https://doi.org/10.17221/255/2016-AGRICECON

A study of production and harvesting planning for the chicken industry

Peng-Sheng YOU[1], Yi-Chih HSIEH[2*]

[1]*Department of Business Administration, National Chia-Yi University, ChiaYi, Taiwan*

[2]*Department of Industrial Management, National Formosa University, Huwei, Yunlin, Taiwan*

*Corresponding author: yhsieh@nfu.edu.tw

You P.-S., Hsieh Y.-C. (2018): **A study of production and harvesting planning for the chicken industry**. Agric. Econ. – Czech, 64: 316–327.

Abstract: To order to raise chickens for meat, chicken farmers must select an appropriate breed and determine how many broilers to raise in each henhouse. This study proposes a mathematical programming model to develop a production planning and harvesting schedule for chicken farmers. The production planning comprises the number of batches of chickens to be raised in each henhouse, the number of chicks to be raised for each batch, what breed of chicken to raise, when to start raising and the duration of the raising period. The harvesting schedule focuses on when to harvest and how many broilers to harvest each time. Our aim was to develop proper production and harvesting schedules that enable chicken farmers to maximise profits over a planning period. The problem is a highly complicated one. We developed a hybrid heuristic approach to address the issue. The computational results have shown that the proposed model can help chicken farmers to deal with the problems of chicken-henhouse assignment, chicken raising and harvesting, and may thus contribute to increasing profits. A case study of a chicken farmer in Yunlin County (Taiwan) was carried out to illustrate the application of the proposed model. Sensitivity analysis was also conducted to explore the influence of parameter variations.

Keywords: chicken business, harvesting schedule, mathematical programming, production planning

Poultry farming describes the raising of domesticated birds such as chickens, ducks, geese, turkeys, guinea fowl, pigeons, quails and pheasants. Among these, and in the current market, chickens have the highest economic value. The greatest difference between farming products and industrial products lies in the restrictions due to the biological characteristics inherent in a living organism. Due to the growing process, poultry farming products cannot be massively produced in a few days and it takes, for example, about six to seven weeks to raise a white broiler chicken to maturity. In order to raise chickens for meat, chicken farmers must determine the breed, quantity and stocking density in each of their henhouses during the planning phase. According to a survey of chicken farmers in Taiwan, feed costs for raising a broiler account for 64.8% of total production costs indicating that the direct costs are very high compared to other costs. To reduce feeding costs, chicken farmers attempt to sell the mature chickens to market in a timely fashion. Because the market demand and sale price of chickens usually fluctuates over time, the sale price at the point when chickens are sold to market is usually different than the price when the chicken production was initiated. Thus, poor chicken production planning may produce products at an unsuitable time and result in higher costs and poor revenues. In order to increase profits, it is necessary for chicken farmers to properly plan the raising and harvesting of different chicken breeds in respective henhouses to maximise their profit.

To help chicken farmers to deal with this problem, this paper investigated chicken production in multi-henhouses and multiple types of chicken and aimed to develop proper production and harvesting schedules to maximise profits over a given planning period. The production planning comprises the number of batches of chicken to be raised in each henhouse, and the decisions of what breed of chicken to raise, when to start raising and the duration of the raising period for each raising batch. The harvesting schedule focuses on the problems of when to harvest and how many chickens to harvest. This paper simultaneously deals with the decision problems associated with production quantity, raising area selection and harvest for chicken raising.

https://doi.org/10.17221/255/2016-AGRICECON

LITERATURE REVIEW

In the past, most production planning-related research has focused on problems of the livestock industry. Stygar and Makulska (2010) pointed out that mathematical models were usually used to derive production planning decisions for livestock management. The methodology used to generate these models can be divided into optimisation approaches (Wang and Leiman 2000; Rodríguez 2009; Yu et al. 2009; Moghaddam and DePuy 2011; Ohlmann and Jones 2011; Rodríguez-Sánchez 2012), and simulation approaches (Coleno and Duru 1999; Yu and Leung 2005; Gradiz et al. 2007; Villalba et al. 2010). Among these reports, Rodríguez-Sánchez et al. (2012) formulated a linear programming model to explore sow production planning problems by considering pig equipment, survival rate, viviparous rate and the number of pig houses. Kristensen and Søllested (2004) applied the multi-level hierarchical Markov process to develop a model to determine the time to sell pigs and purchase piglets. Villalba et al. (2010) proposed a stochastic simulation model to address herd breeding problems. Crosson et al. (2006) developed a linear programming model to investigate beef production problems. Ohlmann and Jones (2011) proposed a mixed-integer linear programming model to determine the optimal selling weight for piglets. Pathumnakul et al. (2009) addressed the optimal breeding and harvesting times for shrimps. Yu and Leung (2005) were also concerned with shrimp harvesting over multiple periods and ponds: a linear programming model was developed to solve the problem. Tian et al. (2000) investigated the production scheduling problem for shrimps. In their model, the size and number of ponds, shrimp stocking density and shrimp survival rate are considered. Forsberg (1996) were interested in determining the optimal breeding and harvesting time for fish. Bjørndal (1988) focused on fish harvesting problems and Hern (1994) addressed the harvesting problems in the farming industry.

The literature mentioned above has mostly focused on developing production planning for shrimps, pigs and cattle. The harvesting problem and the raising area selection/allocation problem were rarely discussed. Plà-Aragonés (2005) formulated farming allocation as a semi-Markova decision problem, and used a simulation approach to solve the proposed model. Coleno and Duru (1999) investigated the distribution of cow grazing areas and forage harvest dates. McCarthy et al. (1998) discussed land allocation for grazing and farming cattle. Engle (1997) proposed a linear programming model to discuss land allocation for fish and agriculture products. Engle et al. (2010) dealt with the production planning problem in relation to catfish. Rupasinghe and Kennedy (2006) discussed the feeding size problem for barramundi. Instead of a single-batch harvesting, Yu et al. (2006) proposed a partial harvesting schedule to investigate a production planning problem with a single cycle for culture species. They also derived necessary conditions to efficiently determine a discrete partial harvesting strategy.

Many studies have proposed strategies for dealing with the problems of animal husbandry and the industry's production planning, but few have simultaneously dealt with the problems of production quantity, raising area selection and harvest for the chicken industry. This study was aimed at developing an integer programming model to investigate these three problems for chicken farmers raising a variety of chicken types in a number of different-sized henhouses. A real case in Yunlin County in Taiwan was also investigated. This study derived decisions by applying this model to maximise profits in a scheduled period with the purpose of helping chicken farms complete proper production and harvesting planning. Sensitivity analysis was also conducted to explore the impact of parameter variations such as cost to feed to maturity, the number of henhouses and the number of chicken types on the computational results.

MODEL AND ASSUMPTION

A chicken farmer runs a farm business raising K-types of chickens in L henhouses. Baby chicken type-k is purchased from a supplier at a cost of c_k^b dollars per unit and needs $n_k^{\min}$ weeks of feeding to reach maturity status. Based on considerations related to chicken meat quality and raising time, baby chicken type-k is raised for at most $n_k^{\max}$ weeks. Depending on the breeding age, the amounts of feed are different. The overall cost of feeding a type-k chick to maturity is roughly c_k dollars. After the age of maturity, the cost of feeding a type-k chicken is c_k^g dollars per week.

The farmer does not raise more than one type of chicken in a henhouse at the same time. The chickens' growth and survival rates will decrease if there are too many chickens in a henhouse. Thus, each

https://doi.org/10.17221/255/2016-AGRICECON

henhouse has a farming capacity/limit for different types of chicks. The farming capacity for chicken type-k raised in henhouse ℓ, g_{kt}^{ℓ}, cannot exceed m_k^{ℓ} chicks. During the breeding periods, chickens may die due to illness and other factors. The ratio of the number of chickens scheduled to be harvested to the number of saleable chickens of chicken type-k in henhouse ℓ is denoted by r_k^{ℓ}. Suppose that it is planned that o_{kt}^{ℓ} type-k chickens will be harvested at the end of period t from henhouse ℓ. Then, the expected saleable chickens are $r_k^{\ell} o_{kt}^{\ell}$. In addition, a new batch of chickens cannot be raised in a henhouse before the henhouse is cleaned. The time required to clean a henhouse is b_k weeks when its previous breeding chicken is type-k.

Demand for type-k chicken in week t is assumed to be d_{kt}. The sales prices for all chickens fluctuate over time. The sales price for type-k chicken in week t is estimated to be p_{kt}. The chicken farmer expects to make a T-week production plan to maximise his/her profit. The notation is summarised as follows.

Parameters

K the number of types of chicken

L the total number of henhouses

T the total planning period (weeks)

b_k the time needed to clean a henhouse after breeding chicken type-k

c_k^b the unit purchasing cost of baby chick type-k

c_k the overall cost of feeding a type-k chick to reach maturity

c_k^g the unit cost of feeding a type-k maturity chick per week

d_{kt} the demand for chicken type-k in week t in market

m_k^{ℓ} the breeding capacity/limit for chick type-k in henhouse ℓ

$n_k^{\min}$ the minimum breeding weeks of a type-k chick

$n_k^{\max}$ the maximum breeding weeks of a type-k chick

p_{kt} the unit sales price for a type-k chicken in week t

r_k^{ℓ} the survival rate (%) for a type-k chick in henhouse ℓ

B a very large number

s_{kt} the number of saleable type-k chickens in week t

v_{kt}^{ℓ} the remaining number of mature type-k chickens raised in henhouse ℓ at the start of week t

Decision variables

x_{kt}^{ℓ} =1 if type-k chicken is breeding in henhouse ℓ in week t and zero otherwise

y_{kt}^{ℓ} =1 if the raising of a batch of type-k chickens begins at the start of week t in henhouse ℓ and zero otherwise

z_{kt}^{ℓ} =1 if the type-k chicken that is raised in henhouse ℓ can be harvested at the end of week t and zero otherwise

g_{kt}^{ℓ} the number of type-k baby chicks that are raised from the start of week t in henhouse ℓ

o_{kt}^{ℓ} the harvest number of type-k chickens from henhouse ℓ at the end of week t

Mathematical model

Before developing the mathematical model, we use the following example to express the relationship among the values of x_{kt}^{ℓ}, y_{kt}^{ℓ} and z_{kt}^{ℓ}. Consider a T = 18 period raising plan with two types of chick (K = 2) and a henhouse (L = 1), namely henhouse 1. Suppose that it requires three periods to raise a baby chick to reach maturity and one period to clean the used henhouse for both chicken types. The maximum breeding period for both chickens is assumed to be six periods. Table 1 illustrates a feasible raising schedule and shows that no chick is raised before period three. The value of y_{14}^1 = 1 means that at the start of period four, a batch of type-1 baby chicks is raised. The batch of chicks is raised from periods four to eight ($x_{1t}^1 = 1$ for $4 \le t \le 8$). At the end of period six, the batch of baby chicks reaches maturity and can be harvested. The harvestable periods are from period six to period eight ($z_{1t}^1 = 1$ for $6 \le t \le 8$). Thereafter, the henhouse is cleaned in period nine. Until period 11, the farmer raises a batch of type-2 chicks ($y_{2,11}^1 = 1$). This batch of chicks is raised until period 16 ($x_{2t}^1 = 1$ for $11 \le t \le 16$). The batch of baby chicks reaches maturity at the end of period 13 and can be harvested over periods 13–16 ($z_{2t}^1 = 1$ for $13 \le t \le 16$).

The purpose of the problem is to maximise the expected profit by determining the values of x_{kt}^{ℓ}, y_{kt}^{ℓ}, z_{kt}^{ℓ}, g_{kt}^{ℓ} and o_{kt}^{ℓ}. The objective function is composed of sales revenues (R), costs of purchasing baby chicks (PC), food costs of feeding baby chicks to maturity (FCB) and costs of feeding chickens after maturity is reached (FCM). Let F be the total expected profit. Then, we wish to:

$$\max\ F = \sum_{k=1}^{K}\sum_{t=1}^{T} s_{kt} p_{kt} - \sum_{k=1}^{K}\sum_{\ell=1}^{L}\sum_{t=1}^{T} g_{kt}^{\ell} c_k^b - \sum_{k=1}^{K}\sum_{\ell=1}^{L}\sum_{t=1}^{T} g_{kt}^{\ell} c_k - \sum_{k=1}^{K}\sum_{\ell=1}^{L}\sum_{t=1}^{T} v_{kt}^{\ell} c_k^g \quad (1)$$

It requires $n_k^{\min}$ weeks to raise a type-k baby chick to reach maturity. Thus, a type-k baby chick raised from the start of week $t - n_k^{\max}$ will reach maturity at week t – 1. Accordingly, the relationship between the

https://doi.org/10.17221/255/2016-AGRICECON

number of mature type-k chickens raised in henhouse ℓ at the start of week t, v_{kt}^{ℓ} and the number of type-k baby chicks raised from the start of week t in henhouse ℓ, g_{kt}^{ℓ}, can be expressed by Equation 2.

$$v_{kt}^{\ell} = \begin{cases} 0, & \forall\, k,\ \ell,\ t \le n_k^{\min} \\ v_{k,t-1}^{\ell} + g_{k,t-n_k^{\min}}^{\ell} - o_{k,t-1}^{\ell}, & \forall\, k,\ \ell,\ t > n_k^{\min} \end{cases} \tag{2}$$

Suppose that it is planned to harvest o_{kt}^{ℓ} type-k chickens from henhouse ℓ at the end of week t. Since the survival rate for type-k chickens raised in henhouse ℓ is r_k^{ℓ}, the expected sales amount is $r_k^{\ell} o_{kt}^{\ell}$. Thus, the number of saleable type-k chickens in week t, s_{kt}, is expressed by Equation 3.

$$s_{kt} = \sum\nolimits_{\ell=1}^{L} o_{kt}^{\ell} r_k^{\ell},\ \forall\, k,t \tag{3}$$

Since s_{kt} cannot exceed demand, we have Constraint (4).

$$s_{kt} \le d_{kt},\ \forall\, k,t \tag{4}$$

In addition, we have the following constraints:

$$\sum\nolimits_{t'=t-b_k}^{t-1} \left(1 - \sum\nolimits_{k'=1}^{K} x_{k't'}^{\ell}\right) \ge y_{kt}^{\ell} b_k,\ \forall\, k,\ell,t > b_k \tag{5}$$

$$x_{k1}^{\ell} = y_{k1}^{\ell},\ \ \forall\, k,\ell \tag{6}$$

$$y_{kt}^{\ell} \le x_{kt}^{\ell},\ \ \forall\, k,\ell,t \tag{7}$$

$$y_{kt}^{\ell} + x_{kt}^{\ell} + x_{k,t-1}^{\ell} \le 2,\ \ \forall\, k,\ell,t > 1 \tag{8}$$

$$y_{kt}^{\ell} \ge x_{kt}^{\ell} - x_{k,t-1}^{\ell},\ \ \forall\, k,\ell,t > 1 \tag{9}$$

$$\sum\nolimits_{t'=t}^{t+n_k^{\min}-1} x_{kt'}^{\ell} \ge n_k^{\min} y_{kt}^{\ell},\ \forall\, k,\ell,t \tag{10}$$

$$\sum\nolimits_{t'=t-n_k^{\min}+1}^{t} x_{kt'}^{\ell} \ge z_{kt}^{\ell} n_k^{\min},\ \forall\, k,\ell,t \ge n_k^{\min} \tag{11}$$

$$\sum\nolimits_{t'=t-n_k^{\min}+1}^{t} x_{kt'}^{\ell} - n_k^{\min} < z_{kt}^{\ell} B,\ \forall\, k,\ell,t \ge n_k^{\min} \tag{12}$$

$$n_k^{\max} - \sum\nolimits_{t'=t-n_k^{\max}}^{t} x_{kt'}^{\ell} \ge 0,\ \forall\, k,\ell,t \ge n_k^{\max} \tag{13}$$

$$g_{kt}^{\ell} \le y_{kt}^{\ell} B,\ \forall\, k,\ell,t \tag{14}$$

$$g_{kt}^{\ell} \ge y_{kt}^{\ell},\ \forall\, k,\ell,t \tag{15}$$

$$g_{kt}^{\ell} \le m_k^{\ell},\ \forall\, k,\ell \tag{16}$$

$$\sum\nolimits_{k=1}^{K} x_{kt}^{\ell} \le 1,\ \forall\, \ell,t \tag{17}$$

$$x_{kt}^{\ell} B \ge v_{kt}^{\ell},\ \forall\, k,\ell,t \tag{18}$$

$$z_{kt}^{\ell} \le x_{kt}^{\ell},\ \forall\, k,\ell,t \tag{19}$$

$$o_{kt}^{\ell} \le z_{kt}^{\ell} B,\ \forall\, k,\ell,t \tag{20}$$

$$o_{kt}^{\ell} \le v_{kt}^{\ell} + g_{k,t-n_k^{\max}+1}^{\ell},\ \forall\, k,\ell,t \ge n_k^{\min} \tag{21}$$

$$x_{kt}^{\ell}, y_{kt}^{\ell}, z_{kt}^{\ell} \in \{0,1\},\ \forall\, k,\ell,t \tag{22}$$

Equation 1 is the objective function (total profit) to be maximised. Equation 2 expresses the number of mature type-k chickens raised in henhouse ℓ at the start of week t. Equations 3 and 4 give the sales amount in week t. Constraint (5) ensures that there are enough clearing periods before the raising of a batch of chicks begins. Constraints (6) and (7) establish the relationship between x_{kt}^{ℓ} and y_{kt}^{ℓ} to ensure that a batch of type-k baby chicks is raised in period t if chick type-k is raised in period t. Constraint (8) confines that $x_{k,t-1}^{\ell} = 0$ if the raising of the type-k chick starts in henhouse ℓ ($y_{kt}^{\ell} = 1$). That is, if $y_{kt}^{\ell} = 1$, then $x_{k,t-1}^{\ell} = 0$. Note that $y_{kt}^{\ell} \le x_{kt}^{\ell}$ in Constraint (7) ensures $x_{kt}^{\ell} = 1$ if $y_{kt}^{\ell} = 1$. Thus, if $y_{kt}^{\ell} = 1$, then $x_{k,t-1}^{\ell} = 0$ due to $y_{kt}^{\ell} + x_{k,t}^{\ell} + x_{k,t-1}^{\ell} \le 2$ in Constraint (8). Constraint (9) confines the relationships of y_{kt}^{ℓ}, x_{kt}^{ℓ} and $x_{k,t-1}^{\ell}$ when no new batch of chicks are raised from period t ($y_{kt}^{\ell} = 0$). Thus, one of the following two situations will occur: (i) a batch of type-k chicks is still being raised in period t, that is $x_{kt}^{\ell} = 1$, or (ii) no chick is raised in this period, that is $x_{kt}^{\ell} = 0$. In case (i), since $x_{kt}^{\ell} = 1$, we have $x_{k,t-1}^{\ell} = 1$ due to $y_{kt}^{\ell} = 0 \ge x_{kt}^{\ell} - x_{k,t-1}^{\ell}$. In case (ii), since $x_{kt}^{\ell} = 0$, Constraint (8) still holds for $x_{k,t-1}^{\ell} = 0$ or $x_{k,t-1}^{\ell} = 1$. Constraint (10) ensures that there is enough time to breed chickens to reach maturity before the end of the planning period. Constraints (11) and (12) ensure harvest if and only if the minimum number of breeding weeks has been reached. Constraint (13) ensures that the raising weeks cannot exceed the maximum number of breeding weeks. Constraints (14) and (15) ensure that a new batch of baby chicks is raised if a raising decision is made. Constraint (16) shows that the number of chicks raised cannot exceed the breeding capacity. Constraint (17) ensures that at most one type of chicken is raised in a henhouse. Constraint (18) ensures that if there are chicks in a henhouse then these are raised. Constraint (19) shows that no chicken can be harvested if no chicken is raised. Constraint (20) ensures that no chicken is harvested during the non-harvest period. Constraint (21) determines that the number of chickens harvested cannot exceed the number of chickens raised. Constraint (22) shows the ranges of variables x_{kt}^{ℓ}, y_{kt}^{ℓ} and z_{kt}^{ℓ}.

APPROACH

A raising plan consists of several chick-raising decisions. Since a raising decision in a previous stage will affect the subsequent ones, the considered raising plan

https://doi.org/10.17221/255/2016-AGRICECON

problem is a constrained combinatorial optimisation problem. Basically, the complexity of a combinatorial optimisation problem is highly influenced by the number of decision variables. In the chick raising problem, the decision variables include x^{ℓ}_{kt}, y^{ℓ}_{kt}, z^{ℓ}_{kt}, g^{ℓ}_{kt} and o^{ℓ}_{kt}. The total number of decision variables goes up to 5**K***L***T*. For example, if $T = 26$, $L = 6$, $K = 5$, then the farmer has to deal with a combinatorial problem with 3900 decision variables. Optimally solving this problem in a reasonable computational time is intractable, especially for larger-scale problems. Thus, a problem-solution approach that can give compromise solutions within a reasonable computational time is important. Several commercial optimisation software programs, such as LINGO solver and CPLEX solver can be adopted to solve this problem. However, computational experiences show that, for larger-scale problems, these commercial optimization software programs cannot guarantee feasible solutions within a reasonable timeframe. Thus, we developed a hybrid heuristic approach to generate comprise solutions within a reasonable time in this paper.

Next, we introduce the following notations to the problem-solution approach.

TD the total unsatisfied demands

t^s the starting time for the raising of a batch of baby chicks

t^e the ending time for a batch of raised chicks

d^r_{kt} the unarranged products of demands for type-*k* chickens in period *t*

F^{ℓ}_{kt} the remaining capacity to raise type-*k* chicks in henhouse ℓ at the start of period *t*

h^{ℓ}_{ktj} =1 if type-*k* chickens can be raised in henhouse ℓ at the start of period *t* and can produce a positive profit for harvesting in period *j*, and h^{ℓ}_{ktj}=0 otherwise

A_n $=(k_n, \ell_n, t_n)$, the raising pair for the n^{th} raising decision

Ω_n selection pool for action A_n

Ψ_{kt} the harvestable periods for type-*k* chicks raised from period *t*

The approach is established on a batch-by-batch raising concept. For each raising decision, the approach determines what kind of chick to raise, where to raise and when to start to raise. Suppose $A_n = (k_n, \ell_n, t_n)$ is the n^{th} raising decision, Then, a batch of type-k_n baby chicks is scheduled to be raised in henhouse ℓ_n from the start of period t_n. In addition, the approach will also determine how many to raise and when to harvest.

The raising decision of A_n is selected from the selection pool Ω_n. The generation of selection pool Ω_n is described in the *pool generation procedure*. The determination of the raising pair is described in the *raising combination procedure*. The raising and the harvesting number are described in the *allocation procedure*. The *status update procedure* renews the raising status after each raising decision. The proposed solution approach performs these four procedures repeatedly until all henhouses are unavailable or all demands are satisfied.

Below, we present the solution approach in detail. First, let R^{ℓ}_{ktj} be the expected profit from the raising of a type-*k* chicken in henhouse ℓ from the start of period *t* and harvested at the end of period *j*. R^{ℓ}_{ktj} is defined by Equation 23.

$$R^{\ell}_{ktj} = \begin{cases} \dfrac{p_{kt} - c^b_k - c_k - (j - t - n^{\min}_k + 1)c^g_k}{r^{\ell}_k} & \\ 0 & \text{otherwise} \end{cases}$$

$$\forall\, k, \ell, t \le T - n^{\min}_k,\ j \in \Psi_t \tag{23}$$

otherwise

where

$$\Psi_t = \{ j \mid t + n^{\min}_k - 1 \le j \le \min\{T, t + n^{\max}_k - 1\}\}, \forall\, t \tag{24}$$

The periods of $t + n^{\min}_k - 1$ and $\min\{T, t + n^{\max}_k - 1\}$ are, respectively, the earliest period and latest period to harvest type-*k* chickens raised from period *t*. The initial values of h^{ℓ}_{ktj}, F^{ℓ}_{kt}, d^r_{kt}, *TD*, x^{ℓ}_{kt}, y^{ℓ}_{kt}, z^{ℓ}_{kt}, g^{ℓ}_{kt} and o^{ℓ}_{kt} are set as follows.

(A) $TD = \sum_{k=1}^{K} \sum_{t=1}^{T} d^r_{kt}$ and $x^{\ell}_{kt} = y^{\ell}_{kt} = z^{\ell}_{kt} = g^{\ell}_{kt} = o^{\ell}_{kt} = 0$

(B) $d^r_{kt} = d_{kt}, \forall\, k, t$

(C) $F^{\ell}_{kt} = m^{\ell}_k\ \forall\, k, \ell, t \le T - n^{\min}_k + 1$ and $F^{\ell}_{kt} = 0$ otherwise

(D) $h^{\ell}_{ktj} = 1$ if $R^{\ell}_{ktj} > 0$ and $h^{\ell}_{ktj} = 0$ if $R^{\ell}_{kt} \le 0$.

In (D), h^{ℓ}_{ktj} is set to zero since harvesting in period *j* for type-*k* chicks raised from period *t* cannot generate positive profit.

(1) *Pool generation procedure*

For each raising batch, a farmer must determine what kind of chick to raise, where to raise and when to start to raise. The pool generation procedure is used to produce a candidate raising pair (k, ℓ, t). At the n^{th} allocation, we compute the profit value of each possible raising pair of (k, ℓ, t) with $F^{\ell}_{kt} > 0$ using Equation 25.

$$U^{\ell}_{kt} = \sum_{j \in \Psi_{kt}} d^r_{kt} R^r_{ktj}, \forall\, k, \ell, t \tag{25}$$

https://doi.org/10.17221/255/2016-AGRICECON

We refer to the raising pair (k,ℓ,t) corresponding to the j^{th} highest positive value in U_{kt}^{ℓ}s as set A_{nj} and set Ω_n as $\Omega_n = \Omega_n\{A_{n1}, A_{n2}, A_{n3}\}$.

(2) *Raising combination procedure*

According to the selection pool and the values of a chromosome (a solution pattern) $(v_1, v_2, \ldots, v_{KL})$, the raising combination procedure is used to select the raising decision A_n from pool Ω_n to determine what kind of chick to raise, where to raise and when to start to raise at the n^{th} raising plan. The solution will stop raising if $U_{kt}^{\ell} \le 0$ for all k, ℓ and t.

The selection rule is based on the element appearing in a chromosome which is codified by KL distinct integer numbers within the range of [1, 3]. For example, suppose that the values of a chromosome are $(v_1, v_2, \ldots, v_{KL}) = (1, 3, \underline{2}, 1, 1, 2, 1, 2, 1)$ and the selection pool at the third raising batch is $\Omega_3 = \{(2, 3, 1), (3, 1, 2), (2, 2, 1)\}$. In this case, since the number appearing in the third position of the chromosome is $v_3 = 2$, we set the raising combination A_3 at (3, 1, 2). That is, we start to raise type-3 chickens from period 2 in henhouse 1.

The number of pairs in Ω_n may be less than the value of v_n. We use the following rule to deal with this problem. Let $\|\Omega_n\|$ be the number of pairs in $\|\Omega_n\|$. At the n^{th} raising decision, if $\|\Omega_n\|$ is less than v_n, we replace v_n with $\|\Omega_n\|$. For example, if $\|\Omega_n\| = \{(2, 3, 1), (3, 1, 2)\}$ and $v_3 = 3$, then, since $\|\Omega_n\| = 2$, we update $v_3 = 2$ and set $A_3 = (3, 1, 2)$ to obtain $y_{32}^{1} = 1$.

Allocation procedure

Suppose that a decision of $A_n = (k,\ell,t)$ is made in the n^{th} raising decision. The procedure solves the problems of how many chicks to raise and when to harvest according to the following steps.

(A) Let $y_{kt}^{\ell} = 1$ and $x_{kt'}^{\ell} = 1$ for $t_n \le t' \le t_n + n_k^{\min} - 1$

(B) Let $t' = \max\{1, t_n + n_k^{\min} - 1\}$

(C) If $h_{ktt'}^{\ell} = 0$ or $F_{kt}^{\ell} = 0$ go to Step (J)

(D) $x_{kt'}^{\ell} = 1$, $z_{kt'}^{\ell} = 1$ and $o_{kt'}^{\ell} = \min\{d_{kt'}^{r} / r_{k'}^{\ell}, F_{kt}^{\ell}\}$

(E) $g_{kt}^{\ell} = g_{kt}^{\ell} + \min\{d_{kt'}^{r} / r_{k'}^{\ell}, F_{kt}^{\ell}\}$

(F) $d_{kt'}^{r} = d_{kt'}^{r} - F_{kt}^{\ell}$ if $d_{kt'}^{r} > F_{kt}^{\ell}$ and $d_{kt'}^{r} = 0$ if $d_{kt'}^{r} \le F_{kt}^{\ell}$

(G) $F_{kt}^{\ell} = F_{kt}^{\ell} - \min\{d_{kt'}^{r} / r_{k'}^{\ell}, F_{kt}^{\ell}\}$

(H) $TD = TD - \min\{d_{kt'}^{r} / r_{k'}^{\ell}, F_{kt}^{\ell}\}$

(I) If $t'+1 = t_n + n_{k_n}^{\min} - 1$, let $t' = t'+1$ and go back to Step (C), otherwise $t^e = t'$.

(J) Raising allocation for the n^{th} allocation steps

In Step-A, $y_{kt}^{\ell} = 1$ since a batch of type-k chicks is raised in henhouse ℓ at the start of period t. The batch of chicks cannot be sold before they reach maturity and they must be raised during periods $t \le t' \le t + n_k^{\min} - 1$. Thus, $x_{kt'}^{\ell} = 1$ for $t \le t' \le t + n_k^{\min} - 1$. The allocation procedure for the n^{th} allocation reports the number of g_{kt}^{ℓ} type-k chickens to raise in henhouse ℓ over period $t^s = t$ to period t^e. The harvest number in period t', $t + n_k^{\min} - 1 \le t' \le t^e$ is $o_{kt'}^{\ell}$.

(4) *Status update procedure*

To guarantee that the produced solutions are feasible solutions (all constraints are satisfied), we have to renew the parameter h_{ktj}^{ℓ}. Suppose the raising of type-k^* chickens has been scheduled for periods t^s to t^e in henhouse ℓ, then h_{ktj}^{ℓ} are updated according to the following rules.

(A) Since there is not enough time to raise a type-k chick from the start of period $t \in \{\max\{1, t^s - b_k - n_k^{\min} + 1\}, t^s - b_k\}$ to reach maturity before period $t^s - b_k$, we set $h_{ktt'}^{\ell} = 0$ for all k, t', $t \in \{i \mid \max\{1, t^s - b_k - n_k^{\min} + 1\} \le i \le t^s - b_k\}$.

(B) Since henhouse ℓ is occupied from period t^s to t^e, type-k chicks cannot be raised from the start of period $t \in \{t^s - b_k, \min(T, t^e + b_k)\}$. Thus, $h_{ktt'}^{\ell} = 0$ for all k, t', $t \in \{i \mid \max\{1, t^s - b_k\} \le i \le \min(T, t^e + b_k)\}$.

(C) Note that henhouse ℓ is occupied from period t^s to t^e. Type-k chicks cannot be harvested in period $t' \in \{t^s - b_k, \min(T, t^e + b_k)\}$, Thus, $h_{ktt'}^{\ell} = 0$ for all k, t, $t' \in \{i \mid t^s - b_k \le i \le \min(T, t^e + b_k)\}$.

(D) Note that henhouse ℓ is occupied from period t^s to t^e. Type-k chicks cannot be raised at the start of period $1 \le t \le t^s$ and harvested after period $t^s - b_k$. Thus, $\sum_{j=1}^{T} h_{ktt'}^{\ell} = 0$ for all k, $1 \le t \le t^s - b_k$, $t' \in \{i \mid t^s - b_k \le i \le T\}$.

(E) Let $F_{kt}^{\ell} = 0$ if $\sum_{j=1}^{T} h_{ktj}^{\ell_n} = 0$.

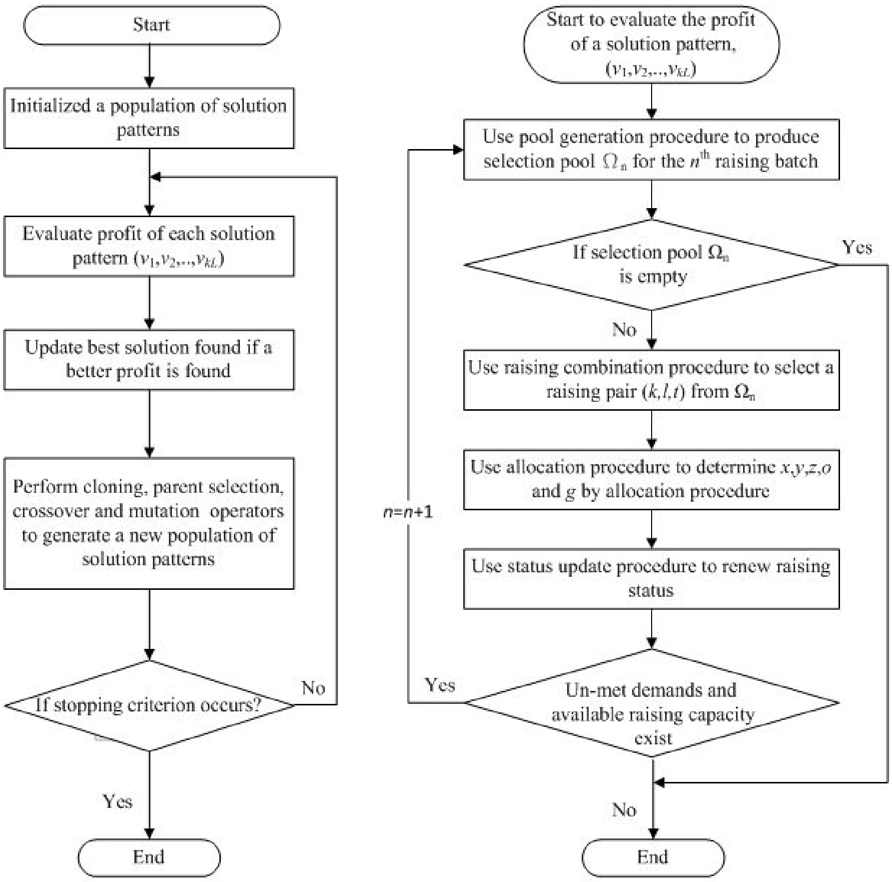
(F) Let $TL = TL - 1$ if $\sum_{k=1}^{K} \sum_{t=1}^{T} F_{kt}^{\ell} = 0$.

The outline of the proposed solution approach is depicted in Figure 1. Figure 1a shows the outline of the solution approach and Figure 1b shows the steps involved in evaluating the profit for each chromosome (solution pattern).

TEST PROBLEMS

We tested two main types of problem to evaluate the performance of the proposed approach. The corresponding parameters are based upon a company in Taiwan. This company has $L = 12$ henhouses and

https://doi.org/10.17221/255/2016-AGRICECON



(a) The steps of the solution approach (b) The steps to evaluate the profit

Figure 1. The hybrid solution approach and steps to evaluate the profil

breeds seven types of chicken. The raising capacity for type-k chicks in henhouse ℓ, m_k^ℓ, is shown in Table 2. The survival rate for the seven types of chicken in each henhouse, r_k^ℓ, are roughly over [0.855, 0.96] and are shown in Table 3. The time needed to grow type-k chickens to maturity is $n_k^{\min} = 13$ weeks. The maximum breeding time for these seven types of chicken must be no larger than $n_k^{\max} = 20$ weeks. The cost of breeding baby chicks to maturity, c_k, and the weekly cost of breeding mature chickens, c_k^g, are estimated and shown in Table 4. Before a new batch of chickens can be raised in a henhouse, the henhouse must be cleaned, a process which requires one week. At maturity, meat weights of the seven types of chicken can reach up to 3.3, 2.7, 2.7, 2.16, 2.7, 3.0 and 2.228 kg, respectively. The average sales prices per chicken for the seven types of chicken are 264.0, 216.0, 225.0, 180.0, 292.5, 390.0 and 296.4 (NT$ dollars), respectively. However, since the sales prices fluctuate over time, we randomly generated the sales prices of p_{kt} over range $[a_k^1, a_k^2]$ where a_k^1 and a_k^2 are shown in Table 5.

We test two main sets of problems as follows.

– *Problem Set A: (problem categories 1 to 4)*

There are four problem categories, categories 1 to 4, and each has seven cases with various demands.

Table 1. A raising schedule

t	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
y_{1t}^1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x_{1t}^1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
z_{1t}^1	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0
y_{2t}^1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
x_{2t}^1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
z_{2t}^1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0

https://doi.org/10.17221/255/2016-AGRICECON

Table 2. The values of m_k^ℓ

ℓ	k 1	2	3	4	5	6	7
1	6 000	4 900	4 900	3 900	4 900	5 500	4 100
2	6 000	4 900	4 900	3 900	4 900	5 500	4 100
3	7 500	6 100	6 100	4 900	6 100	6 800	5 200
4	7 500	6 100	6 100	4 900	6 100	9 500	5 200
5	10 500	8 600	8 600	6 900	8 600	9 500	7 300
6	10 500	8 600	8 600	6 900	8 600	9 500	7 300
7	12 000	9 800	9 800	7 900	9 800	10 900	8 300
8	12 000	9 800	9 800	7 900	9 800	10 900	8 300
9	13 500	11 000	11 000	8 800	11 000	12 300	9 300
10	13 500	11 000	11 000	8 800	11 000	12 300	9 300
11	21 000	17 200	17 200	13 700	17 200	19 100	14 500
12	21 000	17 200	17 200	13 700	17 200	19 100	14 500

Table 3. The values of r_k^ℓ

ℓ	k 1	2	3	4	5	6	7
1	0.930	0.960	0.960	0.855	0.930	0.915	0.855
2	0.960	0.900	0.915	0.960	0.960	0.900	0.930
3	0.915	0.900	0.960	0.900	0.900	0.900	0.915
4	0.930	0.930	0.945	0.930	0.870	0.900	0.915
5	0.870	0.900	0.960	0.890	0.880	0.900	0.945
6	0.885	0.915	0.870	0.960	0.920	0.960	0.945
7	0.960	0.945	0.960	0.930	0.890	0.945	0.900
8	0.960	0.885	0.885	0.930	0.915	0.900	0.885
9	0.930	0.915	0.930	0.900	0.910	0.960	0.915
10	0.930	0.880	0.930	0.870	0.900	0.930	0.945
11	0.900	0.890	0.870	0.915	0.885	0.900	0.930
12	0.960	0.945	0.945	0.880	0.890	0.930	0.960

Table 4. The values of c_k and c_k^g

k	1	2	3	4	5	6	7
c_k	155.1	135.4	143.6	141.3	143.6	161.0	156.8
c_k^g	14.64	14.55	13.64	13.64	13.64	14.01	14.01

Table 5. The range of sales prices per piece, a_k^1 and a_k^2

k	1	2	3	4	5	6	7
a_k^1	239	196	200	160	252	340	246
a_k^2	289	236	250	200	332	440	346

Table 6. Structure of problem categories 1–4

Category	1	2	3	4
K	2	2	3	5
L	5	6	12	12
T	18	26	26	52

The demand for test case n in problem categories 1–4 is set by the formula $d_{kt} + 0.1(n - 4)d_{kt}$. Additionally, the values of (K, L, T) for problem categories 1–4 are shown in Table 6. The main purpose of the test problems in set A is to compare the performance of the proposed approach with those of other well-known solvers, LINGO and CPLEX, for problems of various sizes. The numerical results of problem categories 1 to 4 are summarised in Table 7.

– *Problem Set B: (problem categories 5 to 7)*

There are three problem categories, categories 5 to 7, and each has seven cases with the same demands as those of the 4th case in problem category 4. Problem categories 5 to 7 conduct the sensitivity analysis on the parameters c_k^g, L and K and aim to investigate their impact on the computational results. More specifically, (i) for problem category 5, we set $L = K = 4$. In addition, we replaced c_k^g with ηc_k^g where η varies from 0.85 to 1.15 in increments of 0.05; (ii) for problem category 6, we set L = 2 to 8 for test cases 1 to 7; and (iii) for Problem category 7, we set K = 1 to 7 for test cases 1 to 7. The numerical results of problem categories 5 to 7 are summarised in Tables 8 to 10.

NUMERICAL RESULTS

In this paper, the symbol H/max(L,G) is used to evaluate the performance of the proposed approach (H) and the well-known solvers LINGO and CPLEX are assigned (L) and (G), respectively. More specifically,

H/max(L,G) = 100%×{[profit by HA)/max(profit by CPLEX, profit by LINGO)-1]}

In addition, all solution approaches will terminate if the execution time exceeds four hours; in such cases, the best profits are reported.

From Table 7, it can be seen that:

(1) For small-scale test cases in problem category 1, the CPLEX solver, the LINGO solver and the HA approach can produce nearly optimal solutions for all scale test cases. The gap of solutions for HA and the LINGO solver ranges only between 0.10% and 0.19%. Thus, the LINGO global solver, the CPLEX solver and the HA approach are all suitable approaches to solve the considered problem.

(2) For the medium-scale test cases in problem category 2, neither the CPLEX solver or LINGO solver could converge within 4 hours (14 400 seconds). Additionally, it was also observed that, in seven cases, the HA approach was superior to both the

https://doi.org/10.17221/255/2016-AGRICECON

Table 7. Computational results of problem categories 1–4

Problem Category	Cass No	LINGO		CPLEX		HA		Gap
		profit	time	profit	time	profit	time	H/max(L,G) (%)
1	1	520 079	105	519 852	9	519 124	9	–0.18
	2	594 403	75	594 382	11	593 250	10	–0.19
	3	668 820	104	668 673	22	667 818	11	–0.15
	4	743 073	95	742 999	7	741 971	11	–0.15
	5	817 441	112	817 338	12	816 512	11	–0.11
	6	891 675	73	891 277	7	890 595	11	–0.12
	7	966 129	54	966 132	13	965 185	10	–0.10
2	1	903 331*	14 400	915 536*	14 400	915 688	21	0.02
	2	1 046 530	14 400	1 037 117	14 400	1 040 873	22	–0.54
	3	1 175 542	14 400	1 167 167	14 400	1 176 315	21	0.07
	4	1 297 021	14 400	1 293 410	14 400	1 298 888	21	0.14
	5	1 425 078	14 400	1 421 249	14 400	1 425 617	21	0.04
	6	1 544 894	14 400	1 520 240	14 400	1 544 887	21	0.00
	7	1 659 447	14 400	1 644 691	14 400	1 640 168	22	–1.16
3	1	–**	14 400	1 421 066	14 400	1 449 528	81	2.00
	2	–	14 400	1 637 268	14 400	1 657 650	82	1.24
	3	–	14 400	1 835 917	14 400	1 865 338	81	1.60
	4	–	14 400	2 010 262	14 400	2 071 531	82	3.05
	5	–	14 400	2 258 311	14 400	2 278 582	82	0.90
	6	–	14 400	2 464 207	14 400	2 486 521	81	0.91
	7	–	14 400	2 684 360	14 400	2 693 019	82	0.32
4	1	–	14 400	–**	14 400	6 960 083	670	–
	2	–	14 400	–	14 400	7 944 859	674	–
	3	–	14 400	–	14 400	8 978 135	674	–
	4	–	14 400	–	14 400	9 922 681	679	–
	5	–	14 400	–	14 400	10 870 148	681	–
	6	–	14 400	–	14 400	11 871 746	716	–
	7	–	14 400	–	14 400	12 900 194	693	–

*the best profit within 14400 seconds; **not available within 14400 seconds

LINGO and CPLEX solvers for five cases. This implies that the HA approach is more promising and stable for solving medium-scale problems. Since the CPU time is only 21 or 22 seconds, the HA approach is much more efficient than both the LINGO solver and the CPLEX solver.

(3) For the larger-scale test cases in problem category 3, the LINGO solver failed to report any solution within 4 hours (14 400 seconds); the profits reported by the CPLEX solver within 4 hours were worse than those using the HA approach, and were 0.32% and 3.05%, respectively. The CPU

Table 8. Sensitivity analysis for maturity feeding cost ηc_k^g (problem category 5)

No	η	Profit	R	PC	FCB	FCM	NCR
1	0.85	3 369 597	15 507 818	1 505 486	9 650348	982387	62 308
2	0.90	3 315 138	15 307 454	1 485 592	9 522 845	983 879	61 486
3	0.95	3 260 644	15 307 454	1 485 592	9 522 845	1 038 373	61 486
4	1.00	3 207 696	14 659 925	1 419 820	9 101 311	931 097	58 768
5	1.05	3 162 140	14 102 637	1 362 294	8 735 483	842 721	56 570
6	1.10	3 122 115	14 102 637	1 362 294	8 735 483	882 745	56 570
7	1.15	3 083 323	13 647 017	1 311 563	8 407 481	844 651	54 294

FCB – feeding cost of raising baby chicks; FCM – feeding cost of raising chicks to maturity; NCR – total number of chicks to raise; PC – purchasing cost; R – revenues

https://doi.org/10.17221/255/2016-AGRICECON

Table 9. Sensitivity analysis for available henhouses L (Problem category 6)

No	L	Profit	R	PC	FCB	FCM	NCR	NCT
1	2	2 103 531	8 613 192	809 959	5 191 098	508 605	33 469	1
2	3	2 699 909	11 519 643	1 099 272	7 046 889	673 572	45 522	1, 3
3	4	3 207 696	14 659 925	1 419 820	9 101 311	931 097	58 768	1, 3
4	5	3 651 106	17 357 655	1 875 968	1 692 515	1 150 914	70 919	1, 3
5	6	3 949 274	19 003 622	1 875 968	12 038 882	1 139 498	78 500	1, 3
6	7	4 420 258	21 019 412	2 080 422	13 190 167	1 328 565	87 225	1, 2, 3
7	8	4 818 254	23 253 041	2 324 311	14 621 676	1 488 801	97 298	1, 2, 3

For abbreviations' explanation see Table 8; NCT – number of chick types adopted

Table 10. Sensitivity analysis for available chick types K (Problem category 7)

No	K	Profit	R	PC	FCB	FCM	NCR	NCT
1	1	3 204 153	14 723 021	1 429 214	9 159 964	929 691	59 058	1
2	2	3 204 195	15 024 305	1 459 431	9 353 627	1 007 052	60 307	1
3	3	3 207 697	14 659 925	1 419 820	9 101 311	931 097	58 768	1, 3
4	4	3 207 696	14 659 925	1 419 820	9 101 311	931 097	58 768	1, 3
5	5	5 370 581	18 126 395	1 872 359	9 864 235	1 019 220	66 918	1, 5
6	6	6 691 503	18 717 335	1 641 769	8 871 650	1 512 414	58 496	5, 6
7	7	6 691 503	18 717 335	1 641 769	8 871 650	1 512 414	58 496	5, 6

For abbreviations' explanation see Table 8; NCT – number of chick types adopted

time required for the HA approach is very stable at 81 to 82 seconds, implying that the HA approach is more efficient than both the LINGO solver and the CPLEX solver for large-scale test cases.

(4) For the super-large-scale test cases in problem category 4, the LINGO solver and CPLEX solver could not report any solution within 4 hours (14 400 seconds). However, the HA approach converges and reports the best solution within 670 to 716 seconds. This also implies that the HA approach is more efficient and effective than both the LINGO solver and CPLEX solver for super-large-scale test cases.

From Tables 8 to 10, it can be seen that:

(1) The numerical results for problem category 5 in Table 8 show that the profits and revenues (R) are decreasing with increasing η. For example, the profits are 3 369 597 and 3 083 323 for η = 0.85 and 1.15, respectively. Additionally, Table 8 also implies that increasing feeding cost (ηc_k^g) will reduce the total number of baby-chicks to raise (NCR). However, the farmer does not always reduce NCR. For example, the NCR is 61 486 for both cases 2 and 3. This implies that the farmer will only reduce NCR if the increase of ηc_k^g exceeds a certain value.

(2) The numerical results for problem category 6 in Table 9 show that the profits, revenues (R), baby chick purchasing cost (PC), feeding cost of raising baby chicks (FCB), feeding cost of raising chicks to maturity (FCM) and total number of chicks to raise (NCR) increase as L increases. This implies that more henhouses will increase the profit and the number of chick types (NCT). For example, NCT = 1 for L = 2, while NCT = 3 for L = 8.

(3) The numerical results for problem category 7 in Table 10 show that the profits and revenues (R) increase as K increases. This implies that having more types of chicken available will increase the profit and the number of chick types (NCT). For example, NCT = 1 for K = 2, while NCT = 2 for K = 8. More specifically, to maximise the profit, the farmer raises type-1 chicks when $K \leq 2$, raises type-1 and type-3 chicks when $3 \leq K \leq 4$, raises type-1 and type-5 chicks when K = 5 and raises chicks type-5 and type-6 when $6 \leq K \leq 7$. This phenomenon indicates that the HA approach

https://doi.org/10.17221/255/2016-AGRICECON

is effective in choosing the best strategies for maximal profit.

CONCLUSION

In this paper, we proposed a new mathematical model to investigate the problem of chicken production, including production planning and harvesting schedule for chicken farmers. Due to the high computational complexity of the problem, the proposed model cannot be solved by general commercial software when the problem size becomes large owing to, e.g., the planning period and the number of henhouses. To overcome this problem, in this paper, a hybrid computational approach has been developed to obtain comprise solutions for farmers. The main results are summarised as follows.

(1) The proposed approach is superior to the LINGO solver and the CPLEX solver in terms of solution quality and computational time for larger problems. The proposed approach can generate compromise raising decisions for practically-sized problems for which the LINGO solver and the CPLEX solver cannot produce feasible solutions within a reasonable frame of time.

(2) The numerical results of sensitivity analysis have shown the impact of various parameters on the considered problem, including the cost to feed to maturity, the number of henhouses and the number of chicken types.

(3) The numerical results have shown that the proposed model and approach can support chicken farmers in selecting proper henhouses in which to breed chickens, and in optimally scheduling production and harvesting to increase profits.

REFERENCES

Bjørndal T. (1988): Optimal harvesting of farmed fish. Marine Resource Economics, 5: 139–159.

Coleno F.C., Duru M. (1999): A model to find and test decision rules for turnout date and grazing area allocation for a dairy cow system in spring. Agricultural Systems, 61: 151–164.

Crosson P., O'Kiely P., O'Mara F.P., Wallace M. (2006): The development of a mathematical model to investigate Irish beef production systems. Agricultural Systems, 89: 349–370.

Engle C.R. (1997): Optimal resource allocation by fish farmers in Rwanda. Journal of Applied Aquaculture, 7: 1–17.

Engle C.R., Kumar G., Bouras D. (2010): The economic trade-offs between stocking fingerlings and stockers a mixed integer multi-stage programming approach. Aquaculture Economics and Management, 14: 315–331.

Forsberg O.I. (1996): Optimal stocking and harvesting of size-structured farmed fish: A multi-period linear programming approach. Mathematics and Computers in Simulation, 42: 299–305.

Gradiz L., Sugimoto A., Ujihara K., Fukuhara S., Kahi A.K., Hirooka H. (2007): Beef cow-calf production system integrated with sugarcane production: simulation model development and application in Japan. Agricultural Systems, 94: 750–762.

Hern R.L. (1994): An optimal management model for intensive aquaculture an application in Atlantic salmon. Australian Journal of Agricultural and Resource Economics, 38: 31–47.

Kristensen A.R., Søllested T.A. (2004): A sow replacement model using Bayesian updating in a three-level hierarchic Markov process II. Optimization model. Livestock Production Science, 87: 25–36.

McCarthy N., Janvry A.D., Sadoulet E. (1998): Land allocation under dual individual-collective use in Mexico. Journal of Development Economics, 56: 239–264.

Moghaddam K.S., DePuy G.W. (2011): Farm management optimization using chance constrained programming method. Computers and Electronics in Agriculture, 77: 229–237.

Ohlmann J.W., Jones P.C. (2011): An integer programming model for optimal pork marketing. Annals of Operations Research, 190: 271–287.

Pathumnakul S., Piewthongngam K., Khamjan S. (2009): Integrating a shrimp-growth function, farming skills information, and a supply allocation algorithm to manage the shrimp supply chain. Computers and Electronics in Agriculture, 66: 93–105.

Plà-Aragonés L.M. (2005): A stochastic model for planning swine facilities. In: WSC '05 Proceedings of the 37th conference on Winter simulation, Orlando, Dec 4–7, 2015: 2378–2384.

Rodríguez S.V., Albornoz V.M., Plà L.M. (2009): A two-stage stochastic programming model for scheduling replacements in sow farms. TOP, 17: 171–189.

Rodríguez-Sánchez S.V., Plà-Aragonés L.M., Albornoz V.M. (2012): Modeling tactical planning decisions through a linear optimization model in sow farms. Livestock Science, 143: 162–171.

Rupasinghe J.W., Kennedy J.O.S. (2006): Optimal batch lengths for barramundi farming under seasonal vari-

https://doi.org/10.17221/255/2016-AGRICECON

ations: A dynamic programming approach. In: Proceedings of the Thirteenth Biennial Conference of the International Institute of Fisheries Economics & Trade, July 11–14, 2006, Portsmouth.

Stygar M., Makulska J. (2010): Application of mathematical modelling in beef herd management – a review. Annals of Animal Science, 10: 333–348.

Tian X., Leung P.S., Lee D.J. (2000): Size economies and optimal scheduling in shrimp production: results from a computer simulation model. Aquacultural Engineering, 22: 289–307.

Villalba D., Ripoll G., Ruiz R., Bernués A. (2010): Long-term stochastic simulation of mountain beef cattle herds under diverse management strategies. Agricultural Systems, 103: 210–220.

Wang J.K., Leiman J. (2000): Optimizing multi-stage shrimp production systems. Aquacultural Engineering, 22: 243–254.

Yu R., Leung P.S. (2005): Optimal harvesting strategies for a multi-cycle and multi-pond shrimp operation: A practical network model. Mathematics and Computers in Simulation, 68: 339–354.

Yu R., Leung P.S., Bienfang P. (2009): Modeling partial harvesting in intensive shrimp culture: A network-flow approach. European Journal of Operational Research, 193: 262–271.

Yu R., Leung P.S., Bjørndal T. (2006): Optimal partial harvesting schedule for aquaculture operations. Marine Resource Economics, 21: 301–315.

Received August 11, 2016
Accepted October 3, 2016
Published online March 2, 2018