITQ system.

The problem of excessive discarding does not appear to be the ITQ system itself but it derives from the imperfectness of the quota property rights as modelled in this paper or, alternatively, from the enforcement of these rights. To the extent that the quota restriction applies to landings rather than catch the quota property rights are incomplete. Enforcing the quota restriction by monitoring landings is clearly a case of regulating the wrong target. Fishing firms can still impose stock externalities on each other by discarding the catch. In that way they undermine the economic value of the quota property rights.

Similarly, to the extent that ITQs refer to the aggregate volume of catch, the associated property rights are also incomplete in another respect. Different grades of catch represent different economically different commodities. Quotas, on the other hand, are not differentiated by grades. Consequently, different grades of catch cannot correspond to different quota prices.

Potential remedies are issuing ITQs by grades, using taxes and subsidies and enforcement. If ITQs are issued for each grade, the quota price for each grade will reflect the relevant economics of harvesting, processing and marketing of that grade. In that case, the quota prices will never induce excessive discarding of the catch. However, the implementation of ITQs by catch grades is not a practical solution. There are many problems. First, the grades may be numerous and probably time variant. Second, as the number of grades increases, the market for each grade may become very thin. Third, enforcement of quota rights by grades may easily prove prohibitively costly.

Taxing and subsidising can solve the problem, as discarding is an externality problem. But it is very important to select the correct tax or subsidy rate. Finally, excessive discarding may be regarded as a violation of fishery property rights. Then discarding becomes an enforcement problem. But again it is important to select the socially optimal combination of enforcement effort and sanctions.

The best way of action may well be to employ a mix of some or all of the methods discussed above, as it seems unlikely that a general solution exists.

3. Selectivity

Up to now, the harvesting technology was taken as exogenous. Let us now assume that the fishing technology allows a degree of selectivity over grades of fish at some costs.[4] Fishing with lines and bottom trawl are two examples of harvesting selectivity. Let us define a selectivity parameter for grade i, $a(i)$, and the corresponding cost function $CS(a(i),i)$. Take $a(i) \in [0,1]$, where $a(i) = 0$ represents no selectivity and $a(i) = 1$ full selectivity.

In accordance with this, let the harvesting function for fish of grade i be represented by:

$$y(i) = Y(e,x,i)\cdot(1-a(i))$$

$Y(e,x,i)$ is what may be referred to as the "unselective" harvesting function for fish of grade i and $(1-a(i))$ represents the harvesting modifications due to selectivity measures. Clearly, when $a(i) = 0$ unselective harvesting applies and when $a(i) = 1$ there is full selectivity in the sense that no fish of grade i will be caught.

[4] This could be due to variable fishing gear selectivity and the choice of fishing grounds and fishing seasons.

The selectivity cost functions, $CS(a(i),i)$, $i = 1,2,...I$, are naturally increasing and convex in the selectivity parameter, i.e., $CS_a(i) > 0$, $CS_{aa}(i) > 0$.
Let's refer to the net price of catch of grade i by $P(i)$.

$$P(i) \equiv p(i) - CL_l(l(i)) - \Omega,\ i = 1,2,....I.$$

where as before $p(i)$ represents the gross landing price, $CL(l(i))$ the unit cost of landings and Ω the opportunity cost of quota. In an unmanaged fishery this opportunity cost, Ω is identically zero. In a fully-fledged ITQ system Ω would be measured by the market price of quotas at the time of landings.

Given all this we can define a profit function for firm j as:

$$\pi(j) = \Sigma_i\ P(i)\cdot[Y(e,x,i)\cdot(1-a(i))-d(i)] - CE(e) - \Sigma_i\ CD(d(i),i) - \Sigma_i\ CS(a(i),i)$$

Maximisation of this profit function with respect to fishing effort, discards and selectivity yields the following set of necessary conditions:

$$\Sigma_i\ P(i)\cdot Y_e\cdot(1-a(i)) = CE_e,\ \text{assuming } e > 0.$$

$$-P(i) \geq CD_{d(i)},\ d(i) \geq 0,\ d(i)\cdot(-P(i) - CD_{d(i)}) = 0,\ \text{all } i.$$

$$-P(i)\cdot y(i) \geq CS_{a(i)},\ a(i) \geq 0,\ a(i)\cdot(-P(i)\cdot y(i) - CS_{a(i)}),\ \text{all } i.$$

These first order conditions are quite informative. First notice that for positive selectivity or discarding to be optimal the net price, $P(i)$, must be negative. Second, the conditions highlight that discarding and selectivity are in a certain sense substitute activities. Both are employed to reduce the landings of unwanted fish, i.e. fish for which the net landing price, $P(i) \equiv p(i) - CL(l(i)) - \Omega$, is negative. However, they are not necessarily used to the same extent. If for instance the marginal cost of discarding is less than the marginal cost of selectivity at zero selectivity, i.e.,

$$CD_{d(i)}(d(i)) < CS_{a(i)}(0)$$

then the profit maximising vessel will only employ discarding to avoid unwanted fish. If the marginal cost of discarding at zero discarding is higher than the marginal cost of selectivity on the other hand, then the profit maximising vessel will only employ catch selectivity to avoid unwanted fish and not discard at all. Finally, the rule for the co-existence of selectivity and discarding in the operation of the fishing vessel is:

$$CS_{a(i)}(a(i)) = CD_{d(i)}(d(i)).$$

The basic ideas can be usefully depicted in Figure 2.

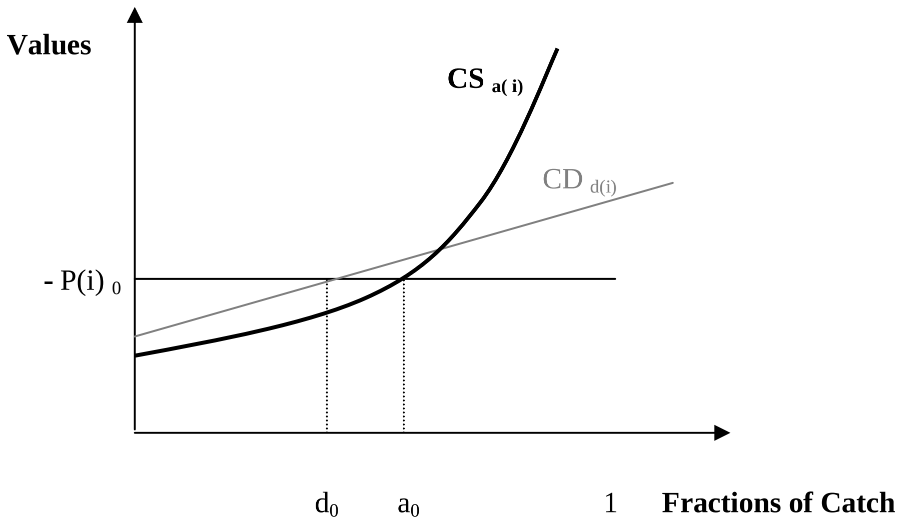

Fig. 2 Optimal discarding and selectivity

In Figure 2, the marginal cost of discarding and selectivity intersect with the benefits of not landings (i.e., the negative of the net price[5]) at d_0 and a_0 respectively. This means that the optimal selectivity will be a_0 and a fraction d_0 of the harvest (after selectivity) will be discarded. Thus the quantity of discards of fish of grade i is $Y(e,x,i)\cdot(1-a_0)\cdot d_0$.

Let us represent the quantity of discarding of fish of grade i by the expression, $D = d\cdot y\cdot(1-a)$, where D denotes the volume of discards and d represents the fraction of harvested fish discarded and y the total catch of grade i and $(1-a)$ the harvesting modification due to the selectivity as before.

The analysis of the effects of an ITQ system on discarding and selectivity is generally quite complicated. A switch to an ITQ system can both increase or decrease the volume of discards. The issue can perhaps be clarified with the help of a diagram. Referring to the diagram in Figure 2, an increase in **Ω** means that the net price of landings is reduced. For a grade of fish with an initially negative net price this means a shift of the $-P(i)$ line upward. Hence both the optimal selectivity fraction and the optimal discarding of harvested fish increase as illustrated in Figure 3.

[5] Which according to the necessary conditions must be negative for discarding or selectivity to be profitable.

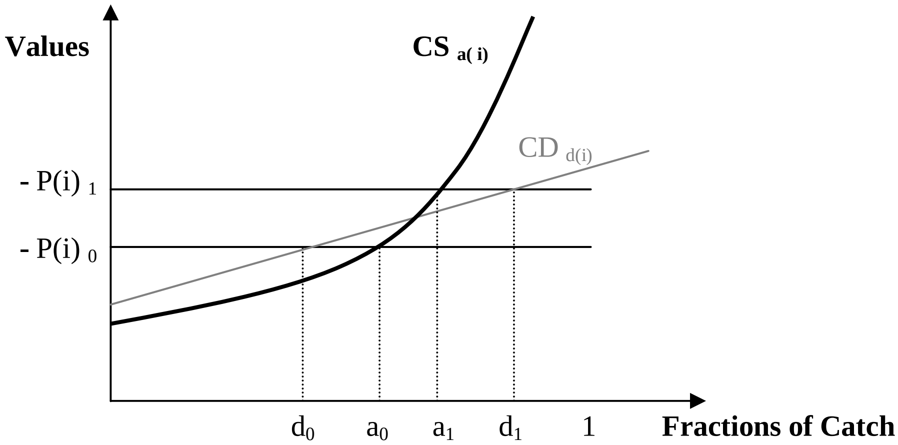

Fig. 3 Effects of an increase in Ω on discarding and selectivity

Figure 3 suggests that whether or not discarding increases as a consequence of an ITQ system depends very much on the shape of the discarding and selectivity cost functions and on whether selectivity responds sufficiently greatly to an increase in Ω to overwhelm the impact on discarding.

Let there be a switch in quota prices from Ω_0 to Ω_1, where $\Omega_1 > \Omega_0$. Let the initial discard and selectivity fractions, d_0 and a_0, be 0.4 and 0.5 respectively. Similarly let d_1 and a_1 be 0.6 and 0.7 respectively which is entirely possible. Then $D_0 = 0.2 \cdot y$ and $D_1 = 0.18 \cdot y$, so the volume of discards actually decreases. This shows that the volume of discards under an ITQ system may actually decrease compared to the volume of discards in an unmanaged fishery.

4. Capacity Constraints

In this section of the paper, the effects of capacity constraints on discarding will be examined. Discarding rule will be analysed under two kinds of constraints: hold capacity and processing capacity.

4.1 Model

Consider a fishing trip of length *T*. The revenue during the trip is represented by the value of landings at the end of the trip:

$$R(T) = \sum_{i=1}^{I} P(i) \cdot l(i,T), \qquad (1)$$

where $P(i)$ denote the unit price of fish of grade *i* and $l(I,T)$ the corresponding volume of landings at the terminal time *T*.[6] $P(i)$ is the net price of fish.

Let the variable $y(i)$ represent the instantaneous rate of catch of fish of grade *i* and $d(i)$ the instantaneous volume of fish of grade *i* discarded at sea. Thus, the accumulated fish of grade *i* in the vessel's hold evolve according to the equation:

$$\dot{x}(i) = y(i) - d(i) \qquad (2)$$

[6] To simplify the analysis, it is implicitly assumed that prices are constant.

At the trip's end, the accumulated catch of grade i, equals the volume of landings:

$$l(i,T) = x(i,T). \tag{3}$$

Also, clearly, $x(i,0) = 0$.

Let $s(t)$ represent free space in the vessel's hold at time t with $s(0) = S$, the total hold capacity. Then the available space evolves according to the equation:

$$\dot{s} = \sum_{i=1}^{I} \left[y(i) - d(i) \right]. \tag{4}$$

Now, there are certain benefits and costs associated with discarding fish. The costs include *inter alia* the economic resources employed to discard and, as the case may be, the psychological discomfort of discarding and the expected penalties (fines) for doing so. The benefits, include the costs avoided by discarding the fish including on-board processing costs to the extent they are not included in the net price of fish, $P(i)$. Let us refer to these benefits net of the costs as the concave profit function $\pi(d(i),i)$. Notice that $\pi(d(i),i)$ may easily be negative for all $d(i) > 0$.

Given this, total operating profits at time t are:

$$\Pi = \sum_{i=1}^{I} \pi(d(i),i) \,. \tag{5}$$

And the profit function of the fishing trip is:

$$J = R(T)\cdot exp(-r\cdot T) + \int_0^{\infty} \Pi\cdot exp(-r\cdot t)dt. \tag{6}$$

4.2 Hold Capacity

Let us first consider the case where there is an upper bound on the hold capacity of the fishing vessel. This case is characterised by the constraint $S < \infty$, where S denotes the hold capacity.

The profit maximisation problem in this case can be formally stated as:

$$\underset{d(i)}{Max}\ J = R(T)\cdot exp(-r\cdot T) + \int_0^{\infty} \Pi\cdot exp(-r\cdot t)dt \tag{7}$$

Subject to $\dot{s} = \sum_{i=1}^{I} \left[y(i) - d(i) \right]$

$$\dot{x}(i) = y(i) - d(i)$$

$$x \geq 0,\ x(0) = 0$$

$$s \geq 0,\ s(0) = S < \infty$$

$$d(i) \geq 0, \text{ all } i.$$

The necessary conditions include the basic discarding rule[7]:

$$d(i) > 0 \text{ iff } \pi_{d(i)}(0,i) > P(i)\cdot exp(-r(T\text{-}t)) - \mu\cdot exp(rt), \text{ all } i \text{ and all } t. \quad (8)$$

The term $\pi_{d(i)}(0,i)$ represents the marginal benefits at time t (possibly negative) of discarding fish of grade i when no discarding takes place. The term $P(i)\cdot exp(-r(T-t))$ represents the marginal benefits of retaining fish of grade i discounted to the same time t. The last term in expression (8), $\mu\cdot exp(rt)$, depicts the shadow value of hold space at time T also discounted to time .$\mu\cdot exp(rt)$, i.e., represents additional benefits of discarding. These benefits are zero, unless the hold space constraint, s ≥ 0, becomes binding during the fishing trip, i.e., s = 0.[8]

Given these explanations, the expression (8) simply states that discarding of fish of grade i will occur at time t, if the current marginal benefits of discarding, represented by $\pi_{d(i)}(0,i)$ + $\mu\cdot exp(rt)$, exceeds the current value of retaining the fish, represented by $p(i)\cdot exp(-r(T-t))$.
Expression (8) is a generalisation of the discarding rule stated in the first section. The third term in (8), represents an increased incentive to discard if hold capacity is expected to become binding (i.e. $\mu > 0$), constitutes an addition to that rule. Thus, the discarding rule derived in the first part is a special case of the discarding rule represented here.

Given the important role of μ in discarding rule (8), it is useful to obtain a measure of its size. If hold capacity never becomes binding, $\mu = 0$, as already stated. However, if hold capacity becomes binding, μ becomes positive. More precisely, we can derive from the first order conditions[9] that:

$$\mu \in [0, (P(i) - \pi_{d(i)})\cdot exp(-rT)], \quad (9)$$

with the upper limit being applicable for any grade i that is being discarded at time T.
The upper limit in (9) makes full economic sense. The expression $P(i) - \pi_{d(i)}$ is the marginal profits of more hold space at time T. $p(i)$ is the marginal revenue in terms of sales and $\pi_{d(i)}$ is the marginal profits in terms of reduced discarding (now that more space is available). The discount factor$\cdot exp(-rT)$ simply provides the present value of this marginal benefit.

4.3 Processing Constraints

Let us now consider the case where there is an upper bound on the capacity of the vessel to process catch. This case is characterised by the constraint

$$Z \geq \sum_{i=1}^{I} \dot{x} = \sum_{i=1}^{I} (y(i) - d(i)), \quad (10)$$

where Z denotes the hold capacity.

The profit maximisation problem in this case can be formally stated as:

$$\underset{d(i)}{Max}\ J = R(T)\cdot exp(-r\cdot T) + \int_0^{\infty} \Pi\cdot exp(-r\cdot t)dt \quad (11)$$

Subject to $\dot{x}(i) = y(i) - d(i)$

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[7] See Appendix 2 for the Hamiltonian equation and the first order conditions for this maximisation problem.
[8] See expression (7.4) in Appendix 2.
[9] See expressions (7.1) and (7.2) in Appendix 2.

$x \geq 0,\ x(0) = 0$

$$Z \geq \sum_{i=1}^{I} (y(i) - d(i)),$$

$d(i) \geq 0$, all i.

The first order conditions yield to the same discarding rule as in (8):

$$d(i) > 0 \text{ iff } \pi_{d(i)}(0,i) > p(i)\cdot exp(-r(T-t)) - \sigma \cdot exp(rt), \text{ all } i \text{ and all } t. \quad (12)$$

It is important to realise, however, that σ in (12), which represents the shadow value of processing capacity, is different from μ in (8), which represents the shadow value of hold capacity.

From the first order conditions[10] $\sigma > 0$ only if processing capacity is binding and zero otherwise. Hence in the case of constraining processing capacity, there is an increased tendency to discard. In that case, discarding will take place to satisfy the processing capacity and the shadow value of processing capacity will be:

$$\sigma = (p(i) - \pi_{d(i)})\cdot exp(-rt), \quad (13)$$

which is similar, but not identical, to expression (10) above and has a similar interpretation.

The discarding rule under both hold capacity and processing capacity constraints is,

$$d(i) > 0 \text{ iff } \pi_{d(i)}(0,i) > p(i)\cdot exp(-r(T-t)) - \mu\cdot exp(rt) - \sigma \cdot exp(rt), \text{ all } i \text{ and all } t, \quad (14)$$

where μ is the shadow value of the hold capacity constraint and σ is the shadow value of the processing capacity constraint.

Rule (14) is a further generalisation of the discarding rule in the first section. If capacity constraints are not binding (14), collapses to the optimal discarding rule (8) stated in the first section. If capacity constraints are (or will be) binding, rule (14) suggests that there will be an increased tendency to discard.

4.4 Discussion

What will be the impact of different fisheries management systems, in particular the ITQ system compared to unmanaged fisheries, on the discarding rule? Retracing the analysis it seems that different fisheries management systems will only affect $p(i)$ directly. Hence, from that perspective, different fisheries management systems should not affect discarding due to capacity constraints. However, it is not unlikely that different fisheries management systems may influence vessel capacity relative to harvesting rates. Hence, the frequency of binding capacity constraints may well differ from one fisheries management system to another. In particular, it seems likely that in an equilibrium position under an ITQ system, capacity constraints are more likely to occur than under free fishing. Hence, for that reason discarding may increase.[11]

[10] See expression (12.3) in Appendix 3.
[11] The reader should notice that along the adjustment path toward equilibrium, however, the situation may be reversed.

Is discarding induced by capacity constraints socially sub-optimal? This is not at all clear. The quick answer is that it is socially optimal conditional upon the capacity level. So, in a sense, discarding due to capacity constraints appears generally to be at least a second best solution. However, if the capacity level is wrong, the discarding level is probably not a first best solution.

II. Empirical Research on Discarding

In this second chapter, the empirical work on discarding is explored. The empirical research bases on the theoretical work of Arnason 1994, 1996(a), 1996(b) presented in the first chapter. The papers from Arnason 1998, T.B. Davíðsson 1997 and C. Therond 1998 are summarised in this chapter.

The paper by Daviðsson describes a general methodology for conducting an indirect measurement of discarding based on a comparison of length distributions for catch and landed catch. *Catch Distribution* reflects the varying lengths of cod, which are caught while the harvesters are at sea. Landed catch distribution, or *Landings Distribution,* on the other hand reflects the varying lengths of cod which fishermen bring ashore to sell on the markets, to distributors or straight to consumers. The discrepancy between these two independent measures of size distribution can be attributed to discarding of catch at the sea. Different fishing gears, line and bottom trawl, are included in the distribution function, as the equipment selectivity can make the catch distribution quite different from the total distribution since its purpose is to target the higher value grades.

The data used to obtain the Catch Distribution is from (Fiskistofa) Fisheries officers and includes a large number of length observations from all fishing grounds. The data is collected upon requests from Fisheries officers; it does not follow any particular pattern. Hence a slight downward bias is expected in this data. But there is data available for cod 1995 and 1996 collected for MRI's annual VPA stock estimation. These measurements on the other hand are collected sequentially from each fishing ground; they are frequent and constitute a major part of the data.

The information for the Landings Distribution, the landed catch, while recorded by the fishing companies may not be available for research purposes. Certain companies are vertically integrated from the harvesting to the processing stage and therefore do not enter the market to sell the landed fish. The MRI has data on landed catch but the measurements are neither frequent nor thorough compared to the data on catch distribution. Hence information from one of the fish markets sales (Islandmarkaður), is used as an alternative method. Each day, the landed catch of non-integrated fishing vessels is bid on and sold through fish markets. 12-15% of the total catch is sold through these markets. Assuming that the daily quantity sold through the market is a good estimation of the actual landed catch distribution, Daviðsson uses the following formula suggested by MRI to convert the weight classes of the market data into length categories to be able to compare both distributions. Weight = A* $(\text{Length})^B$, where 0.01 and 3 are the constants assigned to A and B respectively.

The results are shown in the following figures:

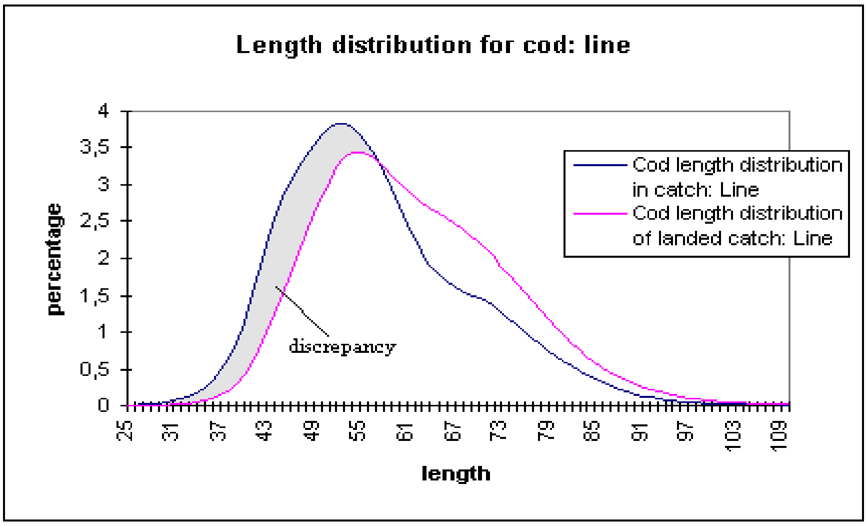

Fig. 4

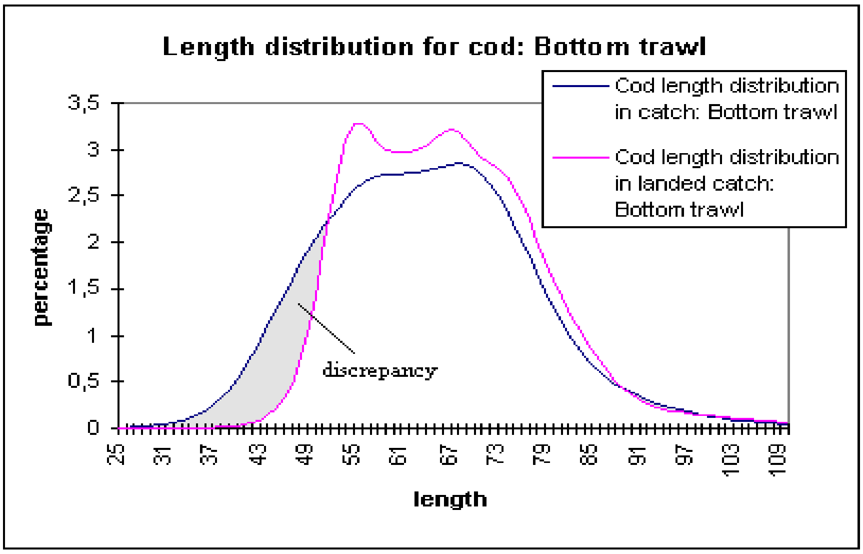

Fig. 5

In the above figures the shaded area shows the discrepancy between catch and landings distribution in line and bottom trawl fisheries. This discrepancy is interpreted as discarding of fish. One can see from above that nearly all cod smaller than 50 cm is being discarded in fisheries using bottom trawl but this tendency decreases rapidly as there is no evidence that fish larger than 50 cm is discarded. The incentive to discard smaller categories in bottom trawl fisheries is higher because the fishermen expect to get a high category catch in the next haul. For the line fisheries discarding is high for the smallest category and decreases gradually It is different from bottom trawl fisheries in that there is some discard of fish larger then 50 cm.

Arnason (1998) argues that the discrepancy between Catch and Landings Distributions can be explained as well by other factors than discarding of fish. The first alternative explanation is the existence of various measurement errors in the data. He detects in the data of Daviðsson

(1997), sampling errors in the data collection at sea and sampling errors in the estimate of size distribution of the landings. Moreover, Arnason criticises the use of landing statistics from only one market, Islandsmarkaður. The reasons are twofold. First this market represents only a small fraction of cod landings in Iceland (5-7%) and second this market disproportionately receives catch from a certain geographical area with a size distribution of cod catches different (in fact larger) from other parts of the country.

Different fishing selectivity in the Catch Distribution and Landings Distribution can be a possible explanation as well. The harvesting selectivity of commercial vessels landing catches to the fish market can be different from that of the overall fleet reflected in the MRI Catch Distribution. The majority of the fleet does not normally sell their catches through the fish market but rather on a variety of long term contracts to processing plants directly. Moreover, the composition of the fishing vessels supplying to the processing plants directly and the ones supplying to the fish markets are probably quite different.

The last explanation, also the one theoretical prediction supports (Arnason 1996) is the discarding of fish. But the author points out that one should be careful in interpreting the size of discrepancy, as there could be several explanations.

Arnason develops a formula to calculate discarding volumes on the basis of size composition of catch and landings. The formula is the following:

$$d(i) = l\cdot[b(I)\cdot a(i) - b(i)\cdot a(I)]/\, a(I)$$

$d(i)$ represents the discard, l total volume of landings, $a(i)$ the percentage share of size class i in the catch of a given species, $b(i)$ the percentage share of size class i in the landings of a given species. $a(I)$ and $b(I)$ are used to estimate y; they are the percentage shares respectively in the catch and in the landings of size class I, the class that is supposed to be not discarded at all. From the above formula one can calculate the discarding volume directly as a function of observable quantities only. The author applies the formula to Daviðsson's data and obtains higher discard rates. It is emphasized therefore in his article that we should be more careful when interpreting the results because of the various simplifying assumptions, because of the inaccuracies of the data and because of the rough nature of the calculations. We should see the results as examples of how particular data in question can, with the help of the above formula, can be used to obtain estimates of the catch.

To test whether there is a significance difference between the Catch Distribution and Landings Distribution used in Daviðsson work, Therond (1998) applies a Kolmogorov Smirnov (K-S) test. This is a method used when the mathematical distribution function is unknown. K-S test consists in using a sample to build a confidence band, in which the function will be contained with a specified probability. Therond finds that both in line and in bottom trawl fisheries there is a significant difference between catch and landings distributions. So she concludes that there has been discards in both fisheries.

Therond also analyses the discards in 1989, before the full adoption of ITQ system. Even though the quotas already existed during this period, the effort quota option allowed fishermen to avoid the quota restriction. Therond tests to see if there was a significant difference between catch and landings distribution in line and trawl fisheries in 1989. These tests show that the discards existed before the full adoption of ITQ system. Therond shows further that the introduction of the ITQ system did not increased the incentive to discard in the line fishery. This is not surprising as in 1995, most of the boats engaged in line fishery were small boats that were still not under the quota system because of small boat exemption. On the other hand, she finds that in the trawl fishery a higher proportion of large cod was landed in 1995 than in 1989. Therond proposes three explanations:

1. Discarding has increased.
2. Some changes occurred in the composition of the cod stock.
3. Some changes occurred in the method of fishing with trawl.

The second explanation is rejected because of the results of the line fishery. Therefore the change in the size distribution of cod can be explained either by the increase of discards or by the change in the way fishing with trawl. Taking account the fact that quotas allow fishermen to take their time to fish more carefully, both explanations can be valid.

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Appendix 1

The necessary conditions for solving problem (I) are :

$$\pi_e - \mu \cdot \Sigma_i Y_e \equiv \Sigma_i (p(i) - CL_l) \cdot \mathrm{Y_e} - CE_e - \mu \cdot \Sigma_i Y_e \leq 0,$$

$$e \geq 0,\ e \cdot (\pi_e - \mu \cdot \Sigma_i Y_e) = 0, \qquad \text{(I .1)}$$

$$\pi_{d(i)} \equiv -p(i) + CL_l(l(i)) - CD_d(d(i)) \leq 0,\ \ d(i) \geq 0,\ \ d(i) \cdot \pi_d(i) = 0,\ \text{ all } i. \qquad \text{(I .2)}$$

Proof of Proposition 1

In an undifferentiated fishery the number of catch grades is unity, $I = 1$. Assume that $d(1) > 0$. Then, according to (I .2), $p(1) - CL_l(1) = -CD_d(1)$. Substituting this into (I .1) yields $-(CD_d(1) + \mu) \cdot Y_e(1) - C_e \leq 0$. But the right hand side is actually strictly negative because profit maximisation requires $\mu \geq 0$. Consequently, by (I .1), $e = 0$. Thus, there is no catch to discard and $d(1) = 0$. This contradiction proves the proposition.

Proof of Proposition 2

This is immediate. For $I \geq 2$ it is clearly possible to select $p(1)$, $p(2)$, such that $e > 0$ and $\Gamma(2) > 0$ for given x, $CL_l(y(i) - 0, i)$ and $CD_d(0,i)$.

Proof of Proposition 3

Again, the proof is immediate. For a given number of grades, I, x, $CL_l(y(i) - 0, i)$ and $CD_d(0,i)$ simply increase all $p(i)$ until $\Gamma(i) < 0$ for all i.

Appendix 2

Hold Capacity

To study this problem, it is useful to form the Hamiltonian Equation:

$$\mathrm{H} = \sum_{i=1}^{I} \pi(d(i),i) \cdot exp(-r \cdot t) + \sum_{i=1}^{I} \lambda(i) \cdot (y(i) - d(i)) - \mu \cdot (\sum_{i=1}^{I} (y(i) - d(i)), \qquad (8)$$

where the Lagrange multipliers $\lambda(i)$, $i = 1,2,\ldots I$, represent the shadow value of landings of fish of grade i and the Lagrange multiplier μ the shadow value of available hold space in the vessel.

The necessary conditions for solving problem (6) include the following[12]:

$$H_{d(i)} = \pi_{d(i)} \cdot exp(-rt) - \lambda(i) + \mu \leq 0,\ \ d(i) \geq 0,\ \ d(i) \cdot H_{d(i)} = 0,\ \forall i. \qquad (7.1)$$

$$\lambda(i) = P(\mathrm{i}) \cdot exp(-rT),\ \forall i. \qquad (7.2)$$

μ is a constant. (7.3)

$$\mu(T) \geq 0,\ \mathrm{s}(T) \geq 0,\ \mu(T) \cdot \mathrm{s}(T) = 0. \qquad (7.4)$$

[12]See e.g. Leonard and Van Long (1992).

Appendix 3

Processing Capacity

The Hamiltonian for this problem is:

$$\text{H} = \sum_{i=1}^{I} \pi(d(i),i) \cdot exp(-r \cdot t) + \sum_{i=1}^{I} \lambda(i) \cdot (y(i) - d(i)) - \sigma \cdot (Z - \sum_{i=1}^{I} (y(i) - d(i)) , \qquad (13)$$

The necessary conditions for solving problem (13) include the following:

$$H_{d(i)} = \pi_{d(i)} \cdot exp(-rt) - \lambda(i) + \sigma \leq 0, \quad d(i) \geq 0, \quad d(i) \cdot H_{d(i)} = 0, \ \forall \qquad (12.1)$$

$$\lambda(i) = \text{p(i)} \cdot exp(-rT), \ \forall i. \qquad (12.2)$$

$$\sigma \geq 0, \quad Z - \sum_{i=1}^{I} (y(i) - d(i)) \geq 0, \quad \sigma \cdot (Z - \sum_{i=1}^{I} (y(i) - d(i)) = 0. \qquad (12.3)$$