A BIO-ECONOMIC MODEL OF A SHRIMP HATCHERY IN THE MEKONG RIVER DELTA OF VIETNAM

by

L.X. Sinh; and T.G. MacAulay

Department of Agricultural and Resource Economics
The University of Sydney, NSW, 2006

D. Brennan

Resource Economics and Policy Research (REAP)
P.O. Box 456, North Perth, WA 6906, Australia

Contributed paper presented to the
47th Annual Conference of the
Australian Agricultural and Resource Economics Society
The Esplanade Hotel, Fremantle
12-14th February 2003

A BIO-ECONOMIC MODEL OF A SHRIMP HATCHERY IN THE MEKONG RIVER DELTA OF VIETNAM

Sinh, L.X.[1] ; T. G. MacAulay [1]; and D. Brennan [2].

[1]: *Department of Agricultural and Resource Economics, University of Sydney, NSW 2006, Australia.*

[2]: *Resource Economics and Policy Research (REAP), P.O. Box 456, North Perth, WA 6906, Australia.*

Shrimp culture areas and production of the Mekong Delta cover about 60 percent of the total shrimp areas and production of Vietnam. Especially, the Delta contributes about 80 percent of the total shrimp production for export. Rapid development of the shrimp industry is raising a number of serious problems that need to be solved. Shrimp seed supply (post larvae production) plays an essential role in the shrimp industry and it is one of the most important constraints to the development of the shrimp industry in the Delta. The focus of this study is aimed at obtaining an improvement in both the profit per day and post larvae production of the shrimp hatchery in the Mekong River Delta of Vietnam. A Monte Carlo simulation approach was applied to develop a stochastic and dynamic bio-economic model of a shrimp hatchery in the Delta. Initial results and policy recommendations are based on the analysis of the hatchery system simulation using a forward recursion approach and by changing the most important assumptions.

Key words: Shrimp hatchery, larval stage, system simulation modelling.

1. Introduction

Vietnam has 3,260km of coastline with a cross-network of rivers, canals, irrigation and hydro-electric reservoirs that has created a great area of inland-water surfaces of about 1,700,000 ha. The climate and weather in Vietnam are dominated by the tropical monsoon regime. Each of the three regions of the country has its own characteristics. The diversified regime of climate, weather and natural conditions create favourable conditions for aquaculture development with many species and culture types. Sixteen major shrimp species are of economic value of which, *Penaneus monodon* (tiger shrimp) is the first priority of the shrimp industry in Vietnam. Since the beginning of 1990s, fisheries and aquaculture have played an essential role in the Vietnamese economy. The export value of the sector has often ranked from fifth to third of the exported commodities of the country.

During the last decade, the Mekong Delta has contributed about 50-60 percent of the total aquatic production of Vietnam. The Delta covers 60 percent of the total cultured areas and production of shrimp, and shares up to 80 percent of the total shrimp production for export of the whole nation. Shrimp seed (post larvae) is one of the three most important inputs (feed, seed, labour) for shrimp aquaculture in the Delta. Shrimp 'grow-out' farmers in the Delta have mostly relied on the shrimp post larvae imported from the Central provinces. Recently, there has been a rapid increase in the number of local shrimp hatcheries sharing about 20 percent of the total shrimp seed provided to shrimp grow-out farms in the Delta. This percentage is soaring quickly due to the establishment of many new hatcheries both along the coats and in the inland areas and because of the disadvantages of importing post larvae from the Central region. Rapid development of the shrimp industry is raising a number of serious problems that need to be solved not only for the short-tem but also in thte longer-term. The production of shrimp seed including both the quantity and quality, as well as the price of the shrimp seed are frequently given as serious concerns in the efforts to have a sustainable shrimp industry not only in the Delta and the whole country but also at the global level (Minister of Fisheries, 1996, 1998, 2000, and 2002; Chanratchakool et al., 1998).

In general, a number of studies on replacement and scheduling in agriculture and forestry have been completed using simulation of the dynamic systems (Throsby, 1964; Burt, 1965; Perrin, 1972; Hochman, 1973; and Kennedy, 1986). However, aquaculture is a young sector, so that the application of dynamic programming and simulation methods in aquaculture are not yet common and those available have usually involved the 'grow-out' activities. Modelling of animal breeding, especially fish and shrimp hatchery operations have had very limited study. System modelling and bio-economic modelling in aquaculture, therefore, is a new field for the application of systems modelling (Allen, 1984; Weller, 1994; Logan and Johnston, 1993; Cacho, 1997; and Meade, 2001).

The focus of this study is on obtaining an improvement in both the profit per day and the production of post larvae in association with a better quality of post larvae produced by the shrimp hatcheries in the Delta. A multi-stage Monte Carlo simulation model was used to develop a stochastic and dynamic bio-economic model of a shrimp hatchery in the Delta. Because of the complex interactions among the variables of the hatchery operation system, a set of assumptions and conditions were developed in order to simplify the modelling activities. Four sets of data were collected in 2001 and 2002, and analysed in order to estimate the parameters for the simulation of the shrimp hatchery model. A number of suggestions for shrimp hatchery operations are made from the results of the model and these are designed to enhance the management of the hatcheries.

2. A Conceptual framework for a shrimp hatchery model

Cacho (1997), Rubinstein and Melamed (1998) called *a system* a set of related entities, sometimes called components or elements. The elements possess certain characteristics or attributes that take on logical or numerical values. Jones and Luyten (1998) considered *a system* is a collection of components and their interrelationships that have been grouped together for studying some parts of the real world, and the objectives of the study help to decide how many components can be included in the system.

Weller (1994) comments that there are three important things in the analysis of animal breeding: (i) system analysis requires that the objective be clearly defined; (ii) a framework is needed for consideration of breeding decisions within the total production framework; and (iii) breeding decisions must be put into perspective with other management decisions. Aquaculture system needs to be well described and analysed before the modelling activities (Allen, 1984; Leung, 1986; Keen and Spain, 1992; Logan, 1993; Cacho 1997).

Aquatic animals, especially shrimp have a number of different characteristics in comparison with that of the other animals. There are a million of eggs from each spawn, and the eggs transit through a number of larval stages and sub-larval stages before being harvested and sold to the shrimp grow-out farmers. There are two major phases for each young shrimp to transform from an ovarian form of female shrimp into eggs released and then post larvae at the harvest. They are: (i) the release of spawns or eggs; (ii) hatching of the eggs and transition of the larvae into post larvae through the larval stages. In the hatchery, these phases are implemented in the spawning tanks and larval rearing tanks. Eggs can be hatched in the hatching tanks or containers separately or directly in the larval tanks. All of these phases and their stages, as well as the time and economic aspects are essential to the success of hatchery operation and management.

Cacho (1993) provided a three-stage approach to the model development in farm management. A similar approach is applied in this study to develop a four-stage approach to the shrimp hatchery model as follows:

(1) *Spawn level* covers the performance of each spawn from the release of eggs to the discharge of larvae or the harvest of the post larvae (PLx);

(2) *Female level* deals with the performance of different spawns released by each female;

(3) *Production cycle level* examines the performance of different females that were bought at the same time (spawns of the same female batch); and

(4) *Whole hatchery level* covers the operation of different production cycles within an operational year.

To apply the sub-models in an aquacultural system, such as that given by Fridley (1987), Martinez-Codero et al., (1995), and Schulstad (1997), the shrimp hatchery system is considered to consist of different production cycles per operational year. Four sub-models are identified in each production cycle, that is:

(1) *Biological model*: The spawning of females and the transition of larvae from eggs through the stages into post larvae at the point of harvest (PLx stage). The number of spawns released as well as the spawning time and number of eggs per spawn by type of females at the point of purchase and spawn number of the spawns are important;

(2) *Physical model*: The use of available tanks for larval rearing activities. The number of tanks that are used and discharged or harvested by larval stage and by the time

from the point of the purchase of females. These are also important to defining the system;

(3) *Production model*: The total number of PLx harvested from each production cycle (in detail, can be presented by type of female and spawn number of the spawns or tanks). This is constituted from the biological and physical models; and

(4) *Economic model*: Production costs of the spawns are calculated based on the stopping stage of the spawns (or tanks), that is, when the egg or larval tanks are discharged (that is, do not reach the PLx stage) or are harvested (at the PLx stage). The total returns of each production cycle are calibrated using the price of post larvae PLx by the time at the point of harvest since price varies over the calendar year. The day when the maximum cumulative net returns per day occur, including the dry-out time for the cycles is then identified using a search process.

The biological system (biological processes) and physical system (physical and equipment associated with the biological system) constitute the production systems. The decision support system is constituted from the production and economic systems.

The problems for modelling a shrimp hatchery system now are as follows:

(1) When to begin the operational season (or when to buy the first female batch)?

(2) What should be the number of females purchased for each production cycle (by ovarian development of the females at the point of purchase)?

(3) How long should be the duration of each production cycle or female batch?

Assumed that the hatchery is operated from a starting date or the time of buying the first batch of females is identified (for instance, on December 1, and a variation of every half month: 15 days, 30 or 45 days is allowed because of the tidal regime in the Delta). As well, the number of females per batch (by ovarian development of the females at the point of purchase) is identified. Therefore, the problem for modelling a shrimp hatchery system is: *"How long should be the duration of each production cycle or female batch". That is, when should the spawns of the current batch of females be stopped and replaced by a new batch of females.*

3. Assumptions and conditions for modelling

Because of the complex interactions among the variables of the hatchery system, and the small sample size of female group 2 (females without ovarian development at the point of purchase), a set of assumptions and conditions are proposed in order to simplify the modelling activities. These assumptions and conditions are based on the references, and logical considerations, as well as the semi-structured interviews between the author and the aquaculturists in CSIRO (Brisbane, Queensland, Australia); The Asian Institute of Technology (Bangkok, Thailand); Nhatrang Fisheries University and Cantho University (Vietnam). In addition, the comments and experience from the hatchery operators in both the Mekong Delta and the Central regions of Vietnam are useful for modelling activities.

The most important assumptions and conditions for modelling the shrimp hatchery system are:

- Operational season: salinity, temperature, pH of the water can all be monitored and be set appropriately for production (a period not longer than 270 days from the 1st December);
- The beginning of the operational year is the point of purchase of the first batch of female shrimp (an interval of 15, 30, or 45 days is allowed between purchase);
- The 'dry-out' time is constant between the production cycles (a variation of 0, 5, 10, or 15 days is allowed);
- Tank design is the same (4 m^3), and can be reused within each production cycle;
- Only one shrimp species, *Penaneus monodon* (tiger shrimp), is reproduced in the hatchery.
- The number of females purchased (specified by ovarian development of the females at the point of purchase) is constant between the production cycles depending on the hatchery size (small, medium and large);
- Sources and size of the female shrimp are constant (wild females, 150-300 g per female);
- The number of spawns per female is not more than 6 spawns;
- Spawning time of the first spawn by female group 2 is not earlier than 14 days from the point of female purchase. This time for female group 3 (females with ovarian development at the point of purchase) is not later than 8 days. Note that the time interval between two spawns is not less than 2 days, and the latest spawn is released not latter than 35 days from the day of purchasing the females for all female groups;
- The larval tanks are single-spawn tanks (one spawn provides enough nauplii for 1 larval tank). It means that there are no merging or splitting of the spawns;
- There is only one source of nauplii owned-produced in the hatchery, that is, there is no nauplii trading activities between the hatcheries;
- The time from the point of the spawn released to the larval stages is constant between spawn number and female group. Therefore, if the spawn is released at day 1 from the point of female purchase, the occurrence time for nauplii is day 2, and the occurrence day for zoea, mysis, PL1, and PLx are 4, 9, 14, and 28, respectively. As well, it means that the duration of each larval stage is constant between female group and spawn number (1 day for egg to nauplii; nauplii to zoea: 2 days; zoea to mysis: 5 days; mysis to PL1: 5 days; and post larvae from PL1 to the harvest of PLx: 14 days);
- Transition rates from eggs into PLx through the larval stages are constant between the female groups but different between the spawn numbers of the spawns);
- Total production costs at the stopping stage of the spawns or tanks are constant between the spawn numbers but different between the female groups;
- The price of major inputs (broodstocks and feed) and the price of outputs (PLx) are exogenous factors, that is, the hatchery operators are price-tackers.

The survival rate of the post larvae harvested using the formalin test 200 ppt for 50 PLx in 1 hour is an important indicator of quality. According to Chanratchakool et al., (1998), in order to satisfy the quality of shrimp seed for stocking in grow-out farms the survival rate of PLx using the 200 ppt formalin test (F200) in one hour should be at least 90 percent. From the statistical analysis of the recorded data, it is shown that if the hatchery operators stop using the spawners after the 4th spawn, both the profit level and the health condition of the PLx

from the spawns are acceptable, that is, the benefit-cost ratio (B:C) and the net returns (TR-TC) are positive, and the survival rate of the PLx using a formalin test (F200) in one hour is higher than 90 percent. Results also reveal that for the later spawns, that is, for the 5th and 6th spawns, both the average benefit-cost ratio and the average net returns are negative. As well, the survival rate of PLx using the F200 test is lower than 90 percent. The spawn number is therefore limited up to the 6th spawn due not only to this reason but also that beyond the 7th and later spawns only 5.6 percent of the total number of spawns were recorded.

4. Model description and model parameters

a. Model description

Maximizing the present value of the expected net returns is assumed to be the final objective of the hatchery operators. This objective is applied to not only the individual spawns and the production cycles but also the whole year operation. The present value of the expected net returns strongly depends on: (i) the type of the females; (ii) the number of spawns per female; (iii) the time of the spawns, both the time within the cycle and time of the operation year; (iv) the number of post larvae, PLx, harvested; (v) the costs of PLx; and (vi) the price of PLx. The first five factors are affected by the type and number, as well as the price of the females purchased. The financial results and duration of the production cycles, in turn, constitute the financial results and the length of an operational year. The financial net return of the cycles may be affected by the following factors:

- Hatchery size or the number of tanks for larval rearing activities;
- Number of the female batches and time at the point of purchase;
- Number and structure of the female shrimp purchased for each batch or cycle;
- Spawning rate and time of the spawns;
- Number of eggs per spawn;
- Transition times from eggs through the larval stages;
- Transition rates from eggs to PLx through the larval stages;
- Number and price of the post larvae harvested and sold;
- Total variable costs per ‘000 eggs up to the stopping time (or the end) of the spawns;

Interaction between components or parts in the hatchery system operation can be considered in terms of mathematical equations (Allen et al., 1984; Fridley, 1987; Manly, 1990; Keen and Spain, 1992; Cacho, 1997; and Dudley, 1998). There are three parts of the mathematical equations characterising the relationship between components or parts of the hatchery system that can be identified as follows:

(a) *State variables* help to quantify the characteristics of the condition of the hatchery system at the time decisions are made. It means that the state variables define the state of the hatchery at a given point of time. Three major state variables are:

- Number of larval tanks in use (or the number of good spawns is used);
- Number of larvae in different larval stages (from nauplii to PLx);
- Net return level of the spawns or larval tanks (spawn, cycle, year).

(b) *Decision or control variables* cause the state variables to change, and help to regulate the state variables to a desired condition for the hatchery system at each decision point. If the hatchery size and both number and structure of female shrimp are given, then the decision is when to stop using a female batch and to prepare for the purchase of a new batch.

- Time of purchasing the first female batch (beginning of the operational year);
- Time of purchasing the other batches of females;
- Number of the females by ovarian development at the point of purchase;
- Time to stop the use of the current batch of females (the number of spawns per female can be decided if the female is still alive and continue to spawn);
- Discharging or continuing an egg or a larval tank at a specific larval stage; and

(c) *Parameters* show the effects of the decision/control variables on the state variables. Parameters can be stochastic or non-stochastic (constant). The major parameters by spawn number and type of females to be used are:

- Probability that a spawns is released and good for egg hatching (stochastic);
- Occurrence time of the spawns (stochastic);
- Number of eggs per spawn (stochastic);
- Transition times from eggs though the larval stages to the end of the spawns, or stopping time of the spawns within each production cycle (stochastic);
- Survival or transition rates of larvae through the larval stages (stochastic).

b. Model parameters

The model parameters can be stochastic or non-stochastic. They were estimated using the following sources of data and information that were collected in 2001 and 2002:

v *Data collection at the regional and national level:*

- Situation of aquaculture and shrimp industry at the regional and national levels;
- Distribution of the hatcheries in the Mekong Delta;
- Number of post larvae produced in the Delta;
- Number of post larvae imported from the Central region into the Delta;
- Market price of male and female shrimp (every two weeks); and
- Market price of post larvae (every two weeks).

v *Survey of 36 hatcheries: to obtain a general point of view on the hatchery operation.*

- Operation season;
- Hatchery size and tank design;
- Number of production cycles per operational year;
- Number and structure of females by type of female shrimp;
- Use of the tank system for larval rearing activities; and
- Economic indicators of the shrimp hatchery operation.

- *Record keeping of 103 female shrimp: to understand the spawning of female shrimp.*
  - Spawning rate and spawning time of the spawns by type of female shrimp and spawn number;
  - Number of eggs per spawn by type of female shrimp and spawn number; and
  - Costs of the spawns and eggs by type of female shrimp and spawn number.
- *Record keeping of 162 spawns from 2 groups of wild female shrimp: to clarify the transition process of shrimp post larvae.*
  - Transition times from eggs through the larval stage (nauplii, zoea, mysis, post larvae stage 1 or PL1, and post larvae at the harvest or PLx);
  - Transition rates from eggs through the larval stages;
  - Cut-off points of the transition rates from eggs through the larval stages;
  - Production costs of the larvae discharged at each larval stage, and that of the PLx at the harvest; and
  - Number and price of the post larvae harvested.

c. Concept of time

Due to a fear of disease infection, overlap of the batches of females (or production cycles) is avoided, and the reuse of tanks in the same production cycle is carefully considered. Therefore, shortening the duration of production cycles by making a better decision on the total number of females and the structure of the female batches (that strongly affect the spawning time and the number of spawns) may help to obtain an improvement in both the economic results and quality of the PLx produced. The transition process for each spawn can include one or more of the six following stages:

(0) Spawning of the female or the release of eggs of the spawn;

(1) Transition from eggs into nauplii;

(2) Transition from nauplii into zoea (protozoea);

(3) Transition from zoea into mysis;

(4) Transition from mysis into post larvae stage 1, PL1;

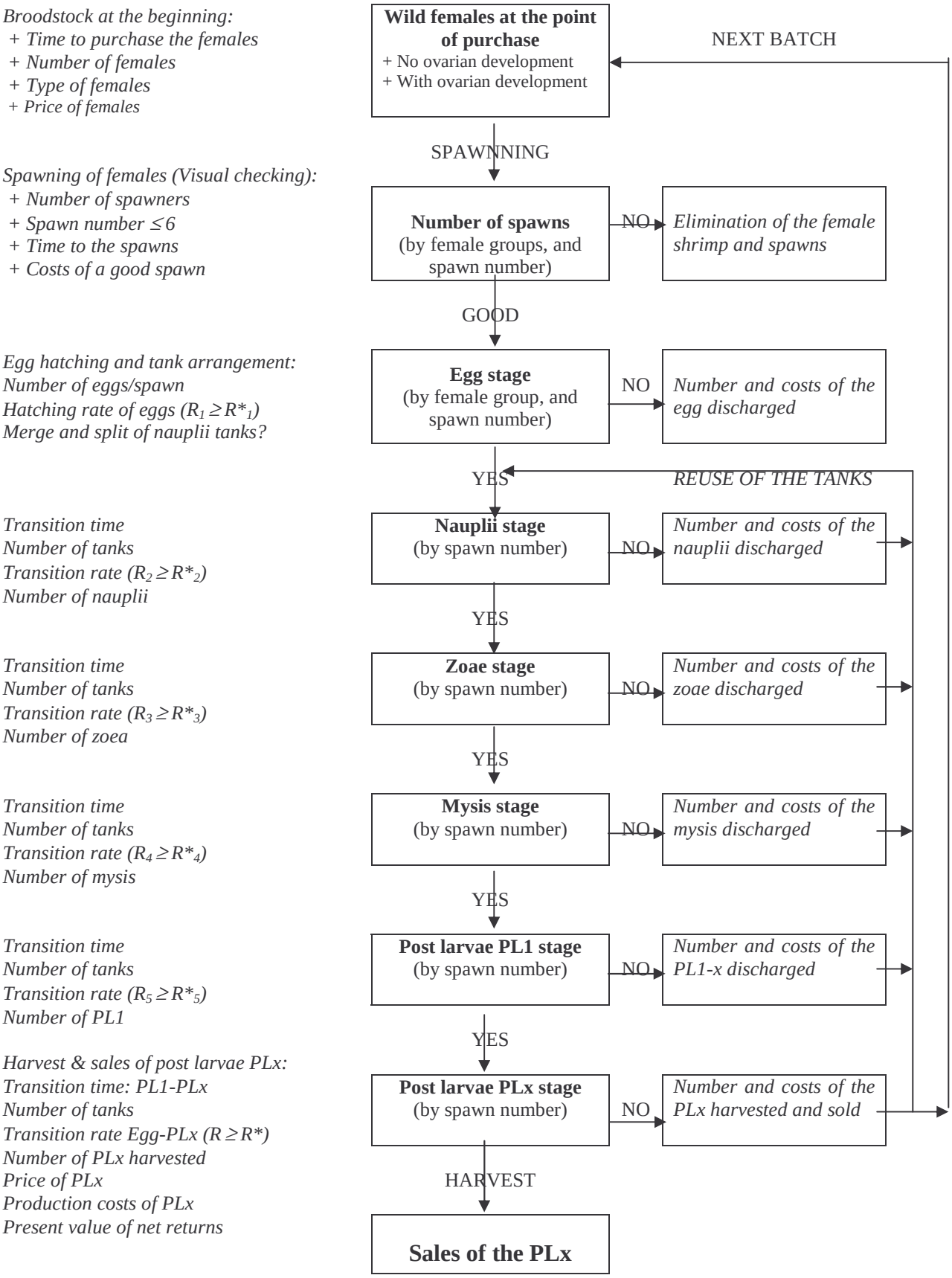
(5) Transition from PL1 into post larvae at the harvest, PLx (PL12-15, is common).

For the stage zero (release of eggs), the spawning time, number of spawns, rate of good spawns to the total number of spawns released, as well as the number of eggs by spawn number and type of females, and the production cost per ‘000 eggs released are important. This can be considered as the spawning phase of the female shrimp.

The stages from 1 to 5 can be grouped into the transition phase of larvae where the eggs transit into PLx through the larval stages. In this phase, the transition times and rates, and the number of tanks by larval stages, as well as the production cost per ‘000 eggs up to the stopping stage by spawn number and type of females, and price of PLx are important.

According to the results of the previous chapters, the integer transition times (in the number of days) between the larval stages, are summarized as follows:

Figure 1: *System analysis of a production cycle operation in the shrimp hatchery ($Q \leq 8$)*



**** Tanks are discharged at stage s if Rs < R*s (R*s = Cut-off value) where s = 1 for hatching rate, and s =5 for PL1-PLx transition rate.***

***** Tanks can be reused if they are discharged before PL1 stage, but not latter than 30 days from the point of female purchase.***

Female => Egg => Nauplii => Zoea => Mysis => PL1 => PLx

T_e = random; d_1 = 1 day; d_2 = 2-3 days; d_3 = 5 days; d_4 = 5 days; d_5 = 14 days

where T_e is the spawning time or the time of egg occurrence based on the age of production cycle; and T_s is the occurrence time of the larval stage. However, the duration from the beginning of production year (or from the 1st December) to the occurrence of the events considered also need to be considered.

Thus, if the spawn successfully transits from eggs into PLx, an average duration of 28 days is needed from the occurrence of the spawn to the harvest of PLx from that spawn. Therefore, the duration of each spawn (or tank) depends on the larval stage, that is, when the larvae or PLx in the tank are discharged or harvested.

In the model, time *t* consists of two aspects:

(1) Time when the females are purchased (production cycle aspect), that is, the beginning of each production cycle term; and

(2) Time of the events that the spawn passes through (spawn transition aspect), that is, the occurrence time and the transition time of the spawns from eggs to nauplii, zoea, and so on up to PLx.

These two aspects of time are simultaneously considered in a dynamic model of the shrimp hatchery. Therefore, the model is developed following a horizontal time line of the hatchery operation:

(a) Release and transition processes of the spawns from the purchase of each female batch to the discharge or harvest of the latest spawns from that batch of females.

(b) After the discharge or harvest of the latest spawns from the current female batch, some dry-out days will be needed for cleaning and disinfecting the hatchery before the next batch of females are purchased.

For the time of the events, if spawn *j* (or eggs from spawn *j*) is released on day *t* of production cycle *q*, then T_e is the occurrence time of that spawn using the number of days from the beginning of operational year (for instance, from the 1st of December). This means that:

(1) $T_e = T_q + t$

If the females are purchased in a batch on day T_q, the duration of a spawn from the purchase of the mother female to the stopping stage (the end) of the spawn be d_s. The time when the spawn stops (harvested or discharged) with its larval stage *s*, T_s, is calculated as follows:

(2) $T_s = T_q + t + d_s = T_e + d_s$

where s = 1, …, 5 for the stop at eggs, nauplii, …, PL. Duration of eggs is d_s = 1; for nauplii: 2-3; zoea: 8; mysis: 13; PL1 = 14. Therefore, d_5 for PLx is 28;

Let the dry-out time between the production cycles, D_r, be constant between the cycles. Also let the duration of a production cycle, that is, the time from the point of female purchase to the stop day of the last tank from that female batch, be D_q. Therefore, D_q is calculated as follows:

(3) $D_q = \text{Max}(d_s + D_r) = \text{Max}(T_s - T_e) + D_r = \text{Max}(T_s - T_q - t) + D_r$

Because of the longest production cycle based on the assumptions is not longer than 63 days, a general view of the variables by the horizontal time line of each production cycle is provided Table 1. There are two special points of time as follows:

- The 1st spawn can be released in the 1st day of the production cycle (the same day as purchasing females). This means that the earliest PLx can be harvested is from the 28th day of the production cycle;
- The latest spawns of FG3 (the 6th spawns) may be released about 35 days after the purchase of females. This means that the latest PLx from FG3 can be harvested at the 63rd day of the production cycle.

Table 1: Major variables by the horizontal time line of each production cycle

Variable	***Time from the point of purchase of the female batch (t ≤ 63)***										***Total, ∑***
Time, from $\mathbf{T_q}$	1	2	….	27	28	….	35	36	…	t	Duration,$\mathbf{D_q}$
No. of females	F_{q1}	F_{q2}	….	F_{q27}	F_{q28}	….	F_{q35}	0	….	F_{qt}	$\sum \boldsymbol{F}^i_{q(j-1)t}$
Chance to spawn	G_1	G_2	….	G_{27}	G_{28}	….	G_{35}	0	….	G_t	$\sum G^i_{jt}$
No. of spawns	S_1	S_2	….	S_{27}	S_{28}	….	S_{35}	0	….	S_t	$\sum S^i_{jt}$
No. of Eggs	E_1	E_2	….	E_{27}	E_{28}	….	E_{35}	0	….	E_t	$\sum E^i_{jt}$
No. of tanks	M_1	M_2	….	M_{27}	M_{28}	….	M_{35}	M_{36}	….	M_t	$\sum M^i_{jt}$
No. of tanks lost	m_1	m_2	….	m_{27}	m_{28}	….	m_{35}	m_{36}	….	m_t	$\sum m^i_{jst}$
No. of larvae lost	l_1	l_2	….	l_{27}	l_{28}	….	l_{35}	l_{36}	….	l_t	$\sum l^i_{jst}$
TVC at the stop*	TVC_{s1}	TVC_{s2}	….	TVC_{s27}	TVC_{s28}	….	TVC_{s35}	TVC_{s36}	….	TVC_{st}	$\sum TVC^i_{jst}$
No. of PLx sold	0	0	….	0	0	….	L_{35}	L_{36}	….	L_t	$\sum L^i_{jt}$
Price of PLx	0	0	….	0	0	….	P_{35}	P_{36}	….	P_t	$\sum P_t$
Revenue, TR	0	0	….	0	0	….	TR_{35}	TR_{36}	….	TR_t	$\sum TR^i_{jt}$
Cumulative net return	$\prod_{D1}$	$\prod_{D2}$	….	$\prod_{D27}$	$\prod_{D28}$	….	$\prod_{D35}$	$\prod_{D36}$	….	$\prod_{Dt}$	$\sum \prod_{Dt}$
Cumulative net return per day	$\prod_{D1}/1$	$\prod_{D2}/2$	….	$\prod_{D27}/27$	$\prod_{D28}/28$	….	$\prod_{D35}/35$	$\prod_{D36}/36$	….	$\prod_{Dt}/t$	$\sum \prod_{Dt}/Dq$

* ***TVC*** *at the stop: Total variable costs of the tanks/spawns that are discharged or harvested at day* ***t****.*

d. Set up the whole hatchery model

From the assumptions, and conditions for modelling, as well as the concepts of time, if the operator starts his or her hatchery operation from the 1st of December (the 1st female batch is purchased), the formulation of the hatchery system now is focused on the following:

(a) How many females per female group in each batch;

(b) How many spawns are used per female batch;

(c) How many batches of females per operational year; and

(d) Time between the batches of females (dry-out time).

If the number of females per batch is identical, the problem is when to stop the current production cycle and to prepare for purchasing another batch of females. If the price of PLx

is constant, as well as the spawning rate of females and the transition rates of larvae are constant (season independent), all of the production cycles will have the same duration.

Assume that the total fixed costs, TFC, are fixed for any operational day, and only the total variable costs, TVC, are considered in the model. The optimal principle for hatchery operation can be considered in two ways:

(4) $\text{Max} \prod = TR - TVC = L.P - TVC = L.(P - AVC)$

where *TR* is the total revenue; *TC* is the total costs, *TVC* is the total variable costs; *L* is the total number of post larvae produced; *P* is the price of post larvae. *AC = TC/L* and *AVC = TVC/L* are the average total costs and the average total variable costs of production, respectively. Equation (4) is subject to a set of major constraints as follows:

(a) Operational season is from the 1st of December to the 31st of August (a delay of 15 to 30 days is allowed);

(b) Number of larval tanks for larval rearing is *M*, where *M = 12, 18, 24;*

(c) Wild females are used, *i = 2, 3 for FG2 and FG3;*

(d) The spawn number *j* of the spawn is limited to 6, so *j = 1, 2, . . ., 6;*

(e) Cut-off numbers of eggs per spawn are set by *i* and *j*, E^i_j; and

(f) Cut-off transition rates of larvae are set by *i, j, s,* that is, R^i_{js}.

Total revenue can be written as a function of the number and price of PLx, and the time of selling the PLx:

(5) $TR = g\{L(t), P(t)\}$

Total variable costs can be written as a function of the number of spawns, number of eggs per spawn, and transition rates between the larval stages, *R*, as well as the stopping stage, *s*, and average total variable cost per '000 eggs at the stopping stage, C_s. These variables depend on the type of female, *i (i = 2, 3)*, spawn number, *j (j = 1, 2, . . ., 6)*, and time, *t*:

(6) $TVC = h\{S(t), E(i, j), R(j), s, C_s(i, j)\}$

The total number of spawns used is a function of the total number of females (F), type of females, as well as spawning time and spawn number of the spawns:

(7) $S = v\{F_q (i, j, t), G(i, j, t)\}$

Total number of post larvae produced is a function of the number of spawns/tanks used, number of eggs per spawn, the aggregate transition rate from eggs into PLx which depend on the type of females, *i*, and spawn number of the spawns, *j*:

(8) $L = z\{F_q (i, j, t), G(i, j, t), E(i, j, t), R(j), s\}$

Let α be the interest term, *r* is the interest rate per day, then $\alpha = 1/(1 + r)^t$. Let D_q be the duration of the production cycle *q* including dry-out time, the optimal stopping point of each production cycle is obtained by maximizing the expected value of profit per operational day of the cycle. However, the discount rate per day is very small (about 0.0015) and the cycle duration is short (not longer than 2 months), then α may reasonably be ignored.

Let Q be the number of production cycles operated per year. If the dry-out time between the cycles q is constant and taken into the model, from (4), the following function is derived:

$$\text{(9)} \qquad \text{Max} \prod_{t=1}^{Dq} / Dq = f\{F_q(i, j, t), G(i, j, t), E(i, j), R(j), s, C_s(i, j), P(t), \alpha, D_q, Q\}$$

e. Decision rules

Following Burt (1965), Perrin (1972), Hochman and Lee (1972), Kennedy (1986), and Hochman et al. (1990), the problem of the study can be stated is a stopping problem of the shrimp hatchery operation. The question is at what point is it appropriate to stop the current batch of females and to buy (or to replace by) a new batch of females. The general stopping rule is to stop the current production cycle and to continue with a new cycle when the expected net return per day of the current cycle is less than that of the average of the future cycles. The solution can be obtained using a set of decision rules applied to the hatchery operational process.

- *For an operational year:* An operational year is assumed to be the time from the 1st of December to the end of August or the middle of September. The beginning and the end of the operational year, as well as the time of the events using calendar time (the number of days from the 1st of December) are important.
- *For each production cycle:* The beginning time or the time at the point of female purchase, the number of females by female group, and the number of tanks in use (or available) are important. The timing of the events is considered in series of both the time within the production cycle (the number of days from the point of female purchase) and the calendar time (the number of days from the 1st of December).
- *For each spawn by female group and spawn number:* A set of cut-off values of the parameters are used such as the spawning time, the number of eggs per spawn, the hatching rate of eggs and the transition rates of larvae through the larval stages from nauplii to PLx. The number of days from the point of buying females (the production cycle aspects of time).

There are several major situations or states in which, the operator has to consider to keep the current cycle for a longer time or to stop the current cycle and to purchase a new batch of female shrimp after a duration of the dry-out time. They are:

(i) If sufficient time is not available for a cycle (the end of production season) => **stop** the hatchery operation when all of the tanks from the current batch of females are discharged or harvested. Do not purchase the next batch of female shrimp.

(ii) If the time available within the production season, even if the females are still alive, but the total number of larval tanks from the current female batch is small (for instance, not more than 20 percent of the total number of tanks of the hatchery after 3 or more weeks from the beginning of the cycle) => **keep** or **discharge** these tanks and purchase the **next** batch of females.

(iii) If time is available (within the production season) but there are no more spawns to be released (all of the females of the current batch are eliminated after 35 days from the beginning of the cycle) and the number of on-going tanks of the current cycle is too small (not more than 20 percent of the hatchery size) => **keep** or

discharge these tanks and purchase the **next** batch of females. This commonly results from the two following situations:

(iv) The number of spawns from the current batch of females is enough for a production cycle => apply the general stopping rule (see above): **keep** the tanks from the current female batch until all of them are discharged or harvested, then purchase the **next** batch of females.

(v) The number of spawns released is more than the number of tanks available (empty tanks). The **extra spawns** can be discharged or hatched and then the nauplii from these spawns are **sold out** => apply the general stopping rule (see above): **keep** the tanks from the current female batch until all of them are discharged or harvested, then purchase the **next** batch of females.

Let $\prod_{Dqt}$ be the net return per day if the operator stops the hatchery operation of the current production cycle *q* at day *t*, and D_{qt} be the duration of the cycle from the point of female purchase to the stopping day (dry-out time is included). If only one separate production cycle is operated per year, the operator expects to stop the cycle at day *t* when the maximum net return per day is obtained. It means that:

(9.1) Stop at *t* if $\prod_{D(t-1)} \leq \prod_{Dt}$ and $\prod_{Dqt} \geq \prod_{D(t+1)}$, where $\prod_{Dqt} > 0$.

However, it is more difficult for the operator to make a decision when the linkage between the cycles for each operational year is considered. Therefore, the expected net returns per day of cycle *q* and cycle *q+1* should be given consideration using the calendar time from the 1st of December. Let $\prod^{*}_{D(q+1)}$ be the maximum expected profit per day of the production cycle *q+1*. Note that the dry-out time between the cycles is constant and included in the duration of the cycles. Four situations for making the decision in this case are:

(9.2) Stop the cycle at day *t* and do not buy the next batch of females if it is too late (not later than 250 days from the 1st of December);

(9.3) Stop the cycle at day *t* and buy the next batch of females if the number of spawn released is too small (not latter the third week of the current cycle) and/or when $\prod_{Dqt} \leq 0$ for all *t* of the current cycle;

(9.4) If the current cycle has $\prod_{Dqt} \geq \prod^{*}_{D(q+1)} > 0$ for all of *t* (note that *t = 1, 2, …, 63* days from the point of female purchase of the current batch), keep continuing the current batch up to the stopping point of the last spawn or larval tank. After completing the current cycle, prepare to buy a new batch of females; and

(9.5) If the time for buying a new batch of females is still acceptable, stop the current cycle at day *t* and continue with a new batch of females if $\prod_{Dqt} > 0$, $\prod^{*}_{D(q+1)} > 0$, and $\prod_{Dqt} \leq \prod^{*}_{D(q+1)}$.

As well, this means that the hatchery operator should stop the hatchery operation when the marginal profit per day is equal or less than zero. It also reveals that if the hatchery operator stops the rearing activities of the current production cycle at day *t*, he/she should not use the spawns released later than *t-28* days before stopping the last larval tank of the current female batch. This procedure is applied to each production cycle using a constant dry-out time between the cycles. Equations (4) and (9) are clarified through the calculations of the variables in the sub-models in the next sections.

f. Spawning and transformation of females and larvae (Biological sub-model)

If G_j is the conditional probability that a spawn with the spawn number *j* is released; G_a is the probability that a spawn is good for egg hatching; G_b is the probability that a spawn is released at time *t*. Note that G_j also consists of the survival rate of females from spawn *j* to spawn *j-1*. Therefore, the probability that a good spawn with spawn number *j* is released by female group *i* at time *t*, G^i_{jt}, is a conditional probability as follows:

(10) $G^i_{jt} = G^i_j . G_a . G_b$

If F_{j-1} is the number of female shrimp that have released *j-1* spawns, the number of good spawns with spawn number *j* released by female group *i* at time *t*, S_{jt}, is:

(11) $S^i_{jt} = F^i_{q\,(j-1)t} . G^i_{jt}$

Let R_{js} be the transition or survival rate of larvae of spawn number *j* from stage *s-1* to stage *s*. The aggregate survival rate of the larvae of spawn number *j* from eggs to the stopping stage *s*, R_j, is assumed constant between the female groups, but variable between the spawn numbers. Therefore, R_j of each spawn *j* is calculated following the survival table:

(12) $R_j = R_{j1} \ldots R_{js} = R_{js}!$

where s = 1, 2, 3, 4, 5 for the transition from egg to nauplii to zoea and so on.

g. Calculation of the number of larval tanks (Physical sub-model)

The number of spawns used for larval rearing is limited by the hatchery size (the number of tanks designed for larval rearing). Let *M* be the number of tanks or size of the hatchery (< 13, 13-18, >18), and *s* is the larval stage of the tanks in which larvae are currently stocked. In the real system, the number of tanks in use is often counted using the number of larval tanks. Eggs can be hatched in a separate container or spawning tanks before the nauplii are removed to the larval tanks. The post larvae in a tank are harvested at size PLx (PL12-15 are in common). The tank is considered empty after the current larvae are discharged or the PLx are harvested.

At any point of time, if the total number of larval tanks in use is equal to the hatchery size, the extra spawns (latest ones) may be sold at the nauplii stage and the costs of these spawns are covered by the money received from selling those nauplii. These extra costs and returns are excluded from the model. For example, if a 12-tank hatchery with all of the 12 larval tanks currently stocked with larvae at different larval stages in different tanks, the latest spawns are excluded regardless the quality and quantity of eggs.

The number of larval tanks in use at any point of time is the sum of the numbers of nauplii tanks, zoea tanks, mysis tanks and PL1-PLx tanks at that time. Because of the different spawning time of the spawns and the delays between the stages in the larval transition process, at any time *t* of the current production cycle, the total number of larval tanks currently in use consists of:

- Number of nauplii tanks within 2-3 days (*Mn*);
- Number of zoea tanks within 5 days (M_z);
- Number of mysis tanks within 5 day (M_m);
- Number of post larvae tanks within 14 days, before harvesting PLx (M_a).

Let R^*_s represents the cut-off values of the larval transition rate from stage *s-1* to stage *s*. Therefore, the total number of larval tanks in use at time *t*, M_t, is derived as follows:

(13) $M_t = M_{nt} + M_{zt} + M_{mt} + M_{at}$

where $M_t \leq M$ *and* $R^i_{js} \geq R^*_s$, *n for nauplii, z: zoea, m: mysis, and a for* P_a *or PL1*

Let the number of larval tanks discharged at stage *s* and time *t* be m_{st}. This is the number of tanks lost due to the unacceptable transition rate of larvae from stage *s-1* to stage *s*, that is, $R^i_{js} < R^*_{js}$, and it is calculated using the following equation:

(14) $m_t = m_{nt} + m_{zt} + m_{mt} + m_{at}$

where $R^i_{js} < R^*_{js}$, *n for nauplii, z: zoea, m: mysis, and a for* P_a *or PL1*

h. Calculation of the number of larvae (Production sub-model)

Let the number of eggs per spawn of female group *i* and spawn number *j* be E^i_j, the number of larvae lost before reaching PLx, l_t, is calculated as follows:

(15) $$l_t = l_{et} + l_{nt} + l_{zt} + l_{mt} + l_{at} = \sum_{t=1}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6}\sum_{s=0}^{4} F^i_{q\,(j-1)(t-ds)}.\ G^i_{j(t-ds)}.\ E^i_j.\ R^i_{js!}$$

where s = 0, 1, 2, 3, 4 for n, z, m, a represent the stopping stage of the tanks: e = egg; n = nauplii; z = zoea; m = mysis; and a = post larvae are not harvested

The number of eggs lost, l_{et}, consists of the number of eggs from the spawns that are not enough for hatching in order to provide an acceptable amount of nauplii for one tank (< 100,000 eggs per spawn), plus the eggs from the spawns used for hatching but the hatching rate is not acceptable. This number depends on the number of eggs within 1 day of the egg-nauplii transition (or the number of eggs from the spawns released 1 day before), and the transition rate from nauplii to zoea. Note that the earliest eggs are released at day 1 of the production cycle.

(15.a) $$l_{et} = \sum_{t=2}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} F^i_{q\,(j-1)(t-1)}.\ G^i_{j(t-1)}.\ E^i_j.\ R_{j1!}$$

where $E^i_j < 100{,}000$; *and when* $E^i_j \geq 100{,}000$ *but* $M_t = M$; *or* $R_{j1} < R^*_1$

The number of nauplii lost, l_{nt}, is based on the number of nauplii within 2 days of the nauplii-zoea transition (or the number of nauplii from the spawns released 4 days before), and the transition rate from nauplii to zoea. Note that the earliest eggs are released at day 1 of the production cycle.

(15.b) $$l_{nt} = \sum_{t=2}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} F^i_{q\,(j-1)(t-2)}.\ G^i_{j(t-2)}.\ E^i_j.\ R_{j2!}$$

where $E^i_j \geq 100{,}000$; $R_{j1} \geq R^*_{j1}$ *and* $R_{j2!} < R^*_2$

The number of zoea lost, l_{zt}, is based on the number of zoea within 5 days of the zoea-mysis transition (or the number of zoea from the spawns released 9 days before), and the transition rate from zoea to mysis.

(15.c) $$l_{zt} = \sum_{t=9}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} F^i_{q\,(j-1)(t-5)}.\ G^i_{j(t-5)}.\ E^i_j.\ R_{j3!}$$

where $E^i_j \geq 100{,}000$; $R_{js} \geq R^*_{js}$ *for* $s = 1, 2$; *and* $R_{j3!} < R^*_3$

The number of mysis lost, l_{mt}, is based on the number of mysis lost within 5 days of the mysis-PL1 transition (or the number of mysis from the spawns released 14 days before), and the transition rate from mysis to post larvae stage 1 (PL1).

$$(15.d)\ l_{mt} = \sum_{t=14}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} F^i_{q\,(j-1)(t-14)}.\ G^i_{j(t-14)}.\ E^i_j.\ R_{j4!}$$

where $E^i_j \geq 100{,}000$; $R_{js} \geq R^*_{js}$ *for* $s < 4$; *and* $R_{j4!} < R^*_4$

The number of PL1 lost, l_{at}, is based on the number of PL1 within 14 days (or the number of mysis from the spawns released 28 days before), and the transition rate from PL1 to post larvae at the harvest (PLx).

$$(15.e)\ l_{at} = \sum_{t=28}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} F^i_{q\,(j-1)(t-28)}.\ G^i_{j(t-28)}.\ E^i_j.\ R_{j5!}$$

where $E^i_j \geq 100{,}000$; $R_{js} \geq R^*_{js}$ *for* $s \leq 4$;*and* $R_{j5!} < R^*_{j5}$

The total number of post larvae harvested at time t, L^i_{jt}, is calculated as follows:

$$(16)\qquad L^i_{jt} = F^i_{q\,(j-1)(t-28)}.\ G^i_{j(t-28)}.\ E^i_j.\ R_j$$

where $R_j = R_1.R_2.R_3.R_4.R_5$; $E^i_j \geq 100{,}000$; *and* $R_{js} \geq R^*_{js}$ *for all s*

Finally, the total number of post larvae harvested from production cycle q with the cycle duration D_q, L_q, is derived as follows:

$$(17)\qquad Lq = \sum_{t=28}^{Dq} Lt = \sum_{t=28}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} \{F^i_{q\,(j-1)(t-28)}.\ G^i_{j(t-28)}.\ E^i_j.\ R_j\}$$

where $R_j = R_1.R_2.R_3.R_4.R_5$; $E^i_j \geq 100{,}000$; *and* $R_{js} \geq R^*_{js}$ *for all s*

i. Calculation of net return per day (economic sub-model)

If the spawn is released at time t, and PLx are harvested in day $t+28$ with the price $P_{(t+28)}$, the total revenue of the production cycle, TR_q, is calculated as follows:

$$(18)\qquad TRq = \sum_{t=1}^{Dq} TRt = \sum_{t=1}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6} \{\alpha\ .F^i_{q\,(j-1)t}.\ G^i_{jt}.\ E^i_j.\ R_j.P_{(t+28)}\}$$

Let the average variable costs per '000 eggs of the tanks up to the stopping stage be C^i_{js}, and α the discount factor. If the duration of the spawn or tank use at the stopping stage is d_s, and TVC_q is the total variable costs of the production cycle q with the cycle duration D_q, then TVC_q is:

$$(19)\qquad TVCq = \sum_{t=1}^{Dq} TVCt = \sum_{t=1}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6}\sum_{s=1}^{5} \{\alpha\ .F^i_{q\,(j-1)(t-ds)}.\ G^i_{j(t-ds)}.\ E^i_j.\ (R_{js}!).C^i_{js}\}$$

where s is the stopping stage of the spawns; and d_s *is the duration of the spawns*

If the duration of a production cycle is D_q, because TR_t is zero for all of $t < 28$, the total net returns obtained from production cycle q, $\prod q$, is:

$$(20)\qquad \prod q = \sum_{t=1}^{Dq}(TRt - TVCt) = \sum_{t=1}^{Dq}\sum_{i=2}^{3}\sum_{j=1}^{6}\sum_{s=0}^{5} \{\alpha.F^i_{q\,(j-1)(t-ds)}.G^i_{j(t-ds)}.E^i_j.[(R_j.P_{(t+28)}) - (R_{js}!).C^i_{js}]\}$$

where $P_{(t+28)} = 0$ *for all of* $s < 5$, *and* $R_{j(s-1)} \geq R^*_{(s-1)}$

Finally, the optimal stopping point of each production cycle is obtained by maximizing the expected value of profit per operational day of the cycle. In each production cycle, the following formula can be derived from (20). This is based on the delay in the transition process between the spawning and larval rearing phases.

$$(21) \qquad Max \prod_{t=1}^{Dq} / Dq = 1/Dq \sum_{t=1}^{Dq} \sum_{i=2}^{3} \sum_{j=1}^{6} \sum_{s=0}^{5} \{\alpha.F^{i}_{q\,(j-1)(t-ds)}.G^{i}_{j(t-ds)}.E^{i}_{j}.[(R_j.P_{(t+28)}) - (R_{js}!).C^{i}_{js}]\}$$

where $P_{(t+28)} = 0$ *for all of* $s < 5$, *and* $R_{j(s-1)} \geq R^*_{(s-1)}$

5. Shrimp hatchery simulation

In order to obtain the approximate optimal solution for the hatchery operation, a simulation of the shrimp hatchery system is conducted using Excel spreadsheets and Visual Basic Applications in Excel (VBA). Kofler (2000) and Roman (2002) provide a great reference on this topic.

A function named TRIANGULAR is used to generate values of stochastic variables drawn from distributions characterised by minimum, mode and maximum values as the parameters, and random numbers generated by using a uniform distribution (Anderson, Dillon, and Hardaker 1977, p. 269). This function is used to calculate variables by spawn number and female group such as: the number of eggs per spawn, the transition rates of larvae, and the average total variable costs (AVC) per '000 eggs by the stopping stage of the spawn or tank.

For the price of PLx, data on the PLx price were collected every two weeks in 2001 and 2002. These prices for 2001 are transformed into daily prices in 2001 using the interpolation method. Therefore, at any day t of the operational year, there is a value of P_t for the PLx harvested at that day.

The simulation method is authorised by a number of authors (Naylor, 1971; Law and Kelton, 1982; Kennedy, 1986; Moore, Lee and Taylor, 1993; Taha, 1997; and Anderson, Sweeney, and Williams, 1998). For a complex system, simulation is a good alternative to obtain the approximate optimal solution using a search approach. The forward recursive simulation of the shrimp hatchery system is applied using the following steps:

a. Identify the size of the hatchery for modelling (the number of larval tanks designed);

b. Start from December 1, search for the optimal number and structure of females for the first purchase based on the hatchery size => obtain the optimal stopping time for production cycle q where the maximum net return per day, $\prod^*_{Dqt}$, including dry-out time, is obtained ($q = 1$ for the first cycle). Calculate the values of variables at the optimal stopping time of the cycle.

c. Based on the initial optimal stopping day obtained in (2), plus 5 days for dry-out time calculate the day for purchasing the next batch of females. Calculate the values of variables of cycle $q + 1$ following the optimal stopping time for this cycle after finishing the search procedure for the following situations:

i. If the maximum net returns per day of cycle *q* is equal to or less than zero, stop cycle *q*, and buy the next batch of females after allowing for the dry-out time;

ii. If the maximum net returns per day of cycle *q + 1*, $\prod^*_{D(q+1)t}$, is less than that of cycle *q*, $\prod^*_{Dqt}$, then keep cycle *q* one more day, that is, to day *t + 1*, and repeat the search for the maximum net return per day of cycle *q + 1*. Compare the updated values of the net returns per day of *q* and *q + 1* until the day when $\prod^*_{Dqt} < \prod^*_{D(q+1)t}$, then prepare to purchase a new batch of females; and

iii. In the case where $\prod^*_{Dqt} > 0$, and $\prod_{Dqt} \geq \prod^*_{D(q+1)t}$ for all of *t*, then keep cycle *q* until the end of all spawns of cycle *q*, then prepare to purchase a new batch of females.

d. Repeat the procedure in (3) for the next cycles with the dry-out time between the cycles until reaching the cut-off time for buying a new batch of females.

e. Calculate the values of variables for the whole year by summing up the values of variables through the cycles following the optimal stopping time of the cycles.

The whole year model with *Q* cycles is then run for 50 or 100 times. The mean and standard deviation of the major variables are analysed for validation and verification of the model. There are several major initial results reported below from the simulation experiment applied to the first production cycle of a 12-tank hatchery if the beginning time or the day of purchase of the first batch of female shrimp is on December 1:

(1) A number of 16 females should be purchased of which, 7 are females without ovarian development at the point of purchase, and 9 are females without ovarian development at the point of purchase.

(2) The maximum net returns per day of VND 276,300 (about A$35) obtained after the purchase of females 53 day;

(3) The level of net returns strongly depends on the following major parameters:

- *Spawning rate of female shrimp:* a 20 percent decrease in the spawning rate causes a decrease of 36.5 percent in the total net returns per day;
- *Number of eggs per spawn:* a 20 percent decrease in the number of eggs per spawn brings about a decrease of 55.3 percent in the total net returns per day because of a bigger chance of the total loss in the number of larval tanks;
- *Hatching rate of eggs:* a reduction of 20 percent in the hatching rate of eggs pulls the total net returns per day down about 188.9 percent. As well, this change makes the cycle longer 3 days;
- *Total variable costs:* a 20 percent change in the total variable cost makes the total net returns per day change by 68.4 percent.

The results imply that, in order to obtain an improvement in the total net returns, a better supply of the major inputs, especially female shrimp should be ensured. This requires better management of the broodstock-catching activities or natural marine resource management, as well as an improvement in the domestication of shrimp for reproduction, and in the technical and managerial skills of the hatchery operators. The results of the model after being validated, can be applied to the management of the hatchery network and the trading of broodstocks and post larvae within the Delta and between the regions of Vietnam.

Table 2: Major initial results from the experiment of the first cycle (12-tank hatchery)*

Description	*Original*	*Spawning rate*	*No.off eggs*	*Hatching rate*	*TVC***
Change of the control variable (%)	-	-20.0	-20.0	-20.0	+20.0
Time of MaxNR*** (day)	53	53	53	56	53
MaxNR (VND'000)	276.3	239.8	221.1	87.5	207.9
Change in MaxNR (%)	-	-36.5	-55.3	-188.9	-68.4
Mean MaxNR (VND'000)	410.6	342.0	328.5	212.9	351.1
Standard Dev. (VND'000)	628.4	511.2	502.7	454.0	580.9
Probability of the total loss	0.12	0.12	0.12	0.18	0.12

**: The papameters (a, m, and b) of the relevant triangular distributions were increased or decreased to carry out the experiment.*

***: TVC is the total variable costs per '000 eggs by the time of discharging or harvesting of the spawn/tank.*

****: MaxNR per day is the maximum total net returns per day, the dry-out time is included in the cycle duration.*

6. Conclusions and recommendations

Shrimp seed production plays an essential role in the development of the shrimp industry in the Mekong River Delta of Vietnam. From a analysis of the production in the shrimp hatchery system, two major phases have been identified, that is, spawning phase of female shrimp and larval rearing phase which consists of five different main stages from eggs through the larval stages to post larvae at the harvest. These stages and four components to the model were used to develop a bio-economic model of a shrimp hatchery in the Mekong Delta.

Major assumptions and conditions were developed for the model. As well, the most important state and decision variables and parameters (both stochastic and non-stochastic) are identified. These variables and parameters are mainly based on the spawn number and type of female at the point of female purchase. A set of cut-off values of the parameters were used in order to obtain acceptable levels of time and quality of the post larvae produced. All of these were combined in a discrete, dynamic and stochastic model of the shrimp hatchery operation processes.

From the development of the model, the following are important to the success of the shrimp hatchery operation: (i) identify the hatchery size; (ii) the number of females; (iii) spawning rate of female shrimp; (iv) the number of eggs per spawn; (v) the hatching rate of eggs; and (vi) the total variable costs. If the number of females in each production cycle is identical, a set of initial useful results can be drawn.

One possibility revealed by this model is that the nauplii can be traded between the hatcheries in order to utilize the empty tanks in the hatcheries, or between the hatcheries and the larvae-rearing-only sites to make the production cycles in the hatcheries shorter. This will help to save eggs and nauplii obtained, and provide more post larvae to the "shrimp grow-out" farms during the peak season of demand for shrimp seed.

At the regional level, this model helps to estimate the number of broodstock required and the number of PLx produced by time of the year. This is good for the management of broodstock-catching and trading activities. This model can be extended by including pond-reared females, so that all of the possible alternatives will be available for making decisions in the shrimp hatchery management.

As well, it is good for the management of the brood stock and post larvae traded between the regions, especially during the peak season of stocking activities conducted by a huge number of "shrimp grow-out" farms.

However, there are some notes for the completion of the model. First, is a concern caused by errors in the estimation of the parameters due to the small sample size in some cases, as well as the time constraint. The issues can be listed as follows:

- The number of spawns per female for female group 2 should be the same as that for female group 3. This can be solved if assume that from the 4th and later spawns, both female groups have the same spawning rate, number of eggs per spawn and costs of the larvae discharged at each larval stage;
- The use of a triangular distribution breaks down when the mode value of the parameters is zero; and
- Difficulty in deriving a stochastic distribution for costs of the spawns/tanks discharged at each larval stage because of the small numbers at some stages in the recorded data.

Acknowledgements

The authors appreciate very much the support from The Australian Centre for International Agricultural Research (ACIAR) who has financially supported this work and to Dr. Nigel Preston, and Dr. Peter Crocos of CSIRO, Brisbane, Australia; Prof. Kwei Lin of Asian Institute of Technology, Bangkok, Thailand; Dr. Hoang Tung, and Dr. Ta Khac Thuong, Nhatrang Fisheries University, Vietnam; Mr. Thach Thanh, and Mr. Tran Ngoc Hai, Cantho University, Vietnam; and to Dr. Matinez Codero, University of Hawaii-Manoa, Hawaii. The help and assistance of the above is greatly appreciated.

Appendix 1: Notations for the hatchery model

The following notations are used for the formulation of the shrimp hatchery model:

M: Number of larval tanks used in a production cycle

q: Production cycle number, $q = 1, 2, \ldots, Q = 8$

Q: Number of production cycles per operational year

D: Duration of an operational season (production year)

D_q: Duration of a production cycle including the dry-out time

D_r: Dry-out duration between two cycles q and $q+1$ (can be set to be 5, 10, 15)

i: Group of females, $i = 2, 3$. Group 1 (pond-reared females, FG1) is excluded. Group 2 (FG2) and group 3 (FG3) are wild females without and with ovarian development at the point of purchase

j: Spawn number of the spawns released, $j = 1, 2, \ldots, 6$

d_j: Duration from the purchase of females to the release of the spawns j (d_{jmax} = 35 days for the last spawn of the females in a production cycle)

T_q: Beginning day of cycle q (female purchase), is counted from the 1st December

T_e: Spawning day of the spawn

T_s: Stopping time of a spawn at larval stage s

t: Time within a production cycle, in day from the point of females purchase (T_q)

F_q: Number of females in each female group for production cycle q

G_a: Probability that a spawn is released

G_b: Probability that a spawn is good for hatching (using the visual checking method)

G_t: Probability that a good spawn is released at time t, $\sum G_t = 1$.

E: Number of eggs released per spawn

e: Egg

n: Nauplii

z: Zoea

m: Mysis (for the larval stage); and the number of larval tank lost (for the tanks)

P_a = PL1: Post larvae stage 1

P_b = PLx: Post larvae at the harvest

R: Accumulated transition rate from eggs into the stopping stage of larvae

s: Event or larval stage of the spawn (also used for the stopping stages of the spawns)

- s = 0: Eggs (from the purchase of the female to the spawn)
- s = 1: Nauplli (also the stage of transition from eggs into nauplii)
- s = 2: Zoea (also the stage of transition from nauplii into zoea)
- s = 3: Mysis (also the stage of transition from zoea into mysis)
- s = 4: Post larvae stage 1 (PL1) (also the stage of transition from mysis into PL1)
- s = 5: Post larvae at harvest (PLx) (also the stage of transition from PL1 into PLx)

R_{js}: Survival rate of larvae from larval stage *s-1* to stage *s* of spawn *j*

l_s: Number of eggs or larvae discharged before reaching the size of PLx (s = e, n, …b)

L: Number of PLx harvested (= l_s where s = 5)

P: Price of PLx sold (returns from each PLx)

C_s: Total cost per '000 eggs stocked in the tank up to the stopping stage s of the spawn

TFC: Total fixed costs, is assumed to be constant between the cycles

TVC: Total variable costs of the events (per spawner, group, cycle, and per year)

TC: Total production costs of the events (per spawner, group, cycle, and per year)

TR: Total revenues of the events

r: Interest rate per day

α: Discount rate per day

u: Random or stochastic term

∏: Net returns (from the spawns, females, cycles, year), ∏ = TR - TVC

REFERENCES

1. Allen, P. G. et al., (1992), *Bioeconomics of Aquaculture*, Elservier; 3rd reprint.
2. Anderson, D, R; Sweeney, D, J.; and Williams, T, A. (1998), *Quantitative Methods for Business*, 7th edn, South-Western College Publishing.
3. Anderson, J.R., Dillon, J.L. and Hardaker, J.B. (1977), *Agricultural Decision Analysis*, Iowa State University Press, Ames, Iowa .
4. Burt, O.R. (1965), "Optimal replacement under risk", *Journal of Farm Economics*, 47(2) 324-346.
5. Cacho, O.J. (1993), "Development and Implementation of A Fish-Farm Bioeconomic Model: A Three-Stage Approach", in *Aquaculture Model and Economics* (edited by U. Hatch and H. Kinnucan), Westview Press (1993), pp: 55-72.
6. Cacho, O.J. (1997), "System modelling and bioeconomic modelling in aquaculture", *Journal of Aquaculture Economics & Management*, 1(1) 45-64.
7. Chanratchakool P. et al., (1998). *Health Management in Shrimp Pond*, 2nd edn, Aquatic Animal Health Research Institute (AAHRI), Bangkok.
8. France, J.; and Thornley, J.H.M. (1984). *Mathematical Models in Agriculture: A Quantitative Approach to Problems in Agriculture and Related Sciences*, Butterworths.
9. Fridley, R.B. (1987), "Modelling, identification and control of aquaculture processes and facilities". In *Automation and data processing in Aquaculture*, J.G. Balchen (Editor), IFAC Proc. Ser. No. 9. A. Wheaton, Exeter, (1987) pp: 17-23.
10. Hoang, T. (1998), Quality of post larvae and its improvement from multiple spawning of *Penaeus monodon* broodstocks. Master thesis, Asian Institute of Technology (AIT), Bangkok, Thailand.
11. Hochman, E. (1973), "An Optimal Stopping Problem of A Growing Inventory", *American Journal of Management Science*, Vol.19, pp: 1289-1291.
12. Hochman, E. et al., (1990), "Optimal Scheduling in Shrimp Mariculture: A Stochastic Growing Inventory Problem", *American Journal of Agricultural Economics*, Vol.? (1990) pp: 372-393.
13. Hochman, E.; and Lee, I.M. (1972). *Optimal Decision in the Broiler Production Firm: A Problem of Growing Inventory*. Giannini Foundation Monograph, No.29, June, 1972.
14. Jones, W.J.; and Luyten, J.C. (1998), "Simulation of Biological Processes", in *Agricultural Systems Modelling and Simulation* (edited by R.M. Peart and R.B. Curry), Marcel Dekker, Inc. pp: 19-62.
15. Keen, R. E.; and Spain, j. D. (1992), *Computer Simulation in Biology: A BASIC Introduction*. Wiley-Liss.
16. Kennedy, J.O.S. (1986), *Dynamic Programming: Applications to Agriculture and Natural Resources*. Elsevier Applied Science Publishers.
17. Kofler, M.; translated by David Kramer, (2000), *Definitive Guide to Excel VBA*, Apress.

18. Law, A.M; and W.D. Kelton, (1982), *Simulation Modelling and Analysis*, MacGraw-Hill Book Company.
19. Leung, P. (1986), Applications of System Modeling in Aquaculture. *Journal of Aquacultural Engineering*, No.5, pp: 171-182.
20. Leung, P.; Hochman, E.; Rowland, L.W.; and Wyban, J.A. (1990). "Modeling Shrimp Production and Harvesting Schedules", *Journal of Agricultural Systems*, No.32, pp: 233-249.
21. Logan, S.H.; and Johnston, W.E. (1993), "A Replacement Model for Rainbow Trout Broodstock Under Photoperiod Control", in *Aquaculture: Models and Economics*| edited by U. Hatch and H. Kinnuca. Westview Press Inc.
22. Manly, B.F.J. (1990). *Stage-Structured Populations*. Chapman and Hall.
23. Martineze-Cordero, F.J.; Seijo, J.C.; and Lua'rez-Mabarak, L. (1995), "The Bioeconomic Analysis of A Penaneus Vannamei Hatchery in Mexico, Applying Time Distributed Delay Functions", *Proceedings of the 7th Biennial Conference of the International Institute of Fisheries Economics and Trade.* International Institute of Fisheries Economics and Trade. Vol.2, pp: 115-126.
24. Meade, J. W. (2001), "Management Considerations and Economics" in *Fish Hatchery Management*, 2nd edn, edited by G.Wedemeyer, American Fisheries Society, pp: 687-705.
25. Ministry of Fisheries (1996), *Vietnam's Fisheries*, Hanoi, Vietnam.
26. Ministry of Fisheries (1997), Regional Workshop on Master plan for Fisheries & Aquaculture in the Mekong Delta to 2010.
27. Ministry of Fisheries (2000), *Coastal Aquaculture of Vietnam*, Hanoi.
28. Ministry of Fisheries (2002), *Annual Report*, Hanoi, Vietnam.
29. Moore, L.J.; Lee, S.M.; and Taylor, B.W. (1993), *Management Science*, 4th edn, Allyn and Bacon.
30. Naylor, T. H. et al., (1966), *Computer Simulation Techniques*, John Wiley & Sons.
31. Naylor, T.H. (1969), *Design of Computer Simulation Experiments*.
32. Naylor, T.H. et al. (1971), *Computer Simulation Experiments with Models of Economic Systems*. Wiley.
33. Perrin, R.K. (1972), "Asset Replacement Principles", *American Journal of Agricultural Economics*, 54(1) 60-67.
34. Roman, S. (2002), *Writing Excel Macros with VBA***,** O'Reilly & Associates.
35. Rubinstein, R.Y.; and Melanmed, B. (1998), *Modern Simulation & Modelling*, Wiley.
36. Schulstad, G. (1997), "Design of a computerized decision support system for hatchery production management", *Journal of Aquaculture Engineering*, Vol.16, pp 7-25.
37. Taha, H.A. (1997), *Operations Research: An Introduction*, 6th edn, Prentice-Hall International, Inc.
38. Throsby, C.D. (1964), "Some dynamic programming models for farm management research", *Journal of Agricultural Economics*, Vol. 16, pp 98-110.
39. Weller, J.I. (1994), *Economic Aspects of Animal Breeding*, Chapman & Hall.