최적생산시기 결정을 위한 의사결정전략 : 추계적 과정과 순현재가치 접근

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The Decision Making Strategy for Determining the Optimal Production Time : A Stochastic Process and NPV Approach

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■ Abstract ■

In this paper, the optimal decision making strategy for resource management is viewed in terms of a combined strategy of planting and producing time. A model which can be used to determine the optimal management strategy is developed, and focuses on how to design the operation of a Markov chain so as to optimize its performance. This study estimated a dynamic stochastic model to compare alternative production style and used the net present value of returns to evaluate the scenarios. The managers in this study may be able to increase economic returns by delaying produce in order to market larger, more valuable commodities.

Keyword : Decision Making Strategy, Markov Chain, Net Present Value, Resource Management

1. Introduction

Resource manager would be faced by how society allocates scarce natural resources such as oil, gas, fresh water, stocks of fish, and other naturally occurring resources. Finding the optimal allocation of natural resources over time can be regarded as a dynamic optimization problem. In such problems it is common to try to maximize some measure of net economic value, over some

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future horizon, subject to the dynamics of the extracted resource and any other relevant constraints.

The general resource management problem can be described using capital theory as presented by Dorfman [5]. Using the capital-theoretic approach, a fish population can be viewed as a capital stock in that, like "conventional" or man-made capital, it is capable of yielding a consumption flow through time. The fish stock can be combined with other resources (inputs) such as fishing boats, the labor of fishermen, costs, etc., to produce a good that people value. Therefore, the management problem is to select an optimal produce path through time [3].

Scallop industry in Korea is increasingly considered a means of augmenting the domestic supply of fresh seafood in order to satisfy the continually increasing demand. The major producing regions are Chumunjin and Kojin. Each region has different environmental and economic characteristics that are important to the success of the scallop industry in Korea. In addition, two alternative production styles can be used (i.e., lantern net or ear-suspended), which are characterized by different growth and mortality rates. Fishery demand is strong year-round (which supports a continuous supply to the market), but seasonal, regional, and technological variations can complicate the determination of optimal production plans. Such optimal plans are important to managers attempting to allocate revenue-generating licenses by production method and geographic region, but are also important to individual investors or community cooperatives.

The current situation in the scallop industry in Korea is characterized by potentially avoidable shortcomings. Production methods and regional characteristics are not adequately considered in the management of the resource. Consequently, the full income potential for an individual scallop aquaculture firm and the industry as a whole is not being realized. More specifically, considerations over production decisions that may need to be considered jointly to optimize the use of the resource (such as production scheduling, and producing methods) are largely ignored. This system fails to consider the potential economic benefits from optimizing firm-level strategies and designing resource management plans that allow the capture of those benefits.

The specific objective of this study is to specify a decision making model for scallop industry. This paper will explore the optimal timing of (season opening) and duration of grow-out (producing date) for each production style and production location (Chumunjin) given stochastic environmental conditions.

2. Theoretical Perspective

To analyze the decision making strategy (i.e. optimal production time) for aquaculture industry, Pontryagin [10] introduced the mathematical theory and maximum theory for optimal decisions. He concluded that the decision to replace or keep the existing stock for another period should be based on a comparison of the returns from replacing (immediate production) with the opportunity costs of keeping the stock or asset another period (delaying production). This theoretical approach to optimal decision-making has since been applied to fisheries management at the private and public level (i.e., for the boat or firm and government regulatory agencies).

In microeconomic theory, a standard assumption is that decision makers have perfect information on, for example, future prices and biological growth rates. However, when risk enters the decision process, the theory must be extended. In such cases, the optimum (net present value maximizing) action depends on the probability that alternative conditions (market and or environmental) will occur. In addition, the attitude of the particular decision maker toward risk would also affect the optimal decision.

Any problem of decision making under risk still involves an objective criterion. Two criteria possible are a) to maximize the expected value of profit or b) to select the best possible action given the most pessimistic environment, which is known as a "maximin" strategy [1]. The approach begins by defining a number of states of nature and assuming a probability of occurrence for each. All alternative actions that could be taken are specified and the payoff matrix (i.e., value of the outcome of each action for each state of nature) is given. The decision maker selects the action that will maximize the value of his particular criterion for the given payoffs and probabilities under the worst state of nature.

A general mathematical model for most types of replacement decisions is provided by the principles of dynamic programming. In order to derive an optimal decision rule, dynamic relationships (e.g., related to asset productivity such as dynamic stock constraints) are needed. In the discrete stochastic case, when the dynamic relationships are also stochastic, Howard's [7] generic theoretical model integrated use of the transition probability matrices to define complete Markov chains. These chains are determined exogenously by forces not controlled by the producer (i.e., the matrix of chance failure or loss) and alternative return functions attached to each of the exogenous transition probabilities.

In the case of the problem of optimal replacement, Perrin [9] adapted a deterministic model for use in agriculture. A variable, m, is defined as the number of periods of remaining life until the asset is replaced. For ongoing decisions regarding the continuation of the operation, the replacement concept is most appropriate for evaluating the asset (m). Each replacement asset (i.e., called challenger) must be optimized with respect to m before it is compared with the asset already in use (i.e., called defender) and other challengers.

Perrin [9] offers a discrete analog that is more appropriate for the case of annual productions typical of many agricultural problems. This model in slightly altered form may be given as

$$Y(m,\infty)=\frac{1}{1-(1+r)^{-m}}\left[\sum_{t=1}^{m}(1+r)^{-t}Z(t)+(1+r)^{-m}R(m)-C\right] \quad (1)$$

where

$Y(m,\infty)$ = net present value of an infinite stream of revenues from an asset replaced every m period ;
t = integer year ;
$Z(t)$ = net revenue from the asset in year t ;
$R(m)$ = salvage value of the asset in year m ;
C = initial cost of the asset ;
r = discount rate.

Equation (1) is the net present value of a single link in the continuous chain and the factor outside the brackets converts this to an infinite chain. In the case of a bivalve species (i.e., hard clams, scallops) the term $\sum_{t=1}^{S}(1+r)^{-t}Z(t)$ was deleted because net revenue occurs only in the replacement period m. Using this approach, the future states can be predicted in a probabilistic manner. Hence, rather than having a single net revenue state, R_m, it is assumed that there are k net revenue states in each period m, $R_{k,m}$, with probability $\Psi_{k,m}$. Thus, the net present value of an infinite stream of revenues from an asset replaced every m periods can be re-specified as:

$$Y(m,\infty)=\frac{1}{1-(1+r)^{-m}}\left[\sum_{k\in k*}(1+r)^{-m}\Psi_{k,m}R_{k,m}-C\right] \quad (2)$$

where

$\Psi_{k,m}$ = probability of having state k in period m ;

$R_{k,m}$ = net revenue from asset in state k in period m ;

C = asset replacement cost ;

$k*$ = the set of all possible states.

In the case of cultured scallops, gross revenue is determined by scallop size, density, and market price. Knowledge of growth and mortality are needed to predict scallop size and density. Markovian transition matrix can be used in order to describe growth and mortality due to genetic and environmental conditions.

If a single defender exists, equation (2) is maximized with respect to replacement age m and the maximum present value Y^* is calculated. If multiple challengers exist (differing by productive capability), equation (2) must be maximized for each replacement asset. The best challenger generates the highest Y^*. That is, the producer at each production period is faced with choosing producing and replacing the defender with the best challenger or allowing the asset to grow and additional period. It shows that the replacement decision is based on a comparison of the infinite net revenue streams of each alternative as follows :

replace if

$$Y^*>\frac{1}{1-(1+r)^{-1}}\left[\sum_{j\in J*}(1+r)^{-1}\theta_{j,1}D_{j,1}\right] \quad (3)$$

keep if

$$Y^*<\frac{1}{1-(1+r)^{-1}}\left[\sum_{j\in J*}(1+r)^{-1}\theta_{j,1}D_{j,1}\right]$$

indifferent otherwise, where

$\theta_{j,1}$ = the probability of having net revenue j if the defender's life is extended 1 period ;

$D_{j,1}$ = the net revenue j from the defender if the defender's life is extended 1 period.

Equation (3) provides the productiont and replacement decision policy related to the scallop producer. If Y^* is less than $\frac{1}{1-(1+r)^{-1}}\left[\sum_{j\in J*}(1+r)^{-1}\theta_{j,1}D_{j,1}\right]$, the product will be kept on the firm (i.e., the decision to sell is delayed for one period). The decision space defines the sets of all possible options available to the producer. Assuming that the operation will continue production in some manner, the decision space has two elements : to keep or to produce and replace.

Dynamic programming is a useful optimization procedure for problems involving a sequence of interrelated decisions [6]. In dynamic programming, state variables are observable or measurable conditions such as scallop size, survival and mortality, prices, etc. A stage is the time (e.g., periodic division unit) at which the system is evaluated and a policy decision required. The action chosen at each stage allows the system to change from state to state according to the processes driving changes in the state variables.

In stochastic systems, transition from state to state follows probabilistic patterns. A stochastic process is defined to be an indexed collection of random variables $\{X_t\}$, where the index t runs through a given set T. Often T is taken to be the set of nonnegative integers, and X_t represents a measurable characteristic of interest at time t. For example, the stochastic process X_0, X_1, X_2, $\cdots$ can represent the collection of monthly inventory levels of a given product, or it can represent the collection of monthly demands for this product. The description and solution of problems involving stochastic systems is simplified if the underlying probability process satisfies the Markovian assumption [7].

Dreyfus and Law [6] show that the maximum expected total discounted net revenue of an asset in state i (in this case, a scallop grow-out starting in state i) following decision policy by equation (4), and evolving for t time periods is :

$$Y_i^t = \max_{\tau}\left\{H_{i\tau} + \rho \sum_{j=0}^{M} p_{ij}(\tau)\, Y_j^{t+1}\right\}$$

$$i = 0, 1, 2, 3, \cdots, n \qquad (4)$$

where $H_{i\tau}$ is the expected return in state i at time t given action τ ; ρ is the discount factor or $1/(1+r)$; and $p_{ij}(\tau)$ is the probability of transition from state i at time t to state j at time $t+1$ when action τ is taken.

3. Model and Methodology

3.1 Submodel Specifications

The objective of the model was to maximize the present value of net returns to the firm's resources over the planning horizon. The objective function incorporates all inputs, namely, price function, cost function, scallop growth function that differ by production style, including environmental conditions (water temperature, dissolved oxygen and salinity). Scallop wholesale prices were obtained from the Kang won Cham Scallop Association (KCSA) and include monthly average price (won) by size category (measured in cm shell height). The cost was obtained through survey.

The survey was included complete information on 28 firms. The biological data consisted of measures related to the characteristics of the water in the primary producing locations of Chumunjin, including daily observations of water temperature, water salinity, and dissolved oxygen. The data was obtained from the Korea National Fisheries Research and Development Institute (KNFRDI).

Scallop prices appear to be determined by scallop size (cm shell length) and season (month of sale). Since this was the case with the shrimp fishery modeled by Tian et al. [11], a similar functional form is initially specified :

$$P = \alpha_0 + \alpha_1 W + \alpha_2 W^2 + \alpha_3 DS + \alpha_4 DW \qquad (5)$$

where P is scallop price (won) per shell, W is cham scallop weight (kg), and DS and DW are dummy variables for the summer ($DS=1$ if sales occur May through September, $DS=0$ otherwise) and winter ($DW=1$ if sales occur December through February, $DW=0$ otherwise) months, respectively. Weight is obtained by using an equation that converts size in cm to weight in kg as estimated by Park [8], specifically :

$$W = 0.005664\ e^{0.3041*\mathrm{cm}} \qquad (6)$$

Using this equation, a scallop measuring 10 cm would weigh 0.118 kg. Estimation of the equation (5) using ordinary least squares and 420 observations (monthly observations over five years and 7 sizes) produced the empirical model in <Table 1>. Using price equation, a 0.118kg scallop would sell for 703.5 won. Price function explained 98% of the observed price variation indicating an extremely good fit. Note that the price equation could have been estimated using size instead of weight ; weight was incorporated at this point since it is a more traditional representation and will be used later to determine production levels.

Price is nonlinearly related to scallop size and varies seasonally. Given a scallop of a particular size (cm), equation (6) will convert the scallop into weight (kg) and then price equation will calculate the price of that scallop in won.

Production using different technologies is likely that these factors could affect costs. To examine cost differences (fixed and variable) by production style, dummy variable is created : DC_s.. The production style is distinguished by index s, which equals 1 for lantern nets and 0 for ear-suspended. Using the reported landings (Q), a cost function can be estimated to test the statistical significance of the fixed and variable cost per unit of landings. Generally, quadratic (Q^2) and cubic (Q^3) functions are used since they exhibit desirable theoretical properties [11]. All second-degree curves (i.e., average total cost, average variable cost, and marginal cost) first decline and then increase as output is expanded. Thus, a cubic function provides a reasonable approximation to virtually any cost function in <Table 1>. Including dummy variable for production style (DC_s) and interactive variables between the dummies and landings, the following model was estimated in <Table 1>.

Obtaining a reliable growth function is an integral part of deriving the optimal producing strategy for any aquaculture operation. The primary factors believed to influence growth have, however, been identified by Park [8]. This study found that cham scallop size is primarily affected by water temperature (T), dissolved oxygen content (O), and salinity levels (S) and that growth rates vary by scallop age (A). The best model forms for each production style are presented in <Table 2> [4].

The specification of the objective function requires information on revenues and costs. Revenues are calculated as price times quantity so we need a price function and a means to calculate production quantity. Production quantity, in this case, was involved an estimation of a log reciprocal growth function for individual scallops and assumptions about the initial biomass (i.e., quantity of spat planted) and natural mortality rates. On the cost side, information is needed on both fixed costs (costs that are independent of

〈Table 1〉 Estimation Results for Price and Cost Function

	Estimation of the equation
Price Function	$P= -197.4+9,232.1\,W^{*}-13.764.8\,W^{2*}-31.9DS^{*}+13.7DW$ (8.34) (73.91) (149.65) (6.87 (7.83)
Cost Function	$TC= 350.9+0.006_1\,Q-1.0E-7Q^{2**}+4.4E-13Q^{3**}-450.4DC_s+0.004Q\cdot DC_s^{**}$ (255.0) (0.004) (5.1E-8) (1.9E-13) (257.0) (0.002)

Note) Standard errors are contained in the parenthesis below each estimated coefficient.
* denote significance at the 1% level.
** denote significance at the 5% level.

〈Table 2〉 Estimated Growth Functions

	Growth Function
Ear-suspended style	$\ln G = 0.480 + 1.731\frac{1}{A}^{*} - 0.104\frac{1}{T} + 0.167\frac{1}{O} - 18.448\frac{1}{S}$ (0.933) (0.379) (0.452) (0.636) (31.525)
Lantern net style	$\ln G = 0.398 + 1.738\frac{1}{A}^{*} - 0.172\frac{1}{T} + 0.049\frac{1}{O} - 15.888\frac{1}{S}$ (0.931) (0.094) (0.451) (0.635) (31.442)

Note) Standard errors are contained in the parenthesis below each estimated coefficient.
* denote significance at the 5% level.

production volumes such as initial set-up expenses, insurance, and license fees) and variable costs (costs that are incurred as a result of production such as cost per hectare or cost per kg).

The objective of the Structural model is to maximized the expected net present value (NPV) :

$$\text{Expected} \quad NPV_{s,i,t} = \left(\frac{1}{1+r}\right)^t \cdot [Y^t|_{s,i}] \qquad (7)$$

where

s = production styles ($s=1, 2$ for lantern net and ear-suspended) ;
i = initial rotation month ($i = 1, 2, \cdots, 12$ for January through December) ;
t = alternative rotation lengths ($t = 2, 3, 31$ months) ; and
r = monthly discount rate

In addition,

$$Y^t|_{s,i} = TR(\hat{P}(W(\hat{cm}_{t,s}), DS, DW), X_{t,s}(\cdot)) - TC(Q_{t,s}(\hat{cm}_{t,s}, X_{t,s}(\cdot)), DC_s) \qquad (8)$$

where total revenue (TR) and total costs (TC) are a function of scallop price (P), individual weight (W), individual size (cm), season (DS, DW), number of surviving scallops (X), total production (Q), and production style (DC_s). The ^ indicates the value is predicted from the empirically estimated underlying equations. Note that i is not included on the right-hand-side ; this is because it is related to the stochastic growth and ultimately the expected size of the individual scallops, $E[\hat{cm}_{t,s}]$, given the alternative environmental states (27 in total) and probability of each as described in the next section.

There are three variables in equation (8) that need further definition, namely : cm, $X(\cdot)$, and $Q(\cdot)$. The size of each individual scallop, as represented by cm for centimeters, is obtained from the growth equation. Recall that growth, G, is measured as the ratio of the final scallop size to initial size :

$$G = \frac{cm_{t,s}}{cm_{t=0}} \qquad (9)$$

where $cm_{t=0}$ is assumed to be 0.34, which is the average size of the scallops at the beginning of the grow-out process. Using the empirically estimated log-reciprocal growth equations for each production style (i.e., growth functions in <Table 2>), the following equation can be used to derive an estimate of $cm_{t,s}$:

$$\hat{\ln}\left(\frac{cm_{t,s}}{cm_{t=0}}\right) = \hat{\beta}_o + \sum_{j=1}^{4} \hat{\beta}_{j,s} \cdot \left(\frac{1}{C_{j,s}}\right) \qquad (10)$$

where C_j represents the four characteristics (explanatory variables) that were used to describe individual scallop growth, namely : scallop age (A), water temperature (T), water salinity (S) and the dissolved oxygen content of the water (O). Specifically, the size of the individual scallops at month t using production style s in Chumunjin is found by taking the anti-log of equation (10) and multiplying by the initial scallop size :

$$\hat{cm}_{t,s} = cm_{t=0} \cdot \exp\left[\hat{\beta}_o + \sum_{j=1}^{4} \hat{\beta}_{j,s} \cdot \left(\frac{1}{C_{j,s}}\right)\right] \quad (11)$$

The number of surviving scallops will differ in each time period and by production style and is calculated as follows :

$$X_{t,s} = X_o \cdot \left[(1 - M_{t,s})^{1/30}\right]^t \quad (12)$$

where

X_o = number of scallops initially planted (450,000)

M = monthly natural mortality rate (zero to 10 percent).

The assumption on the number of scallops initially planted was obtained from assumptions on the standard scale of operations (i.e., three plots of 200m by 200 each or 12 ha in total, which corresponds to the average culture area size of 12.09 from the survey). Each plot can contain 10 production lines and along each line the bundles are spaced at a distance of 1.5 m ; this spacing is the same for each production style. The bundles for the lantern net style typically contain 113 scallops on average and the bundles for the ear-suspended style typically contain 56 rows (or cells) with two scallops per row (112 per bundle). Multiplying the average number of scallops per bundle (112.5) by the average number of bundles per plot (200 m divided by 1.5 m) times the number of lines per plot (10) times the number of plots per farm (3) equals a total of 450,000 scallops planted per farm for both production styles.

Aside from adverse environmental conditions, predators such as starfish are the major cause of scallop natural mortality (this threat will, however, differ by production style since hanging culture technologies provide a barrier to entry for many predators). In terms of the natural morality rate (M), little empirical work exists for bivalve species, especially by age. Askew [2] linked oyster mortality to size and computed monthly mortality from annual data using the assumption that short-term rates concur with long-term rates. Following this approach, the cumulative survival rate as reported by Park [8] was used to derive an estimate of monthly mortality by production style ($M_{t,s}$). For scallops grown out using the ear-suspended style, the mortality rate was determined to be 10% from age (month) 1 to age 29. For scallops grown out using the lantern net style, mortality was found to be 0% from age 1 to age 10 (due to the effectiveness of barriers), but 10% from age 11 to age 29. Note, the 1/30 power used in the calculation of the survival rate is the adjustment for the number of days per month, which (for simplicity) is assumed to be 30 for each month.

Total production quantities in kg per firm are needed to calculate the total costs of production. This quantity is determined as follows :

$$Q_{t,s} = X_{t,s}(\cdot) \cdot W(\hat{cm}_{t,s}) \quad (13)$$

Using this information, the total revenue and total costs are calculated as follows :

$$TR_{t,s} = \hat{P}[W(\hat{cm}_{t,s})] \cdot X_{t,s}(X_o\ M_{t,s}) \quad (14)$$

where the weight and price equations were specified in equations (6) and <Table 1>, and

$$TC_{t,s} = \hat{\eta}_o + \sum_{k=1}^{3} \hat{\eta}_k \cdot Q_{t,s}(\cdot)^k + \hat{\eta}_4 \cdot DC_s + \hat{\eta}_5 \cdot Q_{t,s}(\cdot) \cdot DC_s \quad (15)$$

where the parameter values are from <Table 1>.

3.2 Simulations

Scallop growth was simulated using equation (10) with the mean and the extreme values for each environmental attribute (i.e., water temperature, salinity, and dissolved oxygen). The extreme values were calculated by adding or subtracting two standard deviations from the mean. Thus, there are three possible levels of each environmental attribute in each month. These values are shown in <Table 3> for Chumunjin.

Using the standard deviations, exposure to a mean value had a 68 percent probability and exposure to each of the extreme values had a 16 percent probability. That is, the scallops have different probabilities of being exposed to different levels of each environmental attribute (i.e., the mean or extreme values), which will affect ultimate scallop size. Using each combination of mean, over mean and under mean values, 27 possible environmental states (E) for each production style were calculated.

<Table 4> show the resulting environmental states and probabilities used for each production style. For example, the probability of having environment state E1 (that consists of the mean levels of temperature, dissolved oxygen, and salinity in a given month) is 0.3144 (multiply 0.68, the probability of a mean value by 0.68 by 0.68) or 31.44 percent.

Using the Chumunjin environmental values, the levels of characteristics associated with state E1 in the month of August would be : T = 0.0515, O = 0.1929, and S = 0.0302 (<Table 3>). The probability of E2, consisting of the mean temperature and dissolved oxygen but over mean salinity in a given month is 0.0739 (0.68 multiplied by 0.68 and 0.16) or 7.39 percent. Similarly, the probability of having E3 consisting of mean temperature and dissolved oxygen but under mean salinity in a given month is also 0.0739 (0.68 multiplied by 0.68 and 0.16) or 7.39 percent, and so on.

〈Table 3〉 Monthly Mean and Extreme Environmental Values for Chumunjin

Month	Attribute	Mean	Over Mean	Below Mean
August	Temperature	0.0515	0.0582	0.0447
	Dissolved Oxygen	0.1929	0.2470	0.1389
	Salinity	0.0302	0.0313	0.0290
September	Temperature	0.0506	0.0579	0.0433
	Dissolved Oxygen	0.1864	0.2040	0.1687
	Salinity	0.0305	0.0315	0.0296
⋮	⋮	⋮	⋮	⋮
June	Temperature	0.0811	0.1252	0.0371
	Dissolved Oxygen	0.1664	0.1909	0.1419
	Salinity	0.0297	0.0303	0.0290
July	Temperature	0.0600	0.0723	0.0476
	Dissolved Oxygen	0.1761	0.2043	0.1480
	Salinity	0.0300	0.0304	0.0297

〈Table 4〉 Alternative Environmental States used in the Growth Simulations

State	Temperature	Dissolved Oxygen	Salinity	Probability
E1	*	*	*	0.3144
E2	*	*	+	0.0739
E3	*	*	-	0.0739
⋮	⋮	⋮	⋮	⋮
E25	-	-	*	0.0174
E26	-	-	+	0.0040
E27	-	-	-	0.0040

Note) * is mean, + is over mean, and - is under mean.

The probability of exposure to a given environmental state is assumed to be constant over time (i.e., independent of scallop age). However, actual values for a given environmental state and their impact on growth vary by month due to the age (A) effect.

Growth simulations are conducted for each production style (s), planting month (i), and environmental state ($k = 1, 2, \cdots 27$). The simulations begin with spat of a given initial size ($cm_{t=0}$ = 0.34 cm) and planting month (i). The 27 possible environmental states in period 1 (and resulting scallop sizes) are then exposed to each of the possible 27 environmental states in period 2. The output of growth determined by expose to alternative environmental state (E1) in period 2 is calculated as the average size of the 27 scallops in period 1 transitioning through E1 and into period 2. Thus, the output of each sequential growth period is 27 new scallop sizes. Each new scallop size means an average of 27 potentially different scallop sizes transitioning through a given period. Thus, scallop size at each month will differ due to different environment conditions in the initial month (in addition to differences by production type) even though the process began equal sized scallops (i.e., 0.34 cm).

Examples of the growth simulations by production style assuming the process began in August with 0.34 cm scallops are presented in <Table 5> through <Table 6>. Growth simulations cover 30 months in total and are calculated using a 27×30 matrix of final scallop sizes for each period. Each cell in the matrix shows the size of the scallop at a given month and for a given environment. This process is repeated with each of the 12 calendar months as the initial growth period (i).

Final monthly expected scallop sizes are calculated by the outcomes of the growth simulation and the environmental probabilities in <Table 4>. The expected size of a scallop at month t is the same as the sum of the size of a scallop exposed to environment k in period t times the probability of encountering environment k. Eventually each 27×30 matrix of final scallop sizes is reduced to a 1×27 vector of final sizes.

For comparison, the range of scallop sizes that would be expected in month 30 given the 27 possible environmental states in each period are

〈Table 5〉 Expected Scallop Size for Ear-suspended Style in Chumunjin from Planting a 0.34 cm Scallop in August

Option	Period 1	Period 2	…	Period 14	Period 15	Period 16	…	Period 29	Period 30
E1	0.769	1.293	…	9.114	9.601	10.088	…	13.433	13.517
E2	0.753	1.270	…	8.954	9.483	9.971	…	13.277	13.401
E3	0.785	1.316	…	9.276	9.720	10.206	…	13.591	13.633
E4	0.776	1.296	…	9.140	9.639	10.129	…	13.488	13.548
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
E24	0.793	1.321	…	9.310	9.764	10.255	…	13.655	13.689
E25	0.762	1.290	…	9.094	9.569	10.054	…	13.387	13.510
E26	0.747	1.267	…	8.934	9.452	9.937	…	13.232	13.394
E27	0.779	1.313	…	9.256	9.688	10.172	…	13.545	13.545

〈Table 6〉 Expected Scallop Size for Lantern Net Style in Chumunjin from Planting a 0.34 cm Scallop in August

Option	Period 1	Period 2	…	Period 14	Period 15	Period 16	…	Period 29	Period 30
E1	0.771	1.302	…	9.179	9.698	10.204	…	13.573	13.606
E2	0.758	1.283	…	9.049	9.602	10.108	…	13.479	13.531
E3	0.784	1.320	…	9.311	9.795	10.300	…	13.667	13.680
E4	0.773	1.303	…	9.187	9.709	10.216	…	13.582	13.621
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
E24	0.787	1.323	…	9.331	9.815	10.324	…	13.717	13.762
E25	0.770	1.302	…	9.183	9.696	10.203	…	13.603	13.657
E26	0.757	1.284	…	9.053	9.600	10.107	…	13.509	13.583
E27	0.783	1.321	…	9.315	9.793	10.299	…	13.698	13.732

〈Table 7〉 Summary of Eexpected Scallop Sizes (cm) in period by Beginning Grow-out Month for Each Production Style

Month	Production Style	
	Lantern Net	Ear-suspended
January	13.514~13.903	13.569~14.124
February	13.571~13.817	13.668~14.021
March	13.487~14.062	13.463~14.318
April	13.538~13.989	13.516~14.096
May	13.531~13.860	13.451~13.910
June	13.528~13.849	13.403~13.840
July	13.500~13.780	13.430~13.751
August	13.465~14.762	13.401~13.689
September	13.276~13.763	13.272~13.810
October	13.390~13.714	13.445~13.803
November	13.405~13.762	13.546~13.939
December	13.458~13.767	13.611~13.984

summarized for each production style (lantern net, ear-suspended), and initial planting month (i) in <Table 7>. The extreme values in Chumunjin were 13.27 and 14.76cm. In general the values are relatively high given the average market size of scallops (i.e., 10cm to 12cm), however, these values are associated with a 30-month grow-out, which is at least 6 months longer than typical. A 30 period horizon was used in order to compare the expected discounted net benefits of producing early of delaying production past the traditional production period.

3.3 Decision Making Strategies

The optimal producing plan for each production style is determined by comparing the expected net present values (E[NPV]) associated with each alternative (equation 7). In practice this is accomplished in two stages for each production style. In stage one, the highest E[NPV] is identified among the 27 possibilities that result form all possible stochastic growth simulations given an initial planting month. In the second stage, the highest E[NPV] associated with each initial planning month (i) are compared. The information to make the second stage decisions are summarized in <Table 8> through <Table 9>. Once the maximum E[NPV] is identified for each production style, the associated production month (t) and initial month (i) reveal the optimal rotation length. The resulting optimal scallop size and weight are also indicated.

Examining the results in <Table 8>, the maximum E[NPV] (i.e., 133,504,000 won) for production using the ear-suspended production style is associated with planting spat in March and producing two years (24 months) later in March. At that time, the market size would average 12.95 cm (i.e., 290.7 grams) per scallop.

<Table 8> Optimal Producing for the Ear-suspended Style

Planting Month	Grow-out Months	Production Month	Scallop Weight (g)	Scallop Size (cm)	E[NPV] (thous won)
August	24	August	290.69	12.95	118,840
September	26	November	311.32	13.18	124,977
October	25	November	303.09	13.09	128,177
November	24	November	290.73	12.95	129,109
December	25	January	308.63	13.15	132,090
January	24	January	290.70	12.95	133,499
February	24	February	290.69	12.95	133,498
March	24	March	290.72	12.95	133,504
April	24	April	290.69	12.95	129,098
May	24	May	290.69	12.95	129,099
June	23	May	268.02	12.68	120,078
July	24	July	290.73	12.95	118,850

<Table 9> Optimal Producing for Lantern Net Style

Planting Month	Grow-out Months	Production Month	Scallop Weight (g)	Scallop Size (cm)	E[NPV] (thous won)
August	21	May	223.60	12.09	108,660
September	20	May	201.43	11.74	105,987
October	19	May	183.15	11.43	99,579
November	20	July	209.51	11.87	97,485
December	21	September	233.40	12.23	97,648
January	22	November	250.17	12.46	102,700
February	21	November	230.44	12.19	108,698
March	20	November	211.72	11.91	109,019
April	21	January	236.59	12.27	112,729
May	20	January	212.95	11.93	114,003
June	21	March	228.12	12.15	113,413
July	20	March	204.66	11.80	111,801

For producers using lantern nets to grow-out, <Table 9> indicates that planting spat in May will maximize E[NPV]) if scallops are allowed to grow for just 20 months and are harvested in January. At that time, E[*NPV*] would equal approximately 114 million won from the harvest of scallops averaging 11.93 cm and weighing 212.95 grams. Overall, the ear-suspended style is associated with longer optimal grow-out periods and higher E[*NPV*] values as compared to the use of lantern nets.

Comparing the optimal results from <Table 8> through <Table 9>, maximum E[*NPV*], ranged from 114.0 million won to 133.5 million won per "crop". Neither production style produced consistently higher E[*NPV*] values. In addition, optimal planting months, rotation lengths and production weights varied by production style. One notable commonality, however, is that the optimal production months (i.e., January through March) are generally associated with the months when price is highest. Also, the expected NPV is relatively robust for the ear-suspended production style, which suggests that to opportunity costs of alternative production schedules are smaller and perhaps less risky.

4. Conclusion

In this paper, the decision model relied on several distinct submodels. On the economic side, a seasonal price-weight relationship (at the wholesale level) was estimated in order to account for the added benefit of allowing additional growth by delaying production and to capture seasonal demand effects. Using standard goodness-of-fit tests, the best form of the price model was a polynomial of second order. In terms of costs, total costs from an industry survey were used to estimate fixed and variable costs based on production levels and production style. On the biological side, growth was specified of as a function of scallop age, water temperature, salinity, and dissolved oxygen. The log-reciprocal growth model performed the best. Overall, the empirical submodels were very promising in that they were able to explain a relatively high degree of the observed variation in scallop prices, production costs, and scallop growth.

To account for stochastic growth, simulations were conducted using the probabilities of 27 alternative environmental states. Since the levels of the environmental values varied by month, and the growth equations were specific to each production style, predicted growth differs in each scenario (24 in total) beginning in period 1 (i.e., month 1). For each time period and scenario the probabilities are multiplied by the predicted growth (i.e., scallop size from the estimated equation for that time period and production style) in order to arrive at an estimate of expected scallop size that is carried over into the next period. This process is repeated for each of the 30 periods for each scenario.

The monthly probabilistic growth figures for each scenario were then multiplied by the number of surviving scallops in each period. Scallop weight and the weight-dependent price equations to estimate expected net revenues. By subtracting the estimated cost function, the optimal production times and rotations (i.e., initial planting month and duration of grow-out) were identified. The optimal producing plan was the one that maximized the expected net present value (E[*NPV*]) and optimal plans were identified for each production style.

The results of the model showed (a) the optimal production time for ear-suspended style is longer than with the lantern net method ; (b) the ear-suspended operation generated the highest expected discounted net economic returns (i.e., E[*NPV*]) ; (c) the optimal month for planting spat was March (ear-suspended style) and May (lantern net style) ; and (d) the market size of scallop that maximizes E[*NPV*] is between 11.43 and 13.18 cm, which is larger than traditionally marketed (10~11cm).

The structural model of Markcov process in this study has incorporated biological and environmental data including scallop size-at-age, water temperature, water dissolved oxygen, and water salinity. This specification excluded other, potentially important, environmental values including : water flow and the food profile (or algal content of water) as well as biological factors such as sex (male/female growth rates). These variables would add more realism. Most notably, this study could be extended to consider multiple rotation management and rotation of scallops for different regions, as well as regarding change of discount rate.

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