Australian Journal of Agricultural Economics, Vol. 20, No. 1 (April 1976), pp. 19-32.

OPTIMAL FEEDING POLICIES FOR BROILER PRODUCTION: AN APPLICATION OF DYNAMIC PROGRAMMING*

J. O. S. KENNEDY†, B.H. ROFE†, I. D. GREIG and J. B. HARDAKER

University of New England

The determination of an optimal feeding and selling strategy for broiler production given a space constraint is formulated as a dynamic programming problem. Production equations derived from trial data are used to obtain an optimal sequence of rations in which energy density changes through time. The stability of the plan is explored and the implications of the results for production research and commercial practice are considered.

Decision Problems in Broiler Production

Broiler production is an agricultural enterprise particularly amenable to the application of decision analysis. Feed inputs are the major determinants of growth and hence of output and profitability. The quantity of feed used is easily measured and its nutritional value can be controlled within limits. Because feed is made available on a daily basis the growth process can be continually regulated, principally by varying the nutritional quality of the diet offered. The other main environmental factors affecting growth, temperature and lighting, can also be controlled. Probably the most serious production uncertainty is disease, but appropriate prevention measures can be used to minimize this risk. Consequently, once the relevant production functions have been estimated, the rate of growth of broilers of given genetic characteristics can be both forecast and regulated.

A trial conducted at the University of New England provided data on the input-output relationships involved in broiler production. This article reports on the incorporation of these relationships in a dynamic programming (DP) model[1]. The relationships have already been estimated and successfully incorporated in a simulation model [2] which was used to investigate both the optimal diet for broilers when a diet of constant energy density was fed throughout the feeding period, and the optimal length of the feeding period. However, if changes in the composition of the diet are permitted during the growing period, then the decision problem is of a larger dimension and a more powerful technique than exhaustive search is required. Given that the problem is a multi-stage one, DP is a potential solution technique. It has been used in a similar context for beef cattle by Kennedy [4], and also by

* The authors would like to thank R. B. Cumming and D. J. Farrell for their comments and their instigation of the original trials from which most of the data were drawn. The helpful suggestions of referees are also acknowledged.

† Currently La Trobe University and Australian Bureau of Statistics respectively.

[1] The model and results are described in greater detail in [7].

Hochman and Lee [3] for determining for each decision stage whether to sell broilers given current prices. The use of DP rather than simulation means losing some of the flexibility inherent in a simulation model. In particular, the strong assumption of independence of the current state of the system from previous states of the system is made. Further consideration is given to this assumption later.

Factors assumed to be under management control are the type of ration (starter or finisher), the energy density of the ration, the length of the feeding period, the size of the broiler flock for a given growing space, and the sex of bird. Feed costs and broiler prices are assumed to be exogenously determined and known with certainty. This assumption is reasonable in an industry where contract arrangements are widely employed. The broiler production problem is one of determining optimal values of the management control variables with respect to some management goal. In this application the goal was assumed to be either profit maximization per unit of time or profit maximization per unit of time per unit space. The attainment of these goals presents a complex dynamic decision problem because the input-output relationship changes as the age and weight of the bird change. The empirical input-output relationships which were used in the DP model are described in the following section.

Relationships between Nutrition and Broiler Production

Information on nutritional relationships was obtained from the results of a feeding trial conducted in April 1972. Endogenous variables which must be determined in the model are daily weight gain (G), daily energy intakes (I), killing-out fraction (K) and cumulative mortality (M). These variables are assumed to be functions of the energy density (E) of the ration, ration stage (starter or finisher), and status variables such as weight, age and sex of bird. The regression equations which were finally selected on statistical and pragmatic grounds are[2]:

$$(1)\quad G = \exp[\underset{(\cdot 069)}{-2\cdot 987} + \underset{(\cdot 015)}{0\cdot 9062}\ln(A) + \underset{(\cdot 045)}{0\cdot 8376}\ln(E) + \underset{(\cdot 029)}{0\cdot 2414}\ln(W)S - \underset{(\cdot 069)}{1\cdot 237}\ln(W)Q - \underset{(\cdot 033)}{0\cdot 1875}\ln(A)S + \underset{(\cdot 082)}{1\cdot 375}\ln(A)Q]; \quad \bar{R}^2 = \cdot 96$$

$$(2)\quad I = \exp[\underset{(\cdot 163)}{-0\cdot 3559} + \underset{(\cdot 057)}{0\cdot 1695}\ln(A) + \underset{(\cdot 055)}{0\cdot 6860}\ln(W) + \underset{(\cdot 136)}{0\cdot 6638}\ln(E) + \underset{(\cdot 099)}{0\cdot 5327}Q + \underset{(\cdot 003)}{0\cdot 02352}\ln(W)S - \underset{(\cdot 023)}{0\cdot 1367}\ln(W)Q - \underset{(\cdot 033)}{0\cdot 1487}\ln(W)\ln(E)]; \quad \bar{R}^2 = \cdot 98$$

$$(3)\quad K = \underset{(\cdot 009)}{0\cdot 6237} + \underset{(\cdot 0027)}{0\cdot 009584}\, W/A; \quad \bar{R}^2 = \cdot 02$$

[2] Figures in brackets are standard errors.
Because MM equalled zero for some observations, and $ln(0)$ is undefind, $MM+1$ was originally used as the independent variable in (4). This explains why 1·0 is subtracted from the RHS of (4).

$$(4) \quad M = \exp\,[0{\cdot}0432 + 0{\cdot}780 \ln(A) - 0{\cdot}2444 \ln(W)] - 1{\cdot}0$$
$$(\cdot 199) \qquad (\cdot 168) \qquad\qquad (\cdot 104) \qquad \bar{R}^2 = \cdot 33$$

where G = liveweight gain in kg per day per 100 birds;
A = age of bird in days;
E = energy density of ration (Mcal/kg);
W = liveweight per 100 birds (kg);
S = dummy variable for sex of bird (1·0 for males, 0·0 for females);
Q = dummy variable for starter (0·0) or finisher (1·0) rations;
I = energy intake in Mcal per day per 100 birds;
K = killing out (dressing) fraction;
M = cumulative mortality per 100 birds.

Ration Costs and Market Returns

The range of possible energy densities of the rations is from 1·9 to 3·7 Mcal/kg. The unit costs of rations of particular densities were the estimated least costs obtained from linear interpolation of a series of linear programming (LP) results which covered the same range of E. Each ration formulated by LP contained protein, amino acids and minerals in constant proportions to the E value of the ration, these proportions being ones commonly accepted in broiler nutrition.

Two types of ration are fed to broilers, known as starter and finisher rations. The starter ration contains a larger proportion of protein and is costlier than the finisher ration. LP results were obtained for both types of ration. The rule followed for changing from the starter to the finisher ration in the DP model was the same as that for the trials. The rule was to change to the finisher ration whenever either the weight was 60 kg per 100 birds or the birds were in their sixth week, whichever occurred first.

The schedules for unit costs of starter and finisher rations are shown in Figure 1. Ration cost was calculated as the estimated unit cost multiplied by energy intake as given by (2).

The market return from a batch of birds at any time was calculated by multiplying the price received per unit of dressed weight by the marketable weight of the batch. The marketable weight of the batch was the product of the weight of the birds (W), the fraction of birds surviving (as deduced from M) and the killing out fraction (given by K).

The Dynamic Programming Model

Specification

The DP problem was formulated as follows: Given that the producer wishes to maximize profit per unit of time, and that decisions are made on a weekly basis, for how many weeks should he feed a batch of birds before selling the batch and buying a replacement batch of day-old chicks after a suitable elapse of time for shed cleaning? Further, what E value should be selected for the ration fed to the batch each week?

Decision points, or stages, in the model were therefore at weekly intervals, denoted by $t=1, \ldots, T$ for each batch. The production

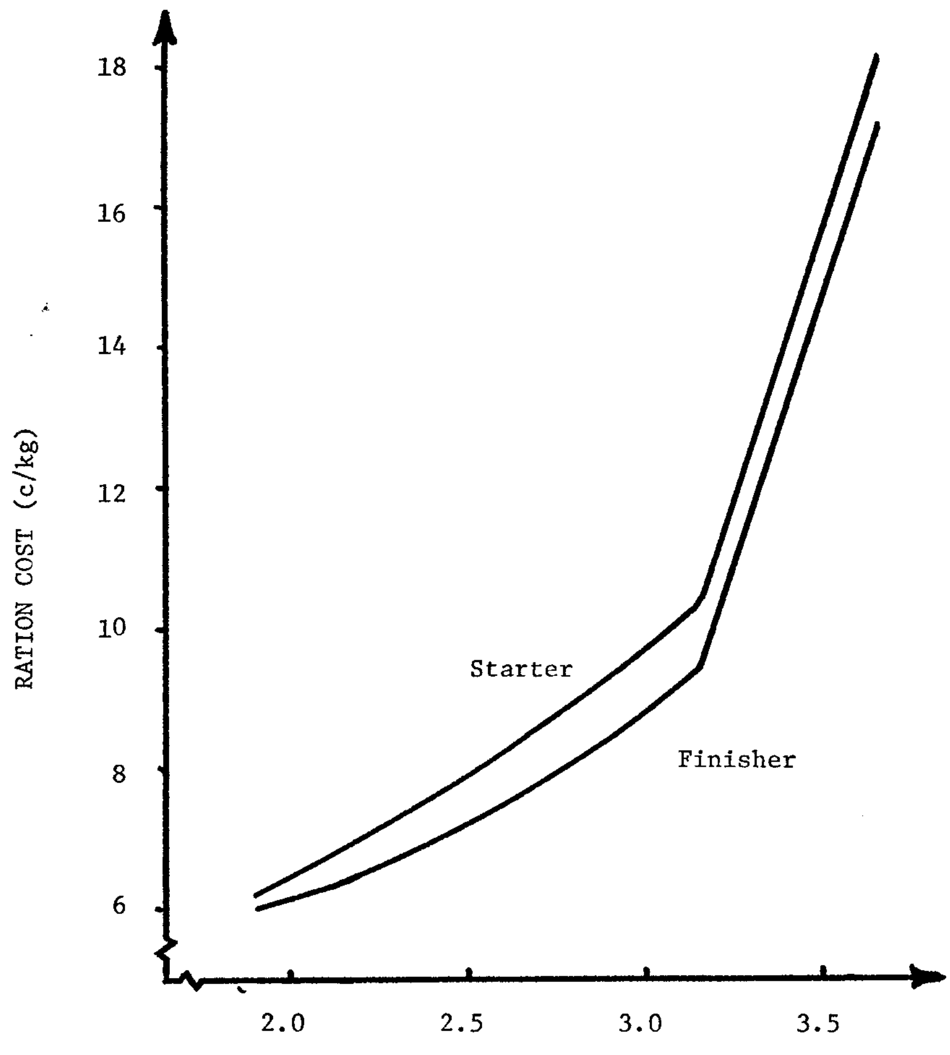

FIGURE 1—*Unit Ration Cost as a Function of Energy Density.*

system was assumed to be fully described at any stage by three state variables: bird weight per 100 birds $W(t)$; the fraction of the initial 100 birds surviving $n(t)$; and the age of birds (t).

The decision to be made at each stage is whether to feed or sell the birds, and if to feed what the E value of the ration should be. The decision made at each stage determines the state variables at the next stage. If the decision is to sell, then the values of the state variables for the beginning of the next production week, $W(l)$, l, l, describe a new batch of day-old chicks bought after shed cleaning. If the decision is to feed, then $W(t+l)$ will be greater than $W(t)$ by an amount dependent on the energy density of the ration, as specified by (1) and (2); $n(t+l)$ will be less than $n(t)$ due to mortality as specified by (4); and the birds will be one week older.

Depending on the decision taken, a financial gain or loss results for the week. If the decision is to sell, then there is a return $n(t)r(W(t))$

less the cost of buying another batch of day-old chicks (b). If the decision is to feed, a cost is incurred equal to $c(W(t), t, E)$.

The recurrence equations which describe the infinite time horizon DP problem are[3]:

(5) $f^* \; (W(T),n(T),T) \; = \; n(T)r(W(T)) + \alpha^2[f^*(d,l,l)\text{-}b]$

(6) $f^* \; (W(t),n(t),t) \; = \max \{\max_E\{\text{-}n(t)c(W(t),t,E) + \alpha f^*(W(t+l),n(t+l),t+l)\}; \{n(t)r(W(t)) + \alpha^2[f^*(d,l,l) - b]\}\}$

$t = T-l, \ldots, l$

with

(7) $W(t+l) = W(t) + 7G(W(t), t, E)$

(8) $n(t) = [100 - M(W(t),t)]/100$

(9) $c(W(t),t,E) = 7I(W(t),t,E) \times$ (unit ration cost)

(10) $r(W(t)) = W(t)K(t) \times$ (unit return from sale of birds)

where

$f^*(W(t),n(t),t)$ = maximum (denoted by $*$) return to infinity from following the optimal strategy;

α = discount factor;

d = weight of 100 day-old chicks;

T = latest week number at the beginning of which birds must be sold.

If the decison to sell is taken it is assumed that selling occurs at the beginning of the week, and that sale proceeds are received immediately. Two weeks elapse before the batch of day-old chicks is bought so that the growing area may be cleaned, and accounts for the α^2 term in (5) and (6).

Ranges of the Variables

The DP problem was solved numerically. This meant that the ranges of discrete values of the state and decision variables had to be specified. The ranges were the largest that were estimated to be biologically feasible, as explained below.

Because weight gain is an increasing function of the E value of the ration, minimum and maximum weight gains are determined by the minimum, 1·9 Mcal/kg, and maximum, 3·7 Mcal/kg, values of E. Starting with the weight of day-old chicks ($d = 4{\cdot}5$ kg/100 birds) it is therefore possible to specify the minimum and maximum possible weight of birds at the beginning of any week t by assuming the rations of 1·9 and 3·7 Mcal/kg respectively are fed. The weight ranges are shown in Figure 2.

The ranges were covered by 20 discrete weights spaced at equal intervals throughout. Twenty was chosen as the number of weights so that the size of the problem was within the multi-stream capacity of the computer available. Only one weight for day-old chicks was considered.

The range of bird weights also determined the possible values of E. Because the range of E was limited to between 1·9 and 3·7 Mcal/kg only a subset of the 20 weights in period $t+l$ was accessible from any

[3] The stage subcripts which are necessary for the finite time horizon formulation of the problem are dropped for the infinite time horizon problem.

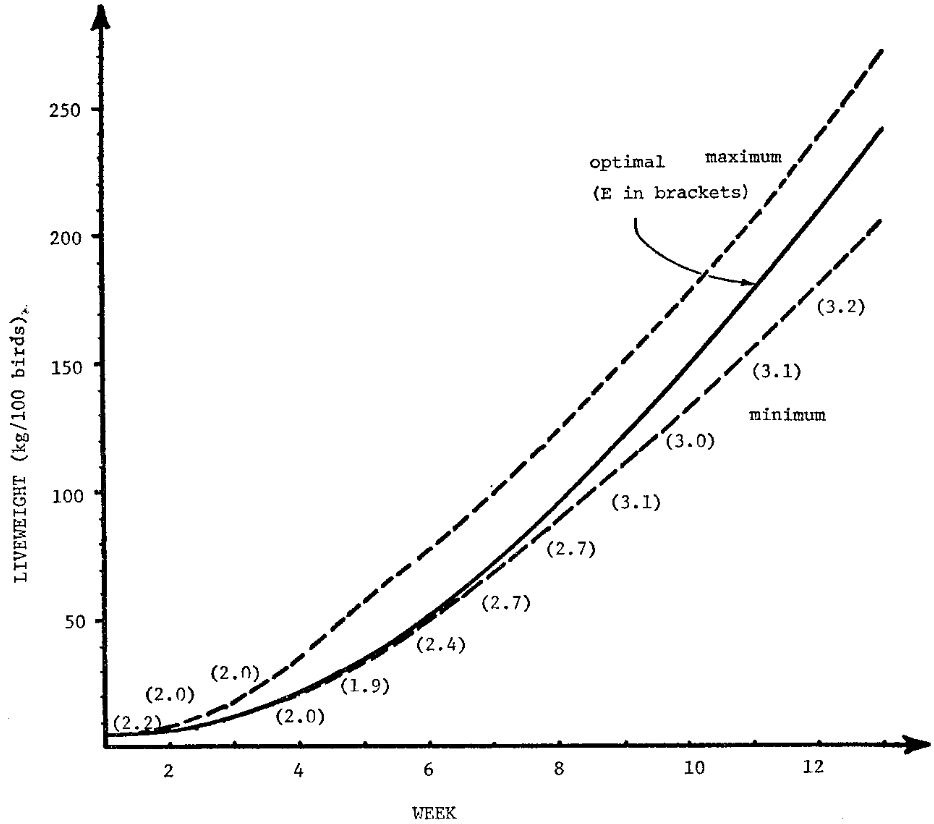

FIGURE 2—*Maximum, Minimum and Optimal Weight Paths.*

particular weight in period t. The feasible subset was found by calculating the minimum and maximum weight gains. The E values for all feasible weight gains were determined using a rearrangement of (1).

The weights used in equations (1) to (4) in the DP model were mid-week weights, estimated from the weight at the beginning of the week and the weight gain.

The maximum number of weeks ($T—l$) for which birds could be held was set at 12. The functions used in the model were estimated from trial data for pens of birds grown to between 10 and 12 weeks of age, and thus cannot be confidently used for weeks later than the twelfth.

Solution Method

If the optimal return to infinity from pursuing the optimal policy starting with 100 day-old chicks, $f^*(d,l,l)$, were known, then $f^*(\cdot,T)$ could be determined. This would enable $f^*(\cdot,t)$ to be found by recursive application of (6). The process would also determine the optimal decision (sell or feed, and if to feed, the E value of the ration) to be made for all liveweights at all stages, $D^*(W,t)$.

In fact $f^*(d,l,l)$ is one of the values to be determined and is initially unknown. However, (5) and (6) may be used to determine $D(W,t)$ conditional on any value substituted for $f^*(d,l,l)$. This suggests one method of successive approximations which could be used to find $f^*(\cdot)$, known as value iteration [1]. A value of $f^*(d,l,l)$ could be guessed, and (5) and (6) used to determine $D(W,t)$ and $f(\cdot)$. But $f(\cdot)$ would include a new estimate of $f^*(d,l,l)$, and this value could be used also in (5) and (6). Another estimate of $f^*(d,l,l)$ would result. If this process were repeated enough times the estimates would converge to $f^*(d,l,l)$, and $D^*(W,t)$ would be determined. The process is known to converge to a unique solution because net returns for each week are discounted [1].

However, another solution method using successive approximation, known as policy iteration, is preferred because convergence is rapid and the exact solution is obtained. It was the method used to solve the broiler problem. Instead of starting with a guess at $f^*(d,l,l)$, one starts with a guess at $D^*(W,t)$. Any $D(W,t)$ implies a corresponding $f(\cdot)$, and in particular a value for $f(d,l,l)$. This may be shown as follows:

Any $D(W,t)$ specifies the feed/sell decision to be taken for day-old chicks, and hence which of the twenty values of $W(2)$ is reached at the beginning of the second week, denoted by W_2. By extension, it is possible to trace the weight paths of the birds through all stages of production up to week s at the beginning of which the birds are sold ($s \leqslant 13$). Thus vectors $E_1, E_2, \ldots, E_{s-1}$ and $d, W_2, \ldots, W_s$ may be derived from $D(W,t)$ and incorporated in the following matrix equation which is based on the relationships specified in (5) and (6):

$$\begin{bmatrix} 1 & -\alpha & 0 & . & . & . & 0 \\ 0 & 1 & -\alpha & . & . & . & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ -\alpha^2 & 0 & 0 & . & . & . & 1 \end{bmatrix} \begin{bmatrix} f(d,l,l) \\ f(W_2,n(2),2) \\ . \\ . \\ . \\ f(W_s,n(s),s) \end{bmatrix} = \begin{bmatrix} -c(d,l,E_1) \\ -n(2)c(W_2,2,E_2) \\ . \\ . \\ . \\ n(s)r(W_s)-\alpha^2 b \end{bmatrix} \tag{11}$$

The RHS is known, and hence the f-vector may be solved, the first element of which is the required $f(d,l,l)$.

The process that was employed in policy iteration can now be explained. A guess at $D^*(W,t)$ was made and a corresponding value for $f(d,l,l)$ found. The value of $f(d,l,l)$ was then substituted in (5) and (6) as an approximation of $f^*(d,l,l)$. Equations (5) and (6) were solved recursively, resulting in a new $D(W,t)$ matrix, optimal conditionally on $f(d,l,l)$. The process was repeated with the new $D(W,t)$, and so on iteratively until $D(W,t)$ obtained in one cycle was exactly the same as $D(W,t)$ obtained in the previous cycle. The coincidence of the two matrices signified that $D^*(W,t)$ had been obtained, together with $f^*(\cdot)$. The correspondence of solutions by policy iteration and by value iteration is shown in [1].

The solution procedure is summarized in Figure 3. The optimal solution was reached rapidly, usually after three iterations. This was despite there being no attempt to make a very plausible initial guess

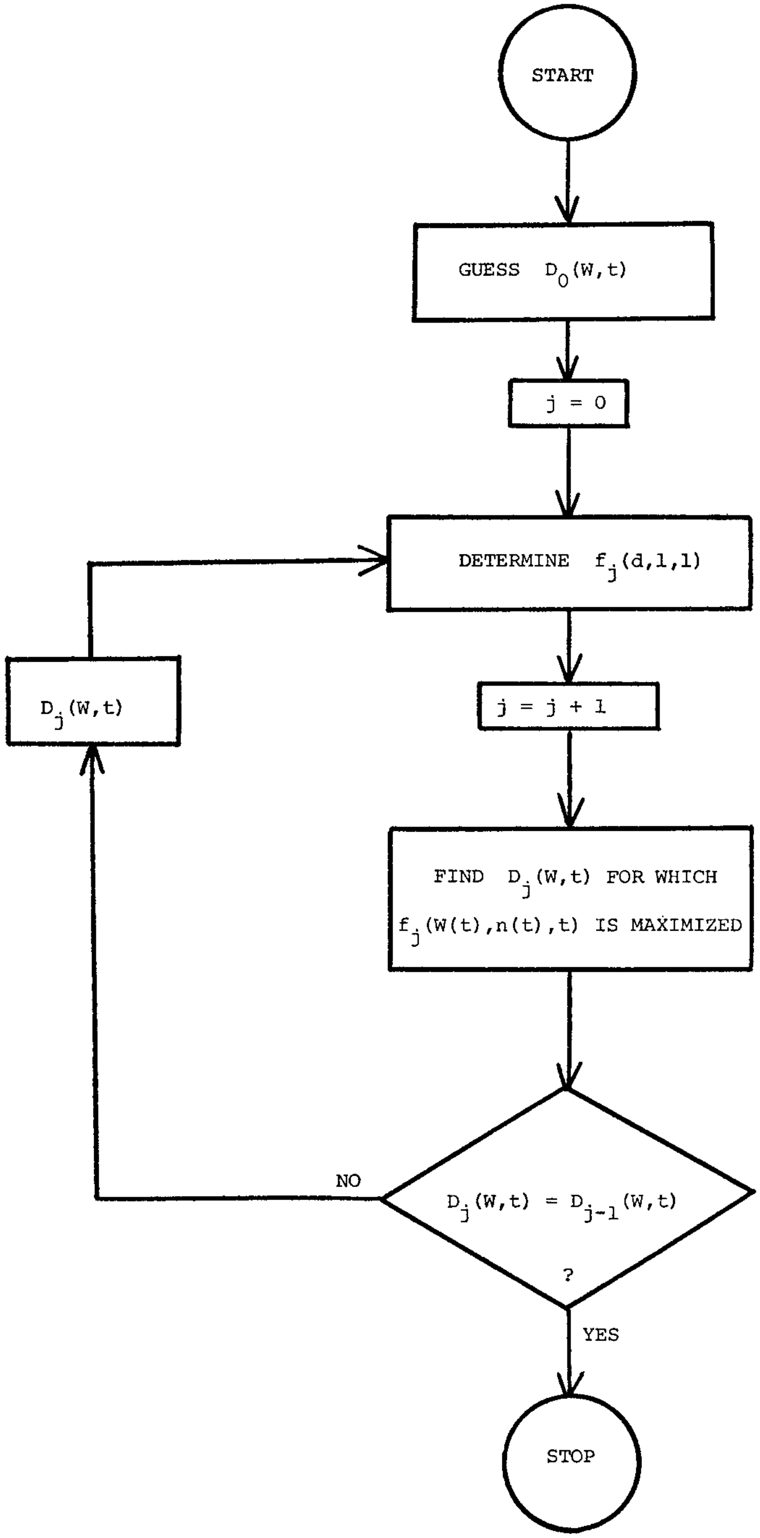

FIGURE 3—*Flow Chart for Policy Iteration.*

at $D^*(W,t)$. The initial $D(W,t)$ specified: feed to the birds rations with the second energy density option, whatever the weight of the birds in all weeks up to and including week 8; for remaining weeks, sell the birds, whatever their weight.

Space may become a limiting constraint as the birds grow. Above a certain stocking rate the birds tend to fight and consequently feed conversion efficiency suffers. Space requirements must therefore be considered. The major determinant of space required is the weight of the birds. The following is an estimate of space requirements (z), in sq. m. per 100 birds, to ensure stresses due to crowding are kept constant for the growing birds[4]:

$$(12) \quad z(t) = 3.08 + 0{\cdot}00984W(t) + 0{\cdot}0000432W(t)^2.$$

The space required per batch at any stage is calculated as $z(t)$ multiplied by the fraction of birds surviving to that stage $n(t)$. A Lagrange multiplier λ was used in the model as the means of finding the optimal policy to pursue when production was subject to a space constraint of $\bar{z}$ sq. m. per bird. Any space which a plan required in any period above the specified maximum amount attracted a charge on the period return, equal to the excess space multiplied by λ. The programme was run several times with various trial values of λ until a value just large enough to eliminate all excess space requirements was found. The search was made by simple interpolation and extrapolation. The final value of λ reflected the marginal value of space.

Thus the maximum return could be calculated for a batch of 100 day-old chicks for any $\bar{z}$. By carrying out this procedure for a suitable range of $\bar{z}$ it was possible to find the policy for which return per unit of space was maximized, by inspection of the results.

Verification of the model was expedited by comparing the DP output with that of the simulation model [2] based on the same production relationships.

Results

A basic scheduling plan emerged which was fairly insensitive to changes in price assumptions. The optimal plan consisted of feeding birds a low E ration, about 2·0 Mcal/kg for the first five weeks, thereafter steadily increasing E to about 3·2 Mcal/kg in the final week of feeding. Weight gains were therefore low in the early weeks, and higher though not maximal in later weeks. The data and results for the standard run of the model are shown in Tables 1 and 2 respectively. The optimal weight sequence is presented diagramatically in Figure 2.

The planned profit is $18.70 per 100 chicks by the end of every 14 weeks, which, at a rate of interest of 10 per cent per annum, implies a present value of the profit stream to infinity of $740.

Results show the plan for maximum profit per bird without consideration of a space constraint. It turns out that the plan is also the

[4] This equation was not estimated directly but was obtained for this study by modifying a function determined in another study. For this reason, no regression statistics are given. For further details, see [2].

TABLE 1

Data used in the Standard DP Run

Number of broilers (50/50 male/female)	100
Rate of interest (α)	10 per cent per annum
Cost of 100 day-old chicks plus medication (b)	$20.57
Ration cost per kg	As shown in Figure 1
Price per kg dressed weight	68c
Space available	7.4 sq. m.

TABLE 2

Optimal Feeding Plan for Standard Run

Week	Weight (kg/100 birds)	Ration		Space Required (m^2/100 birds)
		Energy Density (Mcal/kg)	Cost ($/100 birds)	
1	4·5	2·2	0·88	3·1
2	6·8	2·0	1·41	3·1
3	12·4	2·0	2·12	3·1
4	21·6	2·0	2·98	3·2
5	34·4	1·9	3·96	3·3
6	50·3	2·4	4·47	3·5
7	71·8	2·7	5·22	3·8
8	96·5	2·7	5·88	4·2
9	121·1	3·1	6·70	4·6
10	150·0	3·0	7·27	5·2
11	178·7	3·1	7·91	5·8
12	209·5	3·2	9·33	6·5
13	242·2	—	—	7·4

one for which profit per square metre is maximized[5]. The optimal stocking density is equal to the maximum stocking density consistent with the unconstrained plan, which is 100 birds per 7·4 sq. m. Optimal plans for space per 100 birds less than 7·4 sq. m. showed marginal profit greater than average profit in terms of dollars per square metre. For space available per 100 birds in excess of 7·4 sq. m. marginal profit is zero. Thus for space available per 100 birds of 7·4 sq. m average profit to infinity is maximized (at $100 per sq. m.), and is less than marginal profit to infinity (at $112 per sq. m.).

Starting birds on a low E ration is not usual commercial practice. Industry practice is to achieve a near-maximum rate of gain for the whole of the birds' life span. The results suggest that a reconsideration of this practice might be warranted.

The validity of the plan depends very much on the validity of the assumption of historical independence which was made in the DP model. It was assumed that weight gain in any period t was a function only of E, $W(t)$ and t. Previous E values and weight gains were

[5] A referee has pointed out that the other production costs besides those of feed, and chicks plus medication, may vary with area or number of birds. There is no conceptual problem in incorporating costs which vary with area or number of birds into the DP model. However, in this application, all other costs are assumed to be fixed except with respect to time.

assumed not to influence current weight gain potential. However, if E has changed drastically over the previous life of the birds the weight gain and energy intake predictions of (1) and (2) may be only approximately fulfilled. The equations were derived from trial experiments in which the ration E was held constant for the lifetime of each batch of birds. There is at present no empirical evidence as to whether the birds would be able to adjust immediately to rations with different E values fed each week so that actual weight gains would coincide with the predicted weight gains.

One phenomenon inconsistent with the assumption of historical independence but which appears relevant to the optimal DP plan is compensatory growth. Compensatory growth would apply to birds if birds which are fed on a low plane of nutrition respond to a subsequent higher plane of nutrition with greater weight gain than other birds which are fed consistently on the higher plane of nutrition. To date, little is known about compensatory growth in broilers. Some suggestive work has been carried out in England. The results of one study on a breed of small turkey indicated that for birds fed moderate or high E finisher rations, liveweight gains and energy intakes were similar irrespective of whether they had been fed previously low or high E developer rations [6]. Another study [8] also showed similar liveweight gains for birds fed on high-high and low-high E diets. However, this trial is not of direct relevance because it lasted 24 weeks with the E change occurring in the tenth week.

The sensitivity of the standard run DP plan to changes in the following economic parameters was tested: the rate of interest, the cost of day-old chicks, the price per unit dressed weight of bird and ration cost. Changes of the order of 10 per cent resulted in no significant change in the optimal plan, although the economic returns were markedly affected. For example, a 10 per cent increase in the selling price of birds increased the returns over the infinite planning period by 50 per cent.

Some experimentation was carried out on the rule for changing from the starter to the cheaper finisher ration. When the finisher ration was introduced a week earlier than for the standard DP run the only change in the weight sequence was a slightly higher weight at the end of the final period. When the finisher ration was introduced one week later however, the birds were fed the ration with the lowest E for an extra week before the higher E rations were fed. Model results were therefore sensitive to the timing of the change of ration type, but in both cases the infinite period returns were lower than those for the standard plan, perhaps indicating that the finisher was introduced at the optimal time in the original trial and hence in the standard run of the model.

In the standard DP run the batch of broilers was assumed to consist of males and females in equal numbers. The dummy variable S was set at $0 \cdot 5$ in (1) and (2). Given modern techniques of picking the sex of young birds, single-sex batches may be grown more readily. In order to discover the changes in the optimal policy for single-sex batches the DP model was run with all-male and all-female batches. The results are shown in Table 3.

The E sequence for both male and female batches was very similar to that for the mixed-sex batch. (Compare Tables 2 and 3). The optimal selling date was at the end of the twelfth week in both cases,

TABLE 3

Optimal Feeding Plans for Sexes Segregated

Week	Females		Males	
	Optimal Weight (kg/100 birds)	Ration E (Mcal/kg)	Optimal Weight (kg/100 birds)	Ration E (Mcal/kg)
1	4·5	2·2	4·5	2·1
2	6·6	2·1	7·0	2·0
3	12·1	2·1	12·9	2·0
4	20·7	2·0	22·8	2·0
5	32·3	2·0	37·0	1·9
6	46·6	2·3	55·2	2·4
7	66·7	2·8	78·4	2·8
8	89·3	2·6	105·5	2·7
9	111·7	3·1	132·8	3·1
10	137·6	3·0	165·4	3·0
11	163·2	3·1	198·0	3·1
12	190·4	3·2	233·0	3·2
13	219·4	—	270·6	—

		Females	Males
Return to infinity ($)	(R)	555	985
Space required in final week (m^2)	(S)	6·78	8·26
Return per m^2 (\$/m^2)	(R/S)	81·9	119·2

the same as for the mixed batch. However, the rate of gain was much lower for the female batch than the male batch. Final female weight was 219 kg/100 birds compared with 271 kg/100 birds for the final male weight. Returns to infinity were consequently lower for females ($555) than for males ($985). However, if both females and males are to be raised, the fact that there is little difference in the optimal policies means that there is little to be gained by segregating the sexes and following the optimal plan for each sex. The DP results indicate the same return of $100 per sq. m. whether the mixed batch policy shown in Table 2, or the segregated batch policy shown in Table 3 is followed.

Conclusions

Results from the DP model show that returns from broiler production are maximized by feeding a low E ration in the early weeks and then an increasingly high E ration for the remainder of the feeding period. This policy contrasts with the usual practice of feeding the birds a high E ration throughout and suggests promising lines for further research in broiler production. The effect of previous changes in E on the weight gain potential of broilers is unknown. In the absence of information, the facilitating assumption was made that any effect was negligible. Further research is necessary to determine whether in fact this is the case. If the effect is significant then the DP model would not be applicable because this would contradict the assumption of stage transformations being independent of previous decisions. This problem could be overcome by specifying additional state variables describing the energy density of rations fed in previous periods. However, the increase in dimensions would lead to an unacceptable increase in computation. Simulation would provide a feasible method of analysis if DP could not be used.

No definite recommendations can be made to commercial broiler producers on the basis of the DP results until the suggested policy has been tested in practice. However, to gauge the extent of the economic advantage if the DP results were to be validated, the simulation model described in [2] was used to compare the returns from following the DP plan with the returns from following an optimal feeding strategy with constant E levels. For a broiler production unit of 300 sq. m. floorspace, a profit improvement of around $2000 per annum is suggested for the DP plan, provided only that any extra costs of feeding a diet of changing E levels are negligible.

An important refinement for the model would be to allow for different returns per unit weight of dressed bird for different sizes of bird. If an inverse price-size function were incorporated in the DP model the optimal plan might show that birds should be sold in an earlier period. The information from which such a function could be derived was not available to the authors, but presumably could be specified by integrators who generally are responsible for the more important managerial decisions in broiler production.

The experience gained from operating the DP model suggests that DP is a flexible optimizing technique capable of incorporating the dynamic relationships known to be involved in broiler production. Given the relatively controlled environment for broiler production compared with that for other agricultural enterprises, the application of a technique such as DP can be expected to produce relatively more satisfactory results. Remaining planning uncertainties such as the prices of feeds and marketable birds, and disease, could be dealt with along the lines suggested in [5]. That is, the DP model would be run at the beginning of each decision stage with a rolling time horizon, and only the plan for the immediate stage would be implemented. A check would be kept on production performance and feed quality by periodically weighing a sample of birds, and forecast prices would be updated. In this way revised parameter estimates would be used at each stage and the planning system incorporated in an adaptive control framework. Thus, it is concluded that both potentially and in the manner demonstrated in the paper, DP can be a valuable aid to decision makers in the broiler industry.

References

[1] Beckmann, M. J., *Dynamic Programming of Economic Decisions,* Berlin, Springer-Verlag, 1968.

[2] Greig, I. D., J. B. Hardaker, D. J. Farrell and R. B. Cumming, 'Towards the Determination of Optimal Systems of Broiler Production', *Agricultural Systems,* in press, 1976.

[3] Hochman, E. and I. M. Lee, *Optimal Decision in the Broiler Producing Firm: A Problem of Growing Inventory,* Giannini Foundation Monograph 29, University of California, Berkeley, 1972.

[4] Kennedy, J. O. S., 'A Model for Determining Optimal Marketing and Feeding Policies for Beef Cattle', *J.Ag.Econ.,* 23(2): 147-159, 1972.

[5] Kennedy J. O. S., 'Control Systems in Farm Planning', *Euro. Rev. Agric. Econ.,* 1(4): 415-433, 1973.

[6] Moran, E. T., J. D. Summers and H. L. Orr, 'The Effect of Absolute Alterations in Energy Concentration of Developing and Finishing Diets for the Large White Turkey on Performance and Carcass Quality with a Note

on the Correlation of Back Skin Fat and Grade of Finish', *Brit. Poult. Sci.*, 10(2): 127-138, 1969.

[7] Rofe, B. H., An Optimal Feeding and Scheduling Program for Broiler Chickens: A Dynamic Programming Approach, Unpublished B. Appl. Ec. thesis, University of New England, Armidale, 1974.

[8] Wilson, P. N., 'Growth Analysis of the Domestic Fowl, I: Effect of Plane of Nutrition and Sex on Liveweights and External Measurements', *J. Agric. Sci.,* 42(4): 369-381, 1952.