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OPTIMAL HARVEST SCHEDULE FOR MARICULTURED SHRIMP:

A Stochastic Sequential Decision Model

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ABSTRACT

Successful introduction of advanced intensive technology in shrimp mariculture requires the appropriate management tools. This report presents a management model for determining the optimal stocking and harvesting schedules for a shrimp pond of a mariculture shrimp operation. The developed model is an extension of the classical growing inventory model. It provides a set of simple intra- and interseasonal decision rules expressed as cutoff revenue when both price and weight are assumed random, and as cutoff price or cutoff weight when either price or weight is assumed random. If current realized revenue is less than the cutoff revenue, the decision is to keep the crop and delay the decision to sell for another period; otherwise, the decision is to sell. Application of this model to a hypothetical shrimp farm in Hawaii with 24 0.2-ha round ponds indicates that net return can be increased three times by applying the derived optimal policies, compared with a conventional fixed scheduling scheme. The economics of controlled environment is also evaluated using the model.

Keywords: marine shrimp, decision model, optimal scheduling, aquaculture, growing inventory.

INTRODUCTION

Shrimp aquaculture has emerged as a potential industry in many parts of the tropical region as shrimp catches from the sea are unlikely to meet future world demand (Shang 1983, Uwate 1984). At current world shrimp prices, however, using existing shrimp farming technologies, shrimp aquaculture in this region has not been proven to be economically viable. Successful competition by this region in the world shrimp market depends upon developing management strategies and technologies to increase profitability.

Shrimp ranks second in volume, behind tuna, and first in value of total U.S. seafood consumption. The United States is the world leader in shrimp consumption, consuming over 600 million lb annually. Japan is a close second. Tropical species represent the major part of the shrimp market in the United States and Japan.

Shrimp culture worldwide represents approximately 15 percent of the 4 billion lb of shrimp placed on world markets. The U.S. National Marine Fisheries Service predicts that aquacultured shrimp will constitute about 25 percent of the world market by 1990. It is also estimated that aquacultured shrimp will constitute about 35 percent of the tropical shrimp market, with tropical, or penaeid, species being the type of shrimp popular with U.S. consumers (The Aquaculture Digest's, 1988).

The recent trend in marine shrimp aquaculture is toward more intensive operations, particularly in areas with high land and labor costs such as Hawaii. Innovative facility design and advancements in nutritional knowledge also contributed to this change from the more traditional extensive systems. Associated with this change is the improvement of overall productivity. This improvement, however, has to be accompanied by large investment in specialized facilities such as the innovative round-pond design recently developed by the Oceanic Institute in Hawaii. Efficient system design, good management planning, and control are the means to utilize the large investment fully and help producers to remain competitive.

As intensification of the shrimp production system increases, the decision-making process of the producers becomes complex. They are faced with many investment and operational alternatives. The process is further complicated because of the dynamic and stochastic nature of the biological and economic environments. The survival rate, growth rate, food conversion ratio, and shrimp market price, among other parameters, are stochastic in nature. These parameters depend not only on the genetic traits of the shrimps and natural environmental conditions, but also on management input into the production process, such as stocking density, harvesting schedule, type and quantity of feed, and environmental influence on production facilities. Profitable operations can only be achieved through better understanding of the relevant biological, physical, and economic elements as well as their interrelationships in the entire production process.

This report deals with the development of decision aids to better manage the shrimp farms in the Pacific region. In particular, it addresses the question of optimal stocking and harvesting schedules of cultured marine shrimps. A quantitative management tool that can help the producer locate the optimal management practices in a dynamic, uncertain environment can contribute immensely to the success of the shrimp mariculture industry in the Pacific region and in particular, Hawaii. This in turn can contribute to the diversification of the local economy, reduction in the balance of payments (as this region imports most of its shrimp consumption), and increase in employment opportunities in the region.

Since most farms in the Pacific region can produce several crops of shrimps a year, it is important to use the facility fully so as to maximize profit. One of the major decisions facing a shrimp producer is whether to sell the shrimps and replace with a younger crop or keep the existing crop for another period. The interesting issue in this problem is that shrimps of different sizes command different prices, with higher prices associated with larger shrimps. However, producing larger shrimps entails higher feed and other operating costs and opportunity lost of raising a younger crop. In addition, shrimp prices and rates of growth vary seasonally. Because the decision concerns activities in future time and the decision process is implemented at specified future time intervals, risk is involved. There are two elements of risk: the biological growth process (due to the limited practical experience of the producers) and the uncontrollable market price faced by the Pacific producers, who are a small part of the world market. This complicates the identification of the optimal stocking and harvesting schedules.

Since shrimp farming is relatively new to the Pacific region, there is limited practical experience and generally no agreed-upon management practices. It is imperative at this early developing stage of the industry to have a management tool so as to arrive at the optimal management practices.

This report analyzes an intensive round-pond shrimp-growing technology recently developed at the Oceanic Institute in Hawaii. This technology shows tremendous promise to be economically viable in the Pacific region. The intensity of such a system, however, would require modern management tools for efficient and profitable operation, which is the focus of this report. A sequential decision model of growing inventory is extended to analyze the optimal stocking and harvesting schedules of a shrimp-producing pond. Although the focus here is on a single pond, the optimal policies can be used to approximate the operation of the whole farm for comparative analyses.

Cost-benefit analysis indicates that a loss would have been incurred based on a hypothetical farm with 24 round ponds of 0.2 ha each under conventional management practices. By applying the model developed in this report, however, which defines a more efficient operation, annual net return can range from $279,429 to $322,719. Furthermore, it is demonstrated that net return can be increased by about one-third if the environment can be kept to an optimal level.

REVIEW OF PAST RESEARCH

Management of the exploitation of renewable resources as capital stock has been discussed by Clark (1976) and Clark and Munro (1975). Levhari et al. (1981) considered the interaction between the market systems and the natural biological dynamics.

Models of aquacultural systems for the purpose of system design and operational management are few in comparison to agricultural systems models. Some of these models are documented by Allen et al. (1984) and by Orth (1980) and Leung (1986). The majority of the models developed thus far have been directed toward prediction rather than decision-making.

Several systems models have been developed for operational management of aquacultural facilities. Johnson (1974) used linear programming to optimize both the schedule of release dates for each lot of salmon and the choice of stocks for use in the hatchery facility. Gates et al. (1980a, b) used a multiperiod linear programming model to determine the optimal methods of operation of a full-term salmon culture facility. Lipschultz and Krantz (1980) used linear programming models to make production decisions for oyster culture. Optimal control theory was used to determine the optimal operating methods for lobster culture by Botsford et al. (1974, 1975) and Schurr et al. (1974). They used the model to determine the optimal temperature, recirculating rate, container size, feeding rate, and food type. Emanuel and Mulholland (1975) used optimal control theory to maximize the standing crop of largemouth bass. Kitchell et al. (1977) and Sparre (1976) used dynamic programming to determine the optimal methods of operating yellow perch and rainbow trout cultures, respectively. Talpza and Tsur (1982) used capital theory and optimal control methods to optimize feeding and harvesting schemes under various market and environmental conditions and to calculate optimal initial stocking, length of growout cycles, and water flow rates. Leung et al. (1984) and Leung and Shang (1989) used a variant of dynamic programming to evaluate alternative pond management and marketing strategies for freshwater prawn production. While the prawn producers practice continuous stocking and harvesting, however, the shrimp operations are generally of all-in/all-out nature. The difference in practice is primarily due to the heterogeneous growth of prawns and homogeneous growth of shrimps.

All of the models mentioned above are species-specific and are not directly applicable to shrimp culture. The only operational management model for shrimp culture was developed by Karp et al. (1986). They used dynamic programming to determine the optimal stocking and harvest rates of *P. stylirostris* in the Southwest. However, their dynamic program was exceedingly large, with 3501 different states, which would be very cumbersome to apply in a practical setting. Also, due to the environmental conditions in the Southwest, where poor weather may result in decreased growth rates or loss of the entire stock, their model placed a heavy emphasis on dealing with environmental uncertainty and assumed prices were fixed. Conditions in the tropics allow a year-round growing of shrimps; in that case, price uncertainty is as important as environmental uncertainty.

THE MODEL

This section introduces the conceptual framework of a management model developed to help the shrimp producer determine the optimal harvesting policy of a single pond. It is an important subproblem within the general context of the larger problem of operating a shrimp farm in tropical and subtropical environments (e.g., Hawaii). Focus is on the continuous operation of a single pond.[1] Thus the shrimp producer operates within a given capacity and his decision is short-run in nature. Nevertheless, his production and pond management decisions are carried over time. Time enters at two levels: the age of the growing crop of shrimp and the calendar date of harvesting.

In this context, the case of cultured shrimp is an extension of the sequential decision model of growing inventory developed and applied to a broiler producing firm (Hochman and Lee 1972, Rausser and Hochman 1979). These two "growing" crops resemble each other closely in that at each age there is homogeneity in the size distribution and quality of the animals. For a given age, therefore, the decision of the grower is dichotomous: whether to sell the crop and enter the new period with a new crop or keep the old crop and defer the decision whether to sell it or not to the next period. Note that the decision is of the all-in/all-out nature.

The differences between the two crops require the extension of the framework beyond the "broiler" model. While the broiler growth processes are well known in applying modern biotechnology for the past few decades, the shrimp aquaculture technology is in its infancy. Hence the proportion of uncontrolled elements is considerably higher than that of the broiler case. The physical factors of the shrimp culture environment such as air and water temperatures, waste products, and other water quality determinants are hard to control and subject to random variation. Another feature that characterizes the shrimp production is the positive relationship between price and size, which implies a significant differentiation of the product. These distinctions are absent in the broiler operation. For both crops, however, risk is introduced through uncertain market prices. Thus, in the case of the shrimp operation, risk is introduced through both uncertain weights and uncertain market prices.

The state of the system in shrimp culture is defined by (a) the age of the crop as it relates to weight (the growth process) and by extension to the price of shrimp through the price/size relationship, and (b) the calendar date of the year and the effect of seasonality on the physical growth processes as well as on the shrimp prices. Thus, the current gross revenue per animal[2] received from selling a given crop of age x weeks at a calendar week t is:

$$R_n(x,t) = W_n(x,t)P_n(x,t) \tag{1}$$

[1] Note that in the subsequent analysis of the whole farm, risk is assumed to be identical for each pond. This can be a restrictive assumption but we believe it is a good approximation for the case of shrimp production. With more production data available in the future, this assumption can be relaxed.

[2] The present model is formulated on a per-animal basis, and mortality is introduced explicitly in the profit calculation. Mortality is assumed to be density-independent, due to lack of information. This can be modified easily when additional information becomes available.

for $x = x_0, x_0 + 1, \ldots, X$
and $t = 1, 2, 3, \ldots, 52$ weeks,

where $W_n(x,t)$ is the current weight, $P_n(x,t)$ is the current price, x_0 is the starting age, and X is the terminal age at which the crop will be sold, whatever the revenue is. The age of the crop determines both the weight (or size) and the price. There is also seasonality effect, i.e., the chronological date, t, of the year, that will affect revenue either through the environmental impact (e.g., temperature) on the growth of the animal and/or through the seasonality of demand (e.g., Christmastime).

It is assumed that though the shrimp producer knows the current revenue, next week's revenue includes stochastic (random) elements that make its cash value uncertain. Therefore, without loss of generality, revenue is assumed to be a random variable with a known distribution $h(R)$ that may be one variate if either weight or price is random or a bivariate if both price and weight are random. Thus the value R_n is the current sales revenue from the density $h(R)$. The case of random prices is characterized by a price-taking firm marketing either to local or to export markets. A firm marketing most of its product to a local, stable market may consider the price-quantity relation as deterministic. Stochastic variations in weight may be caused by fluctuations of temperatures as well as other environmental factors. Also, when new technologies are introduced, randomness in weight should be taken into account.

The cost function is defined as a deterministic function $C(x,t)$ that has fixed costs per crop (mainly the postlarva purchase costs) and variable costs that depend on age, such as feed, labor, and energy. The immediate net return can then be calculated as $R_n(x,t) - C(x,t)$.

One approach of solution to this problem is to determine a set of critical values of revenues or cutoff revenues $R^*(x,t)$ that maximizes profit or net return as shown in Figure 1. The decision is such that for each age, x, and calendar week, t, if the current realized gross revenue, $R_n(x,t)$, is less than $R^*(x,t)$, keep the crop and delay the decision to sell for another week, otherwise sell the crop if $R_n(x,t) \geq R^*(x,t)$.

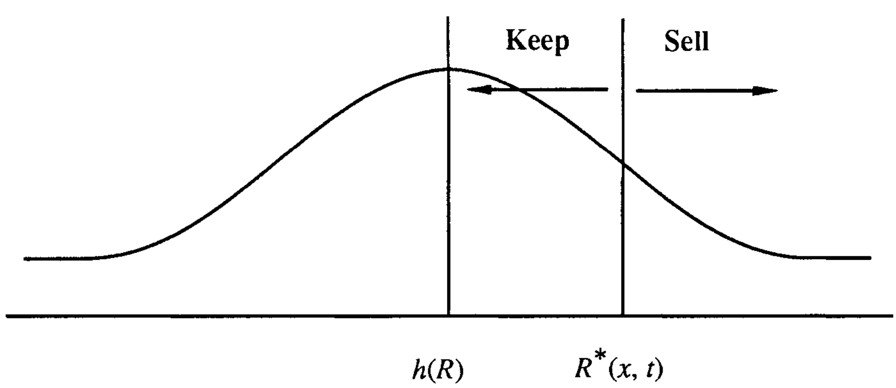

Figure 1. Schematic of the keep-sell decision and cutoff revenue.

This problem of continuous optimal shrimp production and harvesting can be formalized as a Markovian dynamic programming model as a follows. Let f_n represent the maximum expected return for the last n periods (weeks). If the producer begins at stage n with crop of age x and calendar date t, then:

$$f_n(x, t) = \max_{R(x, t)} \left\{ \int_0^\infty M(R_n(x, t), x, t) h(R)_t dR_t \right\} , \tag{2}$$

where

$$M(R_n(x, t), x, t) = \begin{cases} f_{n-1}(x+1, t+1), & if R_n(x, t) < R^*(x, t) \\ R_n(x, t) - C(x, t) + f_{n-1}(x_0, t+1), & if R_n(x, t) \geq R^*(x, t) \end{cases} \tag{3}$$

for $x = x_0, x_0+1, \ldots, X-1$ and $t = 1,2,3, \ldots, 52$ weeks.

Thus, $M(R_n(x,t),x,t)$ is a dichotomous return function that can take one of the two values, according to whether the decision is to keep or to sell the crop. Thus, by Bellman's principle of optimality, for all values of $R_n(x,t)$ that fall within the domain of the decision to keep, $M(R_n(x,t),x,t)$ will take the value of maximum expected returns for the last $(n-1)$ periods, i.e., $f_{n-1}(x+1,t+1)$ and for the decision within the domain of the decision to sell, $M(R_n(x,t),x,t)$ will consist of the realized immediate net returns, i.e., $R_n(x,t) - C(x,t)$ plus the maximum expected returns, in the case of a decision to sell, for the last $(n-1)$ periods, i.e., $f_{n-1}(x_0,t+1)$.

The optimal policies that result consist of 52 vectors of cutoff revenues, $R^*(x,t)$. Each of the vectors represents the solution for a given week, t, in the year. The 52 cutoff vectors depict the effect of the calendar time, while any given vector of cutoff revenues is related to the age of the growing inventory, i.e., for each age there is a critical value of revenue defined such that any current realized revenue that is below it will result in a decision to keep the crop and wait for next week, but otherwise the decision is to sell the crop.

This problem can also be formulated as a Markovian dynamic programming decision model as in Howard (1960). The backward recursive relation of the dynamic program (Equation 2) can be rewritten as:

$$f_n(x, t) = \max_{H_{xt}} \left\{ H_{xt} f_{n-1}(x+1, t+1) + (1-H_{xt}) \left[\int_{R^*(x, t)}^\infty R_n(x, t) \frac{h(R)_t}{1-H_{xt}} dR_t - C(x, t) + f_{n-1}(x_0, t+1) \right] \right\} \tag{4}$$

In Equation 4, H_{xt} is the probability to keep the existing crop of age x at week t for another week. Note that the transition probability, H_{xt}, has a one-to-one correspondence with the cutoff revenue, $R^*(x,t)$. The transition probability matrix, T_t, has the following form:

$$
T_t = \begin{bmatrix} 1\text{-}H_{x_0} & H_{x_0} & 0 & . & . & . & 0 \\ 1\text{-}H_{x_0+1} & 0 & H_{x_0+1} & . & . & . & 0 \\ . & . & . & & & & . \\ . & . & . & & & & . \\ . & . & . & & & & . \\ 1\text{-}H_{X\text{-}1} & 0 & 0 & . & . & . & H_{X-1} \\ 1 & 0 & 0 & . & . & . & 0 \end{bmatrix} \tag{5}
$$

However, the problem at hand differs from the standard Howardian model of dynamic programming with Markov chain in that T_t is endogenous. This prevents us from using the conventional "value iteration method" as developed by Howard. The solution would then require an iterative process that starts with an average cutoff revenue (price or weight) until optimal policy converges.[3] The process is found to converge rapidly on the optimal vector of cutoff revenue (price or weight). Except for the slight difference in the solution process, the interpretation of the solution expressed as a set of invariant optimal policies (IOP) is similar to Howard's. Note that the transition matrix, T_t, has a time subscript that denotes a time-varying Markov chain. If seasonality effects are ignored, the transition matrix will be constant and so is the set of IOP. In other words, the IOP will be identical for each week in a year. This case is defined as the homogeneous (calendar-independent) case. It provides additional insights on the statistical properties of the Markovian decision process. (See Appendix A for a detailed mathematical description of the homogeneous case.)

For computational convenience, the basic functional equation (Equation 2) can be rewritten in a form where the continuous distribution is approximated by a histogram of J equal probability rectangles to yield:

$$
g_n(x, t) = \max \begin{bmatrix} \text{Sell: } R_j(x, t) - C(x) + E_R\left[g_{n-1}(x_0, t+1)\right] \\ \text{Keep: } E_R\left[g_{n-1}(x+1, t+1)\right] \end{bmatrix} \tag{6}
$$

$$
\text{for } j = 1, 2, \ldots, J; \quad x = x_0, x_0+1, \ldots, X-1, X,^4
$$

and

$$
t = \begin{Bmatrix} 1, 2, \ldots, 13 & \text{(fall)} \\ 14, 15, \ldots, 26 & \text{(winter)} \\ 27, 28, \ldots, 39 & \text{(spring)} \\ 40, 41, \ldots, 52 & \text{(summer)} \end{Bmatrix}
$$

where

$$
E_R\left[g_{n-1}(x, t)\right] = \frac{1}{J}\sum_{j=1}^{J} g_{n-1}(x, t)
$$

$$
\text{for } x = x_0 + 2, x_0 + 3, \ldots, X - 1
$$

[3] An efficient algorithm has been developed, and the flowchart of the computer program is presented in Appendix B, with a sample of input and output of the program presented in Appendix C. The computer program is available upon request from the authors.

[4] We assumed $J = 20$ and allowed for a two-week rest between crops. The terminal crop age, X, of selling at any revenue is 15 weeks.

and

$$E_R\left[g_n(X, t)\right] = \frac{1}{J}\sum_{j=1}^{J} R_j(X, t) - C(X) + E_R\left[g_{n-1}(x_0, t+1)\right]$$

In this case, $g_n(\bullet)$ is the discrete counterpart of the functional equation $f(\bullet)$ and E_R is the expected value operator. The solution consists of invariant optimal policies for the 52 weeks of an annual production and marketing plan.

OPTIMAL SCHEDULING OF PRODUCTION AND MARKETING IN A HAWAIIAN SHRIMP-PRODUCING FARM

The Search for an Appropriate Technology

The technologies developed for shrimp production varied according to their operating environments. Scarcity and abundance of natural, physical, and human resources as well as the economic variables, such as prices of inputs and outputs, are important determinants for the choice of the appropriate technologies. For example, in Japan, intensive technologies are prevalent, while in Taiwan and the Philippines semi-intensive technologies are common. In Equador, technologies range from extensive to semi-intensive.

In Hawaii, scarcity of land and the high costs of labor require the adoption of intensive technology in shrimp production. Failure of early attempts to introduce commercial aquaculture production into the Hawaiian islands signals the need for highly competitive marine aquacultural technologies that can be profitable under existing conditions. In this section, the model developed in the previous section is demonstrated as an appropriate managerial tool to analyze the optimal operation of the round-pond technology developed by the Oceanic Institute.

The Round-Pond Technology

In 1985, Oceanic Institute constructed an experimental intensive shrimp pond at its Makapuu facility that incorporates features from intensive systems around the world. It is round, 1 m deep, slightly sloped to the center, 337 m^2 in area, and has a large center sump/drain. The sides of the pond are cement block and the bottom is compacted soil. A paddlewheel aerates and mixes the pond water in a circular pattern that causes organic sedimentation to accumulate in the center of the pond where it can be flushed out the drain.

Four shrimp production trials were conducted in the experimental pond during 1986 and 1987. The Equadorian white shrimp, *Penaeus vannamei*, was selected as the species of choice because of its excellent growth characteristics, disease resistance, and high market value. All trials were stocked with 1-gm animals, with two trials at a density of 50 animals/m^2 and two with 100. Shrimp feed from Taiwan was used in all trials. These trials provided the data for estimation of biological growth. Overall growth averaged 1.75 gm per animal per week over the four trials. Survival was slightly over 80 percent, and feed conversion efficiency ranged from 2.3:1 to 2.7:1. The animals were harvested at a size of 20 gm (Wyban et al. 1988). A 0.2-ha prototype commercial round pond was also constructed at a commercial shrimp farm in Hawaii in late 1987. Production trial results indicate that the experimental round pond is effective when scaled up (Oceanic Institute Newsline 1988).

Estimated Growth Relationship

Several growth relationships were tried, and the most plausible form selected is the log-reciprocal form, presented as follows:

$$W = e^{\alpha_0 - \alpha_1 \left(\frac{1}{x}\right)}, \tag{7}$$

where $\frac{dW}{dx} = \alpha_1 \frac{W}{x^2} > 0$ and $\frac{d^2W}{dx^2} \geq$ or ≤ 0

with an inflection point at $x = \frac{\alpha_1}{2}$

This log-reciprocal equation implies an asymptotic level of weight; it also allows for varying marginal growth rates.

Weekly grow-out data from four trials of the Oceanic Institute round pond were used to estimate the growth function, and the result is presented below:

$$\ln W = 4.92 - \underset{(22.00)}{241.24}(1/x) + \underset{(2.18)}{14.38}D(1/x) \qquad R^2 = 0.91 \tag{8}$$

where

W = average weight of shrimp (gm),
x = days from hatching,
D = dummy variable, 1 if temperature is $\geq 26°C$, 0 otherwise,
ln = natural logarithm,
and numbers in parentheses are t-statistics.

The estimated marginal rate of growth is $dW/dx = 241.24W/x^2 > 0$ and the point of inflection is at 120.5 days. The dummy variable, D, was used to test the impact of temperature differences on the growth coefficient, a_1.

The influence of temperature was found to be significant as shown in Equation 8 and was applied later in deriving the two seasonal semiannual growth periods. The effect of a higher stocking density (100 animal/m^2) was also tested and was found to be insignificant. The estimated growth relations were used in the decision process by incorporating the predicted weight-age relationship as well as their estimated random spread. The estimated standard deviation[5] of 1.34 gm/animal was used to derive $h(W)$ in the case of the univariate normal distribution and to derive $h(R)$ in the case of the bivariate normal distribution. For computational convenience, 20 equal intervals were selected from the normal distribution, such that each has a probability of 0.05.

Estimated Price-Size Relationship

As pointed out, the main market environment the shrimp producer will be facing is that of shrimp prices on the U.S. Mainland, characterized by that of a price-taker producer. Weekly data of shrimp prices by size for the year 1985–1986 was obtained from a weekly summary of Penaeid ex-vessel prices, headless, shell on, from National Marine Fisheries Service Market News Reports.

The data were converted to prices by weight category (there is one-to-one correspondence between size and weight) and were used in estimating the price-weight relationships, allowing for seasonal effects as follows:

[5] We chose to use the standard deviation (error) of the equation as a measure of risk rather than the total sampling variability, which is composed of the equation error and the error in estimating the unknown parameters.

$$P = 0.477 + 0.114W + 0.033DS + 0.233DF + 0.097DW \quad R^2 = 0.96 \tag{9}$$
$$\quad\quad (95.81) \quad (0.68) \quad (5.46) \quad (2.40)$$

where

P = price per pound ($/lb.)
W = mean weight of size category (gm/animal)
DS = dummy variable, 1 if in summer, 0 otherwise
DF = dummy variable, 1 if in fall, 0 otherwise
DW = dummy variable, 1 if in winter, 0 otherwise
and numbers in parentheses are t-statistics.

This relationship was tested for possible heteroskedasticity to see if higher variance is associated with higher weight. No heteroskedasticity was found in this case. The estimated standard deviation was found to be $0.3166/lb. This standard deviation was used to construct the price density function $h(P)$ assuming a normal distribution similar to the weight distribution. This standard deviation was used to construct the univariate normal price density distribution, $h(P)$, in the case of random prices with deterministic growth relation and to construct the bivariate normal distribution, $h(R)$, in the general case of both price and weight having independent normal distributions.[6]

Table 1. Feeding schedule.

Average Size of Shrimp (body weight in gm)	Feed Rate (% of Body weight)
0–1	12.0
1–5	10.75
5–10	9.3
10–15	6.1
15–25	4.0

[6] The distributions of price and weight are assumed to be independent, since the shrimp producers are assumed to be price-takers and their production would not affect the market price.

Feeding Schedule and Estimated Growout Operation Costs

High-protein feed is assumed to be used with application levels according to body weight of shrimp as presented in Table 1.[7]

Growout operation costs include feed, energy, labor, and stocking costs based on a hypothetical farm of 24 round ponds, 0.2 ha each, with stocking density of 100 animals/m^2. Energy cost is for paddle-wheel and resource pumping, while labor cost is for regular sampling and feeding. The energy and labor costs for a particular farm situation must be estimated as a weekly per-pond cost. In this application, energy cost and labor cost are estimated to be $56.26 and $20.31 per week per pond, respectively. The weekly per-pond costs are then divided by the total number of shrimps stocked to get estimates of the cost per shrimp per week. Feed cost per shrimp is calculated as a function of feeding rate and weight. Feed is assumed to cost $0.00125/gm. Stocking cost includes the cost of postlarvae and expenses incurred in the nursery until the age of 65 days. It is assumed to be $0.015 per animal.

[7] We assumed feed is a function of average body weight. Thus, in the case of random weight, feed remains deterministic. For all practical purposes, this assumption matches closely the actual feeding practice, which is based on the average body weight.

Results: The Optimal Policies[8]

Optimal policies are a function of the growth function, the related operating costs, the seasonal price distribution, and the effect or interaction of the other seasons with respect to growth, costs, and price. The seasons in our case have been defined as follows: fall, September to November; winter, December to February; spring, March to May; and summer, June to August. Fall is the best season, with relatively higher prices, and the best rate of growth owing to relatively higher temperatures. Summer has the same rate of growth (temperature) as fall. The least favorable growth and market conditions are shared by winter and spring.

The above information is fed into the developed model to generate the inter- and intraseasonal optimal policies for three cases assuming random revenue, random price, and random weight.[9] The results are presented in Table 2. This table shows for each week in a season and each age of the crop the cutoff revenue, price, and weight for each of the three cases. (Note that weight is uniquely determined for each season from an age-weight relationship.) The numbers in this table are expressed in ordinal scale according to the 20 equal intervals of the assumed normal distributions of price and weight. Using this scale, the number 0 indicates the probability to sell is 1.0, while the number 20 (shown as dashes in Table 2) indicates that the sell probability is 0. Number 17 represents a sell probability of 0.15, and so on. The ordinal scale is used in this table to emphasize the inter- and intraseasonal optimal policies. Table 3 shows the corresponding cutoff revenue, price, and weight. Table 4 summarizes the corresponding cutoff values for week 13 of each case. For example, in the case of random revenue, if a producer comes into week 13 with a crop of age 8 weeks, the decision will be to sell the crop if the current realized gross revenue is above \$124 per 1000 animals. Otherwise, the crop should be kept for another week. Similarly, for the case of random price, if the producer comes into week 13 with a crop of age 14 weeks, the decision will be to keep the crop if the current market price is below \$8.08/kg. Figures in the case of random weight can be interpreted in the same way. It should be noted that 15 weeks is the terminal age when the crop will be sold regardless of the current revenue, price, or weight. This provides a set of simple decision rules that take into account the dynamics and uncertainty of the decision process.

In this application, summer and fall are considered good seasons in terms of growth, while fall is significantly better than winter and winter is better than summer and spring in terms of price. These seasonality effects are captured by the optimal policies as shown in Table 2. For example, in the case of random weight, the decision to sell comes at earlier ages toward the end of the fall season, since winter, which is a bad season in growth, follows. It is also true for the case of random price, as prices in the fall are higher than in the winter. The case of random revenue is a combination of random price and random weight. It is also interesting to note that overall the case of random price shows earlier selling ages than does the case of random weight. This is primarily due to the higher variation in price than in weight. Of course, the case of random revenue would

[8] The results presented are based on experimental growth data, which are used here primarily to demonstrate the application of the developed model. In particular, in the present application, estimated growth is extended beyond the maximum size of 20 gm as reported in the experimental data. The authors are investigating the sensitivity of the results, on the basis of more recent experiments with growth up to 27 gm. The results presented should therefore be treated as preliminary and used as such.

[9] The convergence to the invariant solution was relatively fast (6–8 iterations).

Table 2. Interseasonal and intraseasonal optimal policies.

Case A: Random Revenue

Age	FALL													WINTER													SPRING													SUMMER												
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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8	.	.	.	.	.	.	.	.	19	18	19	18	18	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19	19	19	19	19	.	.	.	.	.	.	.	.	.	.	.	.	.	19	19	18	.	.	.	.
9	.	.	.	.	.	.	.	.	19	18	19	18	17	19	.	.	.	.	.	.	.	.	.	.	.	.	.	19	19	19	19	19	18	.	.	.	.	.	.	.	.	.	.	.	19	19	19	18	19	.	.	.
10	.	.	.	.	.	.	.	.	19	18	18	17	15	19	19	19	.	.	.	.	.	.	19	19	19	19	19	19	19	19	18	18	18	19	.	.	.	.	.	.	.	.	.	19	19	19	18	18	19	19	19	.
11	19	19	19	19	19	19	19	19	19	19	18	16	13	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	18	17	17	18	18	19	.	.	.	.	19	19	19	19	19	19	19	18	17	18	19	19	19
12	18	19	19	19	19	19	19	19	19	19	17	15	10	18	18	18	19	19	19	19	19	19	19	18	18	18	18	18	18	17	17	16	16	17	18	18	19	.	.	19	19	19	19	19	18	18	17	15	16	18	18	19
13	17	17	17	17	17	17	17	17	17	17	17	14	7	16	15	16	17	17	17	17	17	17	17	17	17	16	17	17	17	16	15	14	14	15	16	16	16	19	19	17	17	17	17	17	17	17	16	14	14	15	17	18
14	13	13	13	14	14	14	14	14	13	13	13	13	3	12	12	12	13	13	13	13	13	13	13	13	13	12	13	13	13	13	12	11	11	11	12	12	12	13	18	13	13	13	13	13	13	13	13	10	11	11	11	15
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Converged in 7 iterations

Case B: Random Price

Age	FALL													WINTER													SPRING													SUMMER												
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
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10	.	.	.	.	.	.	.	.	.	19	19	17	14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19	19	18	18	19	19	.	.	.	.	.	.	.	.	.	.	.	19	19	18	19	.	.	.
11	.	.	.	.	.	.	.	.	.	19	18	18	12	19	19	19	.	.	.	.	.	.	.	.	19	19	.	19	19	18	17	17	17	18	19	.	.	.	.	.	.	.	.	.	19	19	18	16	18	19	19	.
12	19	19	19	19	19	19	19	19	19	19	18	15	9	18	18	18	19	19	19	19	19	19	19	19	18	18	19	19	18	17	16	15	16	16	17	18	.	.	.	19	19	19	19	19	19	18	17	15	15	17	18	19
13	17	17	18	18	18	18	18	17	17	17	17	14	8	16	15	16	17	17	17	17	17	17	17	17	16	16	17	17	16	16	14	14	14	14	15	15	16	.	.	17	17	17	17	17	17	17	16	13	14	14	16	18
14	12	13	13	14	14	14	14	14	13	13	13	13	3	12	11	11	13	13	13	13	13	13	13	13	13	11	13	13	12	12	11	11	10	10	11	11	12	13	19	13	13	13	13	13	13	13	13	10	10	10	11	14
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Converged in 8 iterations

Case C: Random Weight

Age	FALL													WINTER													SPRING													SUMMER												
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
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12	.	.	.	.	.	.	.	.	.	.	19	16	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	19	18	14	16	19	.	.	.	.	.	.	.	.	.	.	.	.	.	18	14	16	.	.	.
13	.	.	.	.	.	.	.	.	19	19	19	16	1	.	.	.	.	.	.	.	.	.	.	.	19	18	19	19	19	17	13	12	15	19	.	.	.	.	.	.	.	.	.	19	19	19	18	12	13	16	.	.
14	17	18	18	18	18	18	18	18	16	16	16	16	0	16	17	17	17	17	17	17	17	17	17	17	17	14	15	15	15	15	11	10	9	15	17	17	17	17	.	17	17	17	17	18	18	16	16	9	10	11	14	.
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Converged in 6 iterations

Table 3. Cutoff revenue, price, and weight.

Case A: Random Revenue ($/1000 animals)

	FALL												WINTER													SPRING													SUMMER												
Age	Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	80	80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	59	59	59	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	101	101	101	101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	75	75	75	75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	124	124	124	124	124	-	-	-	-	-	-	-	-	-	-	-	-	-	-	94	94	94	94	94	-	-	-	-	-	-	-	-	-	-	-	-	-	115	115	115	-	-	-	-
9	-	-	-	-	-	-	-	-	149	149	149	142	137	119	-	-	-	-	-	-	-	-	-	-	-	-	-	115	115	115	115	115	115	-	-	-	-	-	-	-	-	-	-	-	140	140	140	140	140	-	-	-
10	-	-	-	-	-	-	-	-	177	177	169	164	158	142	142	142	-	-	-	-	-	-	142	142	142	142	138	138	138	138	131	131	131	138	-	-	-	-	-	-	-	-	-	167	167	167	160	160	167	167	167	-
11	207	207	207	207	207	207	207	207	207	207	199	188	176	168	168	169	168	168	168	168	168	168	166	168	168	168	163	163	163	158	151	151	156	156	163	-	-	-	-	196	196	196	196	196	196	196	198	192	188	198	198	196
12	230	239	239	239	239	239	239	239	239	239	224	214	195	187	187	187	195	195	195	195	195	195	195	187	187	187	182	182	182	176	176	172	172	176	182	182	190	-	-	227	227	227	227	227	218	218	212	202	207	218	218	227
13	256	256	256	256	256	256	258	258	258	256	256	241	214	205	200	205	210	210	210	210	210	210	210	210	210	205	204	204	204	199	195	190	190	195	199	199	199	219	219	244	244	244	244	244	244	244	238	229	229	233	244	250
14	270	270	270	274	274	274	274	274	270	270	270	270	223	217	217	217	221	221	221	221	221	221	221	221	221	217	215	215	215	215	211	207	207	207	211	211	211	215	240	257	257	257	257	257	257	257	257	244	248	248	248	266
15	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a

Converged in 7 iterations

Case B: Random Price ($/kg)

	FALL												WINTER													SPRING													SUMMER												
Age	Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.2	5.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	6.7	6.7	6.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.7	5.7	5.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	7.2	7.0	6.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.2	6.0	6.2	6.2	-	-	-	-	-	-	-	-	-	-	-	-	-	6.8	6.8	-	-	-	-
10	-	-	-	-	-	-	-	-	-	7.8	7.8	7.4	7.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.7	6.7	6.5	6.5	6.5	6.7	-	-	-	-	-	-	-	-	-	-	-	7.3	7.3	7.1	7.3	-	-	-
11	-	-	-	-	-	-	-	-	-	8.3	8.1	7.8	7.5	7.4	7.4	7.4	-	-	-	-	-	-	-	-	7.4	7.4	-	7.2	7.2	7.0	6.9	6.9	6.9	7.0	7.2	-	-	-	-	-	-	-	-	-	7.9	7.9	7.7	7.4	7.7	7.9	7.9	-
12	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.7	8.3	7.7	7.7	7.7	7.7	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.7	7.7	7.7	7.7	7.5	7.4	7.3	7.1	7.3	7.3	7.4	7.5	-	-	-	8.4	8.4	8.4	8.4	8.4	8.4	8.2	8.1	7.8	7.8	8.1	8.2	8.4
13	9.0	9.0	9.2	9.2	9.2	9.2	9.2	9.0	9.0	9.0	9.0	8.7	8.0	8.0	7.9	8.0	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.0	8.0	7.9	7.9	7.8	7.8	7.5	7.5	7.5	7.5	7.7	7.7	7.8	-	-	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.5	8.2	8.2	8.2	8.5	8.7
14	9.0	9.1	9.1	9.2	9.2	9.2	9.2	9.2	9.1	9.1	9.1	9.1	8.1	8.1	8.0	8.0	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.0	8.0	8.0	7.9	7.9	7.8	7.8	7.7	7.7	7.8	7.8	7.9	8.0	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.4	8.4	8.4	8.5	8.8
15	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a

Converged in 8 iterations

Case C: Random Weight (gm/animal)

	FALL												WINTER													SPRING													SUMMER												
Age	Week	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	22.7	22.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.5	20.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22.7	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	24.9	24.2	23.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22.2	21.6	22.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24.9	23.8	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	27.0	26.1	24.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24.6	24.2	23.3	23.7	24.6	-	-	-	-	-	-	-	-	-	-	-	-	-	26.8	25.7	26.1	-	-	-
13	-	-	-	-	-	-	-	-	29.1	29.1	29.1	28.2	24.5	-	-	-	-	-	-	-	-	-	-	-	26.6	26.2	26.6	26.6	26.6	25.9	25.1	24.9	25.5	26.8	-	-	-	-	-	-	-	-	-	29.1	29.1	29.1	28.7	27.4	27.8	28.2	-	-
14	30.4	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.2	30.2	30.2	30.2	a	27.6	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.2	27.4	27.4	27.4	27.4	26.7	28.5	26.4	27.4	27.9	27.9	27.9	27.9	-	30.4	30.4	30.4	30.4	30.2	30.2	30.2	30.2	28.9	29.1	29.3	29.8	-
15	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a

Converged in 6 iterations

a—The crop will be sold regardless of the current revenue, price, or weight

Table 4. Cutoff revenue, price, and weight for week 13.

	Case A: Random Revenue			Case B: Random Price			Case C: Random Weight		
Age (x)	Ordinal Scale	Probability to Sell	Cutoff Revenue ($ per 1000 animals)	Ordinal Scale	Probability to Sell	Cutoff Price ($/kg)	Ordinal Scale	Probability to Sell	Cutoff Weight (g/animal)
1–6	20	0.00	keep	20	0.00	keep	20	0.00	keep
7	19	0.05	101	20	0.00	keep	20	0.00	keep
8	19	0.05	124	19	0.05	6.70	20	0.00	keep
9	17	0.15	137	17	0.15	6.90	20	0.00	keep
10	15	0.25	156	14	0.30	7.09	19	0.05	22.73
11	13	0.35	176	12	0.40	7.45	14	0.30	23.55
12	10	0.50	195	9	0.55	7.71	5	0.75	24.04
13	7	0.65	214	6	0.70	7.95	1	0.95	24.51
14	3	0.85	223	3	0.85	8.08	0	1.00	sell
15	0	1.00	sell	0	1.00	sell	0	1.00	sell

show even earlier selling ages, as it would have even higher variation. In general, planned sales are higher in the fall, with the peak at the end of the fall to take full advantage of favorable prices at Christmas. On the other hand, the recommended optimal policy is to postpone harvesting during the last weeks of spring in order to use the favorable growth conditions during the summer.

Note that if the 13th week could be considered to be prevalent over the rest of the year, i.e., the homogeneous model will apply, one could proceed to calculate the conditional expected net profit per week, π, as well as the expected length of the production cycles (Appendix A). Since we witness seasonal variations both in prices and in weights, however, there are different policies over the various weeks. Thus, even though the optimal policy patterns for the 52 weeks of the year can be calculated in advance, the long-run steady-state probabilities and the resulting expected net profits cannot be calculated in a straightforward way as in the homogeneous case—they depend on the vector of initial stocking dates.[10] Thus, the optimal solution supplies the producer with *a priori*, normative guidelines, but the actual realized policies may take numerous alternative trajectories. This was one of the factors that motivated us to trace the behavior of the hypothetical shrimp farm during a specific year in the next section.

Simulation of Optimal Policies Using 1985–1986 Prices

In this section, the invariant optimal policies derived above for the random price case are used to simulate the optimal harvesting schedule based on the actual 1985–1986 shrimp prices reported in the National Marine Fisheries Service Market News Reports. Table 5 shows the sequence of optimal actions assuming the starting date is the first week of fall. For example, at the beginning of week 12 in the fall, the age of the shrimps is 11 weeks and their average weight 22.94 gm. Table 2 shows an ordinal cutoff value of 16, which refers to a cutoff price of $7.84/kg (Table 3). Comparing this number with the actual shrimp price ($7.83/kg) during the same period in the year, the decision is to keep the crop, since it is less than the cutoff price. This "tracing" process is continued until the current market price is greater than the cutoff price. In that case, a sell decision is

[10] The Markov chain is not a complete ergodic one, but has periodic cycles.

Table 5. Simulation of optimal policies for the case of random price.

Season	Beginning of Week	Age of Shrimp From Stocking (wks)	Average Weight (gm)	Cutoff Price Ordinal Scale	Cutoff Price $/kg	Current Price ($/kg)	Decision
Fall	1						stock
	11	10	20.81	19	7.78	7.63	keep
	12	11	22.94	16	7.84	7.83	keep
	13	12	25.06	9	7.71	8.29	sell
Winter	14						rest
	15						stock
	26	11	20.63	19	7.44	6.20	keep
Spring	27	12	22.64	19	7.73	6.58	keep
	28	13	24.64	17	7.88	8.54	sell
	29						rest
	30						stock
Summer	42	12	25.06	19	8.41	8.07	keep
	43	13	27.14	17	8.58	8.07	keep
	44	14	29.18	13	8.66	8.93	sell
	45						rest
	46						stock
Fall	6	12	25.06	19	8.85	8.73	keep
(next year)	7	13	27.14	18	9.17	8.65	keep
	8	14	29.18	14	9.19	9.31	sell

recommended and the pond will be rested two weeks for cleaning. A new stock will then be introduced and the keep-sell decision will be determined as discussed above for another cycle. This tracing is done for one full year as shown in Table 5. The tracing produces 3.57 crops (in a year) with an average harvesting weight of 27.02 grams. The annual net return is estimated to be $322,719 for the hypothetical farm with 24 0.2-ha round ponds. Similar tracings are also performed using starting dates at the first week of winter, spring, and summer; Table 6 shows the results.

The operation that has the first stocking starting at the first week of spring yields the highest net profits, $357,453 per year for the 24-pond farm. It has, on average, the highest marketing age (and weight) and therefore receives the highest price. Note that the operation depends on the performance during all four seasons, and it seems that starting in the spring allows for the best appropriate policies. Such a solution, however, does not take into account the labor constraints. If all ponds are started at the same date in spring, there is a peak load problem in allocating the labor needed for harvesting.

On the other extreme, if harvests are spaced equally, at age 11 weeks (four crops per pond) and thus having 96 harvests per year, which is approximately two harvests per week, they will result in a loss of $82,464 ("Fixed Scheduling," Table 6). A hybrid policy that will start in the spring and use fixed scheduling at marketing age of 13 weeks would yield a profit of $100,008.

Economics of Controlled Environment

This conceptual framework can be

helpful, also, in answering an important question often asked by the farmer: How much should I invest in a new technology? As an example, the researchers at Oceanic Institute are interested in the possibility of creating a controlled environment of a constant high temperature of 28°C. To address this possibility, the tracing procedure used in obtaining the results in Table 6 was rerun assuming summer conditions (≥ 26°C) during the whole year. The results, shown in Table 7, indicate an increase in annual net returns of approximately $100,000 in comparison with the operation of the hypothetical farm under the existing environmental constraints. This provides the upper limit of the annualized investment cost.

SUMMARY AND CONCLUSIONS

A dynamic decision model has been developed to determine the optimal stocking and harvesting strategies (policies) of a shrimp-producing pond. The model captures both the dynamics of the decision process and the risk involved. Risk is represented by randomness in market prices and growth of shrimps.

The model provides a set of simple optimal policies for each calendar week of a year and for each given age of the growing shrimps. The policies are expressed as a set of cutoff revenues when both price and weight are considered random, and as cutoff price or cutoff weight when either price or weight is considered random.

Table 6. Summary of tracing results.

Start Stocking In	Average Harvest Age From Stocking (wks)	Average Harvest Weight (gm)	Cycle Per Year	Market Price ($/kg)	Net Returns ($)
Case B: Random Price					
Spring	14.00	27.89	3.31	8.84	357,453
Summer	12.50	25.42	3.79	8.43	279,429
Fall	13.25	27.02	3.57	8.78	322,719
Winter	13.50	26.91	3.46	8.69	303,806
Fixed Scheduling					
Spring	13.00	25.89	3.54	7.81	100,008
Any Season	11.00	21.79	4.00	6.84	–82,464

Table 7. Summary of tracing results for controlled environment (summer).

Start Stocking In	Average Harvest Age From Stocking (wks)	Average Harvest Weight (gm)	Cycles Per Year	Market Price ($/kg)	Net Returns ($)
Spring	14.00	29.18	3.36	9.17	450,879
Summer	13.50	28.15	3.50	9.28	491,672
Fall	13.50	28.15	3.50	8.93	390,147
Winter	13.75	28.67	3.43	9.26	425,630

This model was applied to analyze the economics of the round-pond technology recently developed at the Oceanic Institute in Hawaii. By using the management tool developed here, which provides efficient scheduling policies of production and marketing of a single pond, it has been shown that an operation can increase its profitability about threefold compared with a fixed scheduling scheme.

In the operation of the shrimp farm, experimental trials were used. As a result of these experiments, commercial shrimp farms are starting to apply the round-pond technology. The importance of using the introduced model is further increased.

The model is well equipped to analyze the economics of alternative production strategies. As presented in this paper, investment in controlled environment is worthwhile if the annual cost is less than $100,000.

The strength of the present model is that it provides a simple and practical managerial tool and yet it captures both the dynamics and uncertainties of the shrimp production process.

It should be noted, however, that the optimal decision rules are derived for a single shrimp pond and no resource constraint, such as labor shortage, exists. In this respect, the present model only solved an important subproblem of a large problem of operating a shrimp farm. Otherwise, this model can very well be adapted to other growing crops, as long as they are homogeneous and production is of an all-in/all-out nature.

REFERENCES

Allen, P.G., L. W. Botsford, A. M. Schuur, and W.E. Johnston. 1984. Bioeconomics of aquaculture. Amsterdam, The Netherlands: Elsevier Applied Science Publishers.

Botsford, L. W., H. E. Rauch, and R. A. Schleser. 1974. Optimal temperature control of a bolster plant. IEEE Trans. Automatic Control AC-19:541–543.

Botsford, L. W., H. E. Rauch, A. M. Schuur, and R. A. Schleser. 1975. An economically optimum aquaculture facility. Proc. World Maric. Soc. 6: 407–420.

Clark, C.W., and G. R. Munro. 1975. The economics of fishing and modern capital theory: A simplified approach. J. Environ. Econ. Mgmt. 2:92–106.

Clark, C.W. (1976). Mathematical bioeconomics. New York: Wiley-Interscience, John Wiley & Sons.

Emanuel, W.R., and R. J. Mulholland. 1975. Energy based dynamic model for Lago Pond, Ga. IEEE Trans. Automatic Control, AC-20:98–101.

Gates, J. M., C. R. MacDonald, and B. J. Pollard. 1980a. Salmon culture in water reuse system: An economic analysis. Univ. Rhode Island Marine Technical Report 78. 52 pp.

_______. 1980b. A dynamic linear programming model of fish culture in water reuse systems. Rhode Island Agric. Exp. Sta. Contrib. No. 1892. 20 pp.

Hochman, E. 1970. An optimal stopping problem of a growing inventory. Mgmt. Sci. 19(11):1289–1291.

_______. 1979. Producing deterministic and stochastic formulations: The case of growing inventories. *In* Rausser, G. D., and E. Hochman, Dynamic agricultural systems: Economic prediction and control. New York: Elsevier Science Publishing Co., Inc.

Hochman, E., and I. M. Lee. 1972. Optimal decision in the broiler producing firm: A problem of growing inventories. Giannini Foundation Monograph 29, Univ. California Div. Agric. Sci., Berkeley.

Howard, R. A. 1960. Dynamic programming and Markov process. MIT Press, Cambridge, MA.

Johnson, F.C. 1974. Hatch—A model for fish hatchery analysis. National Bureau of Standards Report NSBIR 74-521. Washington, D.C. 51 pp.

Karp, L., A. Sadeh, and W. L. Griffin. 1986. Cycles in agricultural production: The case of aquaculture. Amer. J. Agric. Econ. 68:553–561.

Kitchell, D. R., D. J. Stewart, and D. Weininger. 1977. Applications of a bioenergetics model to yellow perch (*Perca flavesceus*) and walleye (*Stizostedion vetreum* v). J. Fish. Res. Board Canada 34:1922–1935.

Leung, P. S., and Y. C. Shang. 1989. Modeling prawn production management system: A dynamic Markov decision approach. Agric. Syst. 29(1): 5–20.

Leung, P. S. 1986. Applications of systems modeling in aquaculture. Aquacult. Engrg. 5(2–4):171–182.

Leung, P. S., L. A. Fallon, and Y. C. Shang. 1984. Bioeconomic modeling of freshwater prawn production: The Hawaiian experience. J. Int. Soc. Ecol. Modeling 6(1-2):25–37.

Levhari, D., R. Michener, and L. J. Mirman. 1981. Dynamic programming models of fishing: Competition. The Amer. Econ. Rev. 74(4):649–661.

Lipschultz, F., and G. E. Krantz. 1980. Production optimization and economic analysis of an oyster (*Crassostrea virginica*) hatchery on the Chesapeake Bay, Maryland USA. Proc. World Maric. Soc. 11:580–591.

National Marine Fisheries Service. 1985–1986. Fishery market news reports, New Orleans, LA. National Oceanic Atmospheric Administration, U. S. Department of Commerce.

Oceanic Institute. 1988. Newsline. July, p. 2.

Orth, J. 1980. Applications of operations research and systems science in aquaculture. Fisheries Bull. Amer. Fisheries Soc. 5(1):7–9.

Rausser, G.C., and E. Hochman. 1979. Dynamic agricultural systems: Economic prediction and control. New York: Elsevier Science Publishing Co., Inc.

Shang, Y.C. 1983. The economics of marine shrimp farming: A survey. Proc. 1st Intl. Conf. on Warm Water Aquaculture—Crustacea. Brigham Young Univ., Hawaii. Pp. 7–18.

Shurr, A. M., P.G. Allen, and L. W. Botsford. 1974. An analysis of three facilities for the commercial production of *Homarus americanus*. Winter Mtg., Amer. Soc. Agric. Engr., Paper No. 74-5517. 19 pp.

Sparre, P. 1976. A Markovian decision process applied to optimization of production planning in fish farming. Meddeklser fra Danmarks Fiskeri-Og Havundersogelser N. S. 7:111–197.

Talpza, H., and Y. Tsur. 1982. Optimizing aquaculture management of a single-species fish population. Agric. Sys. 9: 127–142.

The Aquaculture Digest's. 1988.Shrimp farming in the United States. Feb.

Uwate, R.K. 1984. A review of aquaculture activities in the Pacific Islands region. Pacific Islands Development Program, East-West Center, Honolulu, HI.

Wyban, J.A., J.N. Sweeney, and R.A. Kanna. 1988. Shrimp yields and economic potential of intensive round pond systems. Unpublished manuscript.

APPENDIX A

The Homogeneous (Calendar-Independent) Case

In the homogeneous case the calendar week, t, is omitted from Equation 1 to yield:

$$R_n(x) = W_n(x)P_n(x) \tag{A1}$$

for $x = x_0, x_0+1,\ldots,X$, where $W_n(x)$ and $P_n(x)$ are the corresponding current weight and price. Note that the calendar date, t, is not in the equation as it will not affect the current value in the homogeneous case. Also, the revenue distribution, $h(R)$, that may have either random prices or random weights or both, will remain the same for all weeks of the year.

In this case the dichotomous decision, sell or keep for each week, can be depicted by the following set of optimal decision rules for each corresponding age group:

$$V(x) = \max\left\{R(x) - C(x),\ \int_{R^*(x+1)}^{\infty} V(x+1)h(R)dR - \pi\right\} \tag{A2}$$

for $x = x_0, x_0+1, \ldots, X-2, X-1$

where $V(X) = \int_0^{\infty} R(X)h(R)dR - C(X)$ corresponds to the age X of termination at any current revenue; $R^*(x)$ is the cutoff revenue at age x; $C(x)$ is the cost of keeping the crop until age x; and p is the expected returns of one week as the system operates for a long period (see discussion of Equation A3.3 below). The meaning of this set of equations (A2) is best explained by their first order conditions. Thus, the solution of the set of Equations A2, which contains the optimal policy of harvesting the given shrimp pond, will define a unique vector of cutoff revenues, $R^*(x_0), R^*(x_0+1),\ldots, R^*(X-1)$ such that:

$$\begin{aligned} R^*(x) - C(x) &= M[R^*(x+1),\,(x+1)] - \pi \\ &\quad + H_{x+1}\left\{M[R^*(x+2),\,(x+2)] - \pi\right\} + \ldots \\ &\quad + H_{x+1}\,H_{x+2}\,\ldots\,H_{X-1}\left\{M[R^*(X) = 0,\,X] - \pi\right\} \end{aligned} \tag{A3}$$

where

$$M[R^*(x), x] = \int_{R^*(x)}^{\infty} R(x)h(R)dR - C(x) \tag{A3.1}$$

given

$$H_x = \int_0^{R^*(x)} h(R)dR$$

for $x = x_0, x_0+1, \ldots, X-2, X-1,$

$$M[R^*(X) = 0, X] - \pi = V(X) - \pi \tag{A3.2}$$

given $H_X = 0$, and

$$\pi = \frac{M[R^*(x_0), x_0] + H_{x_0} M[R^*(x_0+1), x_0+1] + \ldots + H_{x_0} H_{x_0+1} \ldots H_{X-1} M[R^*(X) = 0, X]}{(1-H_{x_0}) + 2(1-H_{x_0+1}) H_{x_0} + 3(1-H_{x_0+2}) H_{x_0+1} H_{x_0} + \ldots + (X-x_0) H_{X-1} H_{X-2} \ldots H_{x_0+1} H_{x_0}} \tag{A3.3}$$

Equation A3 states that after deducting $C(x)$, the cutoff revenue at a given age, $R^*(x)$, is determined such that it equals the conditional net expected returns of the shrimp crop edited from herefrom age x to the termination age, X, of the specific shrimp pond. Thus, for example, the last term on the RHS consists of the product of the probability of a crop at age x to reach the age of $(X - 1)$ times the net returns at the terminal age X. The term "net" (for the RHS of Equation 6) is used, since the opportunity costs of deferring the harvest for one week, π, are deducted from the conditional expected return of each of the following weeks of operation.

In A3.1, the conditional expected return at any given age, x, is defined over the domain of "Sell," while H_x is the probability to wait for harvest at the age, x, for another week. Condition A3.2 is a transversality condition stating that at the age X the shrimp producer will harvest and sell at any current revenue, i.e., $H_X = R^*(X) = 0$.

In A3.3 the opportunity costs of deferring the harvest of a crop by one week are measured, where the numerator of π measures the expected return per crop up to age X and the denominator measures the expected life of the crop. Thus, the shrimp producer that follows the optimal harvesting policy will harvest the crop if the immediate realized net returns are greater than the expected net return over the remaining period (from age x to X), and he will keep the stock of shrimp if immediate returns are smaller than expected returns. The recursive nature of the decision process means that, starting from the termination age X, the shrimp producer is concerned at each stage only with ages greater than the age under consideration. The reason is intuitively obvious because at age x the decision to keep would have already been made for earlier ages.

As pointed out in the general case (Equation 1), the distribution of the revenue may depend on a one-variate distribution of the price or the weight, or on a bivariate distribution that depends on both. The same is true in the homogeneous case, e.g., Equation A1 may be rewritten as:

$$R_n(x) = W(x)P_n(x) \tag{A1.1}$$

or

$$R_n(x) = W_n(x)P(x) \tag{A1.2}$$

Thus, in the case of A1.1, only prices are random and the growth relations are deterministic. In this case the optimal solution will define a unique vector of cutoff prices, for each age a $P^*(x)$, such that if the current price, $P_n(x)$, is lower than the cutoff price, $P^*(x)$, keep the crop for another week; otherwise harvest the crop and start a new one.

In the case of Equation A1.2 where the weight is random and prices are given and fixed for each age, the optimal policy will consist of a vector of cutoff weights, $W^*(x)$, that replace the vector of cutoff prices $P^*(x)$. Thus, if the average weight of the shrimp in the pond, $W_n(x)$ is larger than or equal to $W^*(x)$, harvest and start a new crop, otherwise wait for another week and check to see if $W_n(x+1) \geq$ or $<$ $W^*(x+1)$, and so on.

The general case of the homogeneous model is when allowing both weight and price to be stochastic. Thus, if the reasonable assumption is made that the current revenue R_n is depicted from a revenue distribution i.e. assuming that the weights and prices are independently distributed, it can be shown that the vector of cutoff revenues $R^*(x)$ has the same properties as those of the previous vectors $P^*(x)$ and $W^*(x)$.[11]

Note that the decision process can be described as a Markovian process; defined in the homogeneous case, it is an ergodic Markov chain. Each strategy chosen by the shrimp producer determines simultaneously the cutoff revenue $R^*(x)$, the transition probabilities H_x, and the immediate reward. Moreover, because H_x is connected in a one-to-one correspondence with the cutoff revenue, at each age one and only one decision variable determines the strategy taken. Note that H_x is without the time subscript, t, and so is the transition probability matrix, T.

T is a complete ergodic Markov chain, with steady state probabilities q_x, to be at a given age group such that:

$$\pi = \sum_{x=x_0}^{X} M[R^*(x), x] q_x \tag{A4}$$

The General Model-Interseasonal Effects

The solution for the general model described in Equation 1 consists of 52 vectors of cutoff revenues $R^*(x,t)$. The Markov chains are no longer completely ergodic, and hence the steady-state probabilities depend on the initial state. In this case randomness of prices and weights may also be introduced separately and simultaneously.

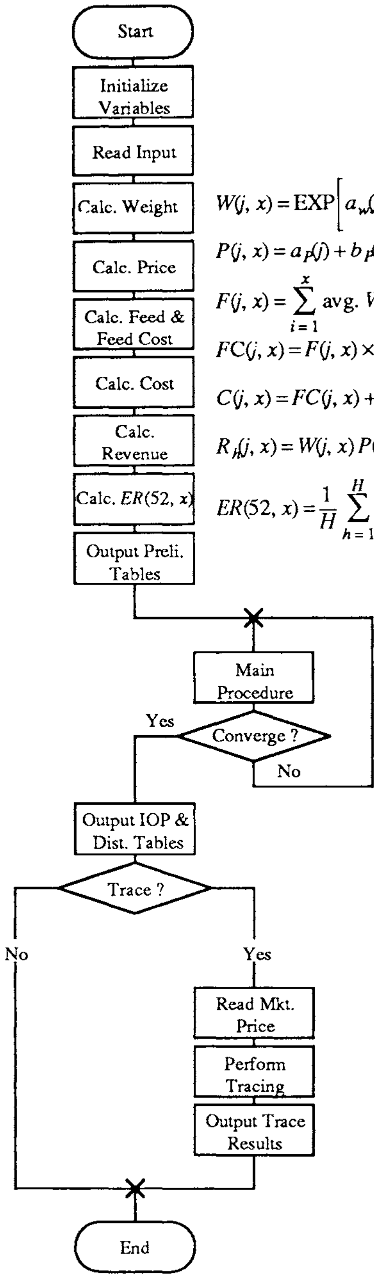
The optimal policies, differing from the homogeneous case, will take into account the new dilemma the shrimp producer faces, i.e., to sell the crop and enter a new season with a young stock or to keep the old one and enter the new season with an old stock. Each of the weekly vectors can be interpreted as in the homogeneous case. The property of the negative relations between the cutoff revenues and the age of stock still hold. Moreover, as an approximation, one may derive the steady-state probability and the corresponding π for each of the weekly vectors assuming the conditions of this week will hold for the rest of the period.

---

[11] A formal proof of the random price case can be found in Hochman (1972). The same rationale can be extended to the random weight and the more general random revenue cases.

APPENDIX B

Flow Chart of Optimal Shrimp Harvest Scheduling Program



$$W(j, x) = \mathrm{EXP}\left[a_w(j) + b_w(j)\frac{1}{age(x)}\right] \qquad \text{for } j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$$

$$P(j, x) = a_p(j) + b_p(j)W(j, x) \qquad \text{for } j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$$

$$F(j, x) = \sum_{i=1}^{x} \text{avg. } W(j, i) \times \text{Feed rate} \times \text{day} \qquad \text{for } j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$$

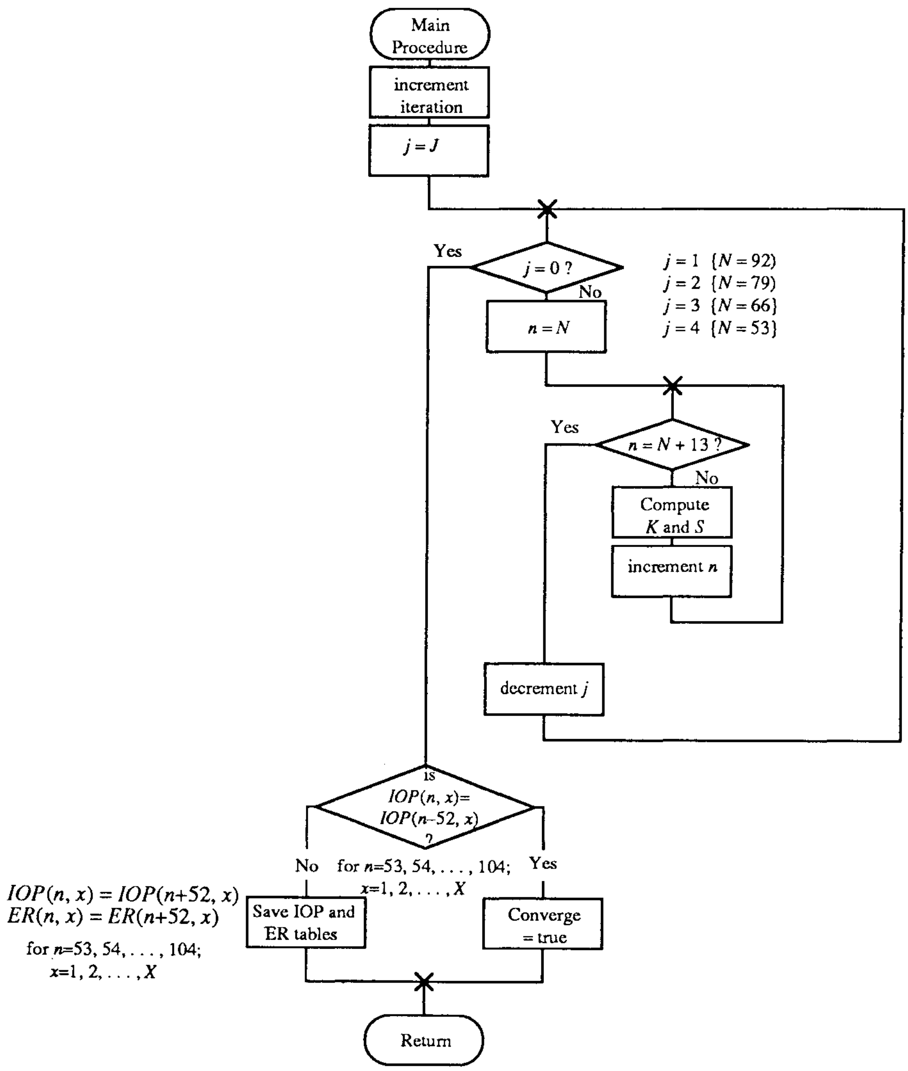
$$FC(j, x) = F(j, x) \times \text{price of feed} \qquad \text{for } j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$$

$$C(j, x) = FC(j, x) + \text{fixed cost} + (\text{variable cost} \times x) \qquad \text{for } j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$$

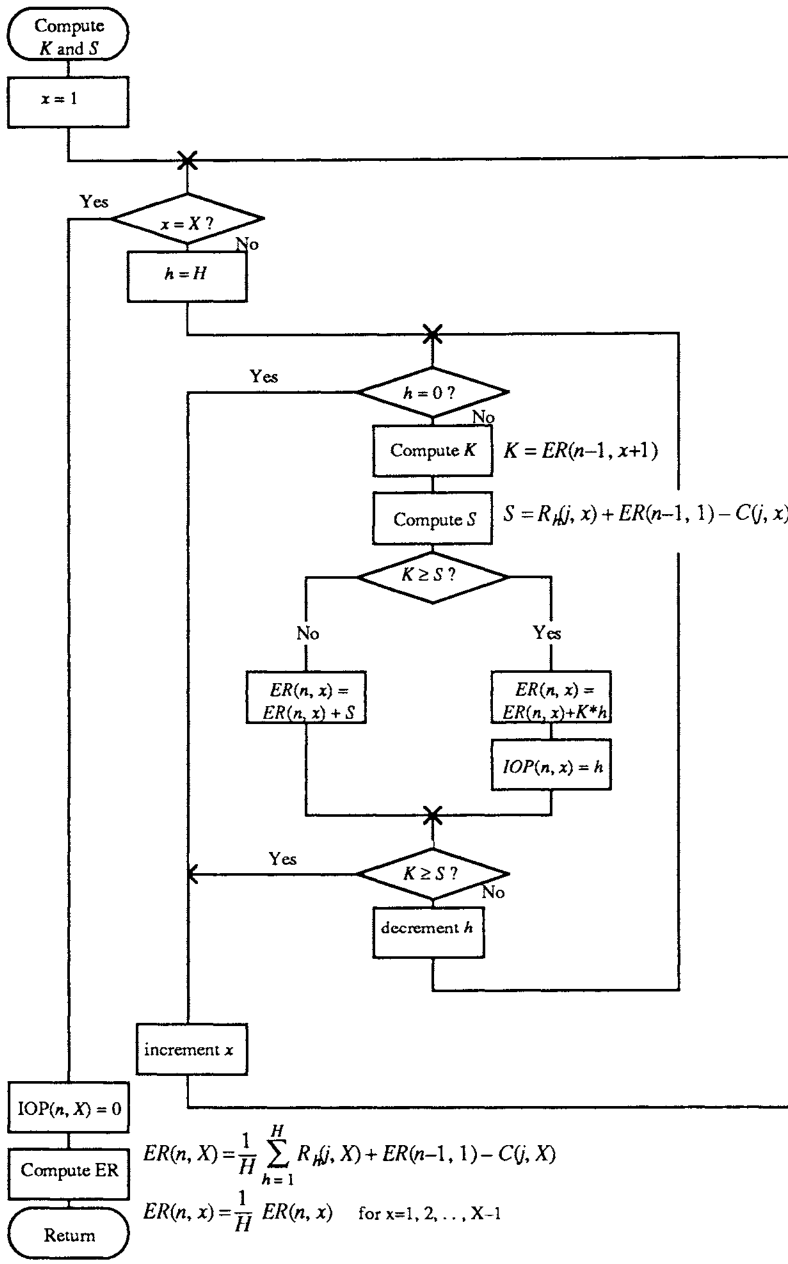
$$R_h(j, x) = W(j, x)\,P(j, x) + \left[W(j, x)\,Z_p(h, j)\,\sigma_p(j)\right]$$

Case b: Random price
for $h = 1, 2, \ldots, H;\ j = 1, 2, \ldots, J;\ x = 1, 2, \ldots, X$

$$ER(52, x) = \frac{1}{H}\sum_{h=1}^{H} R_h(J, x) \qquad \text{for } x = 1, 2, \ldots, X$$



Main Procedure
increment iteration
j = J
j = 0 ?
Yes
No
j = 1 {N = 92}
j = 2 {N = 79}
j = 3 {N = 66}
j = 4 {N = 53}
n = N
n = N + 13 ?
Yes
No
Compute K and S
increment n
decrement j
is IOP(n, x)= IOP(n–52, x) ?
No
for n=53, 54, . . . , 104; x=1, 2, . . . , X
Yes
IOP(n, x) = IOP(n+52, x)
ER(n, x) = ER(n+52, x)
for n=53, 54, . . . , 104; x=1, 2, . . . , X
Save IOP and ER tables
Converge = true
Return


Compute K and S
x = 1
x = X ?
Yes
No
h = H
h = 0 ?
Yes
No
Compute K
K = ER(n–1, x+1)
Compute S
S = R_h(j, x) + ER(n–1, 1) – C(j, x)
K ≥ S ?
No
Yes
ER(n, x) = ER(n, x) + S
ER(n, x) = ER(n, x)+K*h
IOP(n, x) = h
K ≥ S ?
Yes
No
decrement h
increment x
IOP(n, X) = 0
Compute ER
ER(n, X) = 1/H Σ_{h=1}^{H} R_h(j, X) + ER(n–1, 1) – C(j, X)
ER(n, x) = 1/H ER(n, x)   for x=1, 2, . . . , X-1
Return

Description of Variables

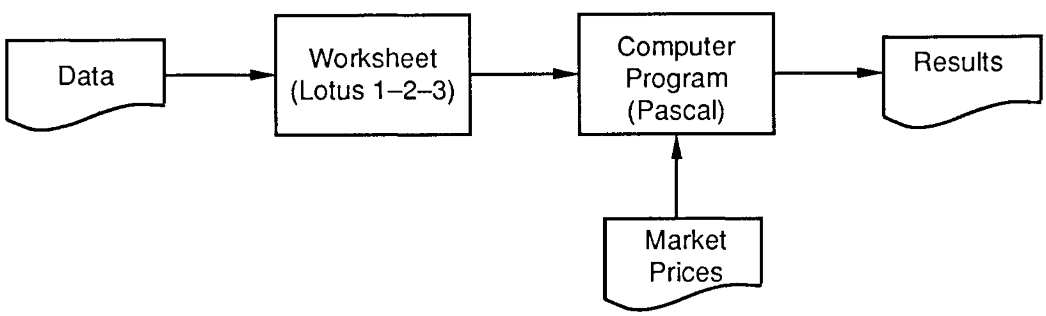
Variable	Description
age	age of shrimp in days
a_P	price-size intercept
a_w	growth intercept
b_P	price-size coefficient
b_w	growth coefficient
C	total cost
ER	expected revenue
F	feed
FC	accumulated feed cost
H	maximum number of distribution interval
h	distribution interval counter
IOP	invariant optimal policy
J	maximum number of season
j	season counter
N	last week of a season
n	week counter
P	price of shrimp
R	revenue
s_P	standard deviation of price
W	weight of shrimp
X	terminal age
x	age counter
Z_P	standard normal variant of price distribution

APPENDIX C

Optimal Shrimp Harvest Scheduling System and Input/Output Sample Printouts

Optimal Shrimp Harvest Scheduling System

The system consists of two separate components, an input worksheet and a computer program. It requires an MS–DOS based computer and Lotus 1–2–3 program Release 2.x to operate. The menu-driven input worksheet is written in Lotus 1–2–3 macros language to facilitate the inputs. The computer program for the calculation of the Invariant Optimal Policies is written in Pascal. The following diagram depicts the input and output flows of the system:



Sample Input Worksheet Screens (Lotus 1–2–3)

```
                          GENERAL INPUTS

                                                          Selection
Weight option
 A = Actual weight, F = Functional form                        F

Type of Growth
 L = Linear Form, G = loG-reciprocal form                      G

Price option
 F = Fixed price, D = price Distribution                       D

                      End of GENERAL INPUTS
```

GENERAL ANIMAL INPUTS

	Value
Maximum allowed growout period (weeks, max = 30)	15
Stocking age (days)	65
Product type (H = Heads on, T = Tails)	T

End of GENERAL ANIMAL INPUTS

ANIMAL INPUTS
(Functional form)

Growth equation intercepts

Fall	4.92
Winter	4.92
Spring	4.92
Summer	4.92

Growth equation coefficients

Fall	-241.24
Winter	-255.62
Spring	-255.62
Summer	-241.24

PgDn to continue

ANIMAL INPUTS (continue)

Number of intervals of distribution of weight 20

Enter standard normal variates for weight distribution

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
-1.96	-1.438	-1.15	-0.941	-0.76	-0.6	-0.45	-0.32	-0.191

10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
-0.061	0.061	0.191	0.32	0.45	0.6	0.76	0.941	1.15

19	**20**
1.438	1.96

Standard deviation of weight 1.34

End of ANIMAL INPUTS

FEED INPUTS

	Value
Feed cost per gram	0.00125
Feeding rates (% body weight of shrimp)	
Shrimp weight in grams	
< 1	0.12
1-4	0.1075
5-9	0.093
10-14	0.061
>15	0.04

End of FEED INPUTS

SHRIMP MARKET PRICE INPUTS
FALL

Number of intervals of distribution of price 20

Enter standard normal variates for price distribution

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
-1.96	-1.438	-1.15	-0.941	-0.76	-0.6	-0.45	-0.32	-0.191

10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
-0.061	0.061	0.191	0.32	0.45	0.6	0.76	0.941	1.15

19	**20**
1.438	1.96

Standard deviation of price 0.3166

PgDn to continue

PRICE INPUTS (continue)

Price-size equation intercepts

Fall	0.71
Winter	0.574
Spring	0.477
Summer	0.51

Price-size equation coefficients

Fall	0.11397
Winter	0.11397
Spring	0.11397
Summer	0.11397

End of PRICE INPUTS

SHRIMP MARKET PRICE INPUT

Price of shrimp (pound) (fixed price $/lb)	4.00

End of Fixed PRICE INPUT

COST INPUTS

	Value
Fixed cost (per animal)	0.015
Variable cost (per animal)	
Energy	0.00190
Labor	0.00069

Total	0.00259
	=======

End of COST INPUTS

Sample Input Data File (For the Computer Program)

15 65 *growout period (week), stocking age (day)*
0.015 0.00259 *fixed cost ($/animal), variable cost ($/animal)*
4.92 4.92 4.92 4.92 *growth intercept (Fall, Winter, Spring, Summer)*
-241.24 -255.62 -255.62 -241.24 *growth coefficient (Fall, Winter, Spring, Summer)*
0.00125 0.12 0.1075 0.093 0.061 0.04 *feed cost ($/gm), feed rate (% of body weight)*
0.71 0.574 0.477 0.51 *price-size intercept (Fall, Winter, Spring, Summer)*
0.11397 0.11397 0.11397 0.11397 *price-size coefficient (Fall, Winter, Spring, Summer)*
20 *number of equal intervals of a assumed normal distribution of price*
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96 *twenty standard normal variates for price distribution (Fall, Winter, Spring, Summer)*
0.3166 0.3166 0.3166 0.3166 *standard deviation of price (Fall, Winter, Spring, Summer)*
20 *number of equal intervals of an assumed normal distribution of weight*
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96
-1.96 -1.438 -1.15 -0.941 -0.76 -0.6 -0.45 -0.32
-0.191 -0.061 0.061 0.191 0.32 0.45 0.6 0.76
0.941 1.15 1.438 1.96 *twenty standard normal variates for weight distribution (Fall, Winter, Spring, Summer)*
1.34 1.34 1.34 1.34 *standard deviation of weight (Fall, Winter, Spring, Summer)*
4 *price of shrimp ($/lb)*
F *weight option: F = functional form, A = actual weight*
G *type of growth function: G = log-reciprocal form, L = linear form*
D *price option: F = fixed price, D = price distribution*
T *product type: T = tail only, H = head and tail*
2 100 0.2 0.8 24
number of resting week, stocking density (animal/m^2), pond area (ha), survival rate, number of pond

Note: Explanations are in italics.

Sample Output (From the Computer Program)

Summary of the Input Data

```
                              -Input Data-
Input file name: WASRP.PRN
Stocking age (day): 65
Grow out period (week): 15
Weeks between harvesting and stocking:  2
Animal stocked per sq. m:  100
Pond area in hectare: 0.200
Number of ponds:  24
Survival rate: 0.800
Fixed cost:   0.0150
Variable cost:   0.0026
Feed cost ($/gram):   0.0012
Feeding Rate:    <1gm    1-4gm   5-9gm  10-14gm  >15gm
                 0.12    0.11    0.09    0.06    0.04

Weight option: Functional form.
Growth function: Log/recip. form.
Price option: Price distribution.
Product type: Without head.

                             Fall        Winter       Spring       Summer
Growth Intercept:         4.92000      4.92000      4.92000      4.92000
Growth Coefficient:    -241.24000   -255.62000   -255.62000   -241.24000
Price-size Intercept:     0.71000      0.57400      0.47700      0.51000
Price-size Coefficient:   0.11397      0.11397      0.11397      0.11397
```

Weight Table and Total Feed Table

-Output Data-

		-Weight (gm)-				-Cum. Total Feed (gm/animal)-			
Week	Age(Day)	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer
1	65	3.35	2.68	2.68	3.35	0.00	0.00	0.00	0.00
2	72	4.80	3.93	3.93	4.80	3.07	2.49	2.49	3.07
3	79	6.46	5.39	5.39	6.46	6.74	6.00	6.00	6.74
4	86	8.29	7.01	7.01	8.29	11.54	10.03	10.03	11.54
5	93	10.24	8.77	8.77	10.24	17.57	15.17	15.17	17.57
6	100	12.28	10.63	10.63	12.28	22.37	21.49	21.49	22.37
7	107	14.37	12.57	12.57	14.37	28.06	26.44	26.44	28.06
8	114	16.51	14.55	14.55	16.51	32.39	32.23	32.23	32.39
9	121	18.66	16.57	16.57	18.66	37.31	36.59	36.59	37.31
10	128	20.81	18.60	18.60	20.81	42.84	41.51	41.51	42.84
11	135	22.94	20.63	20.63	22.94	48.96	47.00	47.00	48.96
12	142	25.06	22.64	22.64	25.06	55.68	53.06	53.06	55.68
13	149	27.14	24.64	24.64	27.14	62.99	59.68	59.68	62.99
14	156	29.18	26.61	26.61	29.18	70.87	66.85	66.85	70.87
15	163	31.19	28.55	28.55	31.19	79.32	74.58	74.58	79.32

Feed Cost Table and Total Cost Table

		-Cum. Feed Cost ($/animal)-				-Cum. Total Cost ($/animal)-			
Week	Age(day)	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer
1	65	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018
2	72	0.004	0.003	0.003	0.004	0.024	0.023	0.023	0.024
3	79	0.008	0.007	0.007	0.008	0.031	0.030	0.030	0.031
4	86	0.014	0.013	0.013	0.014	0.040	0.038	0.038	0.040
5	93	0.022	0.019	0.019	0.022	0.050	0.047	0.047	0.050
6	100	0.028	0.027	0.027	0.028	0.059	0.057	0.057	0.059
7	107	0.035	0.033	0.033	0.035	0.068	0.066	0.066	0.068
8	114	0.040	0.040	0.040	0.040	0.076	0.076	0.076	0.076
9	121	0.047	0.046	0.046	0.047	0.085	0.084	0.084	0.085
10	128	0.054	0.052	0.052	0.054	0.094	0.093	0.093	0.094
11	135	0.061	0.059	0.059	0.061	0.105	0.102	0.102	0.105
12	142	0.070	0.066	0.066	0.070	0.116	0.112	0.112	0.116
13	149	0.079	0.075	0.075	0.079	0.127	0.123	0.123	0.127
14	156	0.089	0.084	0.084	0.089	0.140	0.135	0.135	0.140
15	163	0.099	0.093	0.093	0.099	0.153	0.147	0.147	0.153

Revenue Table

		-Revenue ($/animal)-			
Week	Age(day)	Fall	Winter	Spring	Summer
1	65	0.0054	0.0035	0.0031	0.0044
2	72	0.0089	0.0059	0.0053	0.0075
3	79	0.0137	0.0094	0.0086	0.0118
4	86	0.0201	0.0141	0.0131	0.0177
5	93	0.0282	0.0202	0.0190	0.0252
6	100	0.0380	0.0278	0.0263	0.0344
7	107	0.0495	0.0370	0.0352	0.0453
8	114	0.0627	0.0476	0.0456	0.0579
9	121	0.0776	0.0598	0.0575	0.0721
10	128	0.0940	0.0735	0.0708	0.0879
11	135	0.1119	0.0885	0.0855	0.1052
12	142	0.1310	0.1048	0.1015	0.1237
13	149	0.1514	0.1222	0.1187	0.1434
14	156	0.1727	0.1408	0.1370	0.1642
15	163	0.1951	0.1603	0.1563	0.1859

Invariant Optimal Policy (IOP) Table

Season=Fall Iteration= 8

Age | Week	1	2	3	4	5	6	7	8	9	10	11	12	13
1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	19	19	19
9	-	-	-	-	-	-	-	-	-	-	19	18	17
10	-	-	-	-	-	-	-	-	-	19	19	17	14
11	-	-	-	-	-	-	-	-	-	19	18	16	12
12	19	19	19	19	19	19	19	19	19	19	18	15	9
13	17	17	18	18	18	18	18	17	17	17	17	14	6
14	12	13	13	14	14	14	14	14	13	13	13	13	3
15	0	0	0	0	0	0	0	0	0	0	0	0	0

The IOP table provides values in ordinal scale in order to find the corresponding cutoff revenue, price, and weight. For example, using the above random price IOP table, if the producer enters the first week of the fall season with a crop of age 12 weeks, the cut-off price can be found on the price distribution table (next page) under the 19th column at age 12 weeks.

Price Distribution Table

Price Distribution Table for Fall ($/Kilogram)

Age	Price Index 1	2	3	4	5	6	7	8	9	10
1	1.04	1.40	1.60	1.75	1.87	1.98	2.09	2.18	2.27	2.36
2	1.40	1.76	1.97	2.11	2.24	2.35	2.45	2.54	2.63	2.72
3	1.82	2.18	2.38	2.53	2.65	2.76	2.87	2.96	3.05	3.14
4	2.28	2.64	2.84	2.98	3.11	3.22	3.33	3.42	3.51	3.60
5	2.76	3.13	3.33	3.47	3.60	3.71	3.82	3.91	4.00	4.09
6	3.27	3.64	3.84	3.98	4.11	4.22	4.33	4.42	4.51	4.60
7	3.80	4.16	4.37	4.51	4.64	4.75	4.85	4.94	5.03	5.12
8	4.34	4.70	4.90	5.05	5.17	5.28	5.39	5.48	5.57	5.66
9	4.88	5.24	5.44	5.58	5.71	5.82	5.93	6.02	6.11	6.20
10	5.41	5.78	5.98	6.12	6.25	6.36	6.47	6.56	6.65	6.74
11	5.95	6.31	6.51	6.66	6.79	6.90	7.00	7.09	7.18	7.27
12	6.48	6.84	7.04	7.19	7.32	7.43	7.53	7.62	7.71	7.80
13	7.00	7.36	7.57	7.71	7.84	7.95	8.05	8.14	8.23	8.32
14	7.51	7.88	8.08	8.22	8.35	8.46	8.57	8.66	8.75	8.84
15	8.02	8.38	8.58	8.73	8.85	8.96	9.07	9.16	9.25	9.34

Age	11	12	13	14	15	16	17	18	19	20
1	2.44	2.53	2.62	2.72	2.82	2.93	3.06	3.20	3.40	3.77
2	2.81	2.90	2.99	3.08	3.18	3.30	3.42	3.57	3.77	4.13
3	3.23	3.32	3.41	3.50	3.60	3.71	3.84	3.98	4.18	4.55
4	3.68	3.77	3.86	3.95	4.06	4.17	4.30	4.44	4.64	5.01
5	4.17	4.26	4.35	4.44	4.55	4.66	4.78	4.93	5.13	5.49
6	4.68	4.77	4.86	4.95	5.06	5.17	5.30	5.44	5.64	6.01
7	5.21	5.30	5.39	5.48	5.58	5.70	5.82	5.97	6.17	6.53
8	5.74	5.83	5.92	6.01	6.12	6.23	6.36	6.50	6.70	7.07
9	6.28	6.37	6.46	6.55	6.66	6.77	6.90	7.04	7.24	7.61
10	6.82	6.91	7.00	7.09	7.20	7.31	7.43	7.58	7.78	8.14
11	7.36	7.45	7.54	7.63	7.73	7.84	7.97	8.12	8.32	8.68
12	7.89	7.98	8.07	8.16	8.26	8.37	8.50	8.65	8.85	9.21
13	8.41	8.50	8.59	8.68	8.78	8.90	9.02	9.17	9.37	9.73
14	8.92	9.01	9.10	9.19	9.30	9.41	9.53	9.68	9.88	10.24
15	9.42	9.51	9.60	9.70	9.80	9.91	10.04	10.18	10.38	10.75

The Price Distribution Table provides the cutoff price for every age of shrimp in each season. Using the previous example, the cutoff price is $8.85/kg if the producer enters the first week of the fall season with a crop of age 12 weeks having an average weight of 25.06 gm. (See Weight Table).

Sample Tracing Results

```
                    **  TRACE RESULT  **

           (Market Price File: MKTPRICE.DAT)

STOCK 1 -- Start Stocking in Fall   Week  1
-----------------------------------------------------------------
Current week   : Fall   Week 11
Age of Shrimp  : 10 week          Wt. of shrimp : 20.807 gm
Price Index    : 19              Cost per shrimp : $ 0.094
Cut-off Price  : $ 7.78/kg
Market Price   : $ 7.63/kg
      ------>  KEEP


STOCK 1 -- Start Stocking in Fall   Week  1
-----------------------------------------------------------------
Current week   : Fall   Week 12
Age of Shrimp  : 11 week          Wt. of shrimp : 22.944 gm
Price Index    : 16              Cost per shrimp : $ 0.105
Cut-off Price  : $ 7.84/kg
Market Price   : $ 7.83/kg
      ------>  KEEP


STOCK 1 -- Start Stocking in Fall   Week  1
-----------------------------------------------------------------
Current week   : Fall   Week 13
Age of Shrimp  : 12 week          Wt. of shrimp : 25.056 gm
Price Index    :  9              Cost per shrimp : $ 0.116
Cut-off Price  : $ 7.71/kg
Market Price   : $ 8.29/kg
      ------>  SELL


Revenue per pond                          $  21638.96
Cost per pond                                18508.98
                                           ----------
Net Profit per pond                       $   3129.99
                                           ==========

Net Profit for 24 ponds                   $  75119.66
                                           ==========
```

```
STOCK 2 -- Start Stocking in Winter Week  2
---------------------------------------------------------------
Current week  : Winter Week 13
Age of Shrimp : 11 week              Wt. of shrimp : 20.625 gm
Price Index   : 19                  Cost per shrimp : $ 0.102
Cut-off Price : $ 7.44/kg
Market Price  : $ 6.20/kg
     ------>  KEEP

STOCK 2 -- Start Stocking in Winter Week  2
---------------------------------------------------------------
Current week  : Spring Week  1
Age of Shrimp : 12 week              Wt. of shrimp : 22.643 gm
Price Index   : 19                  Cost per shrimp : $ 0.112
Cut-off Price : $ 7.73/kg
Market Price  : $ 6.58/kg
     ------>  KEEP


STOCK 2 -- Start Stocking in Winter Week  2
---------------------------------------------------------------
Current week  : Spring Week  2
Age of Shrimp : 13 week              Wt. of shrimp : 24.641 gm
Price Index   : 17                  Cost per shrimp : $ 0.123
Cut-off Price : $ 7.88/kg
Market Price  : $ 8.54/kg
     ------>  SELL


Revenue per pond                             $  21901.57
Cost per pond                                   19722.74
                                              ----------
Net Profit per pond                          $   2178.83
                                              ==========

Net Profit for 24 ponds                      $  52291.96
                                              ==========
```

```
STOCK 3 -- Start Stocking in Spring Week  4
------------------------------------------------------------------
Current week   : Summer Week  3
Age of Shrimp  : 12 week          Wt. of shrimp : 25.056 gm
Price Index    : 19               Cost per shrimp : $ 0.116
Cut-off Price  : $ 8.41/kg
Market Price   : $ 8.07/kg
      ------>  KEEP

STOCK 3 -- Start Stocking in Spring Week  4
------------------------------------------------------------------
Current week   : Summer Week  4
Age of Shrimp  : 13 week          Wt. of shrimp : 27.138 gm
Price Index    : 17               Cost per shrimp : $ 0.127
Cut-off Price  : $ 8.58/kg
Market Price   : $ 8.07/kg
      ------>  KEEP

STOCK 3 -- Start Stocking in Spring Week  4
------------------------------------------------------------------
Current week   : Summer Week  5
Age of Shrimp  : 14 week          Wt. of shrimp : 29.183 gm
Price Index    : 13               Cost per shrimp : $ 0.140
Cut-off Price  : $ 8.66/kg
Market Price   : $ 8.93/kg
      ------>  SELL


Revenue per pond                       $  27141.57
Cost per pond                             22376.21
                                        ----------
Net Profit per pond                    $   4765.35
                                        ==========

Net Profit for 24 ponds                $ 114368.47
                                        ==========
```

```
STOCK 4 -- Start Stocking in Summer Week  7
-----------------------------------------------------------------
Current week    : Fall    Week  6
Age of Shrimp : 12 week              Wt. of shrimp : 25.056 gm
Price Index    : 19                 Cost per shrimp : $ 0.116
Cut-off Price : $ 8.85/kg
Market Price   : $ 8.73/kg
     ------>  KEEP


STOCK 4 -- Start Stocking in Summer Week  7
-----------------------------------------------------------------
Current week    : Fall    Week  7
Age of Shrimp : 13 week              Wt. of shrimp : 27.138 gm
Price Index    : 18                 Cost per shrimp : $ 0.127
Cut-off Price : $ 9.17/kg
Market Price   : $ 8.65/kg
     ------>  KEEP


STOCK 4 -- Start Stocking in Summer Week  7
-----------------------------------------------------------------
Current week    : Fall    Week  8
Age of Shrimp : 14 week              Wt. of shrimp : 29.183 gm
Price Index    : 14                 Cost per shrimp : $ 0.140
Cut-off Price : $ 9.19/kg
Market Price   : $ 9.31/kg
     ------>  SELL


Revenue per pond                          $  28278.04
Cost per pond                                22376.21
                                           ----------
Net Profit per pond                       $   5901.82
Percentage of cost in current year        x    0.571
                                           ----------
Adjusted Net Profit per pond              $   3372.47
                                           ==========

Net Profit for 24 ponds                   $  80939.28
                                           ==========
```

** ANNUAL PROFIT **

Stock 1	$ 75119.66
Stock 2	$ 52291.96
Stock 3	$ 114368.47
Stock 4	$ 80939.28

Annual Profit	$ 322719.37
	=========

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