Selected Paper

2005 Annual Meeting of the Southern Agricultural Economics Association

"System Level Economic Analysis of Swine Diet Modifications"[a]

Yi-Hung Lin[b,c], Arthur L. Stoecker[b,c]

ABSTRACT. Experimental data from low nitrogen and phosphorus diets (Carter *et al*, 1999, 2000, 2003) are being used to validate and/or modify the NRC swine growth model. A profit maximizing daily growth model that considers feed costs, excretion, waste management costs, and length of feeding period is being developed.

Keywords: Water Resource, Growth Model, Nutrient Requirements, Feed Ration Management, Swine Waste Management.

---

[a] This Paper is a project sponsored by the College of Agricultural Sciences and Natural Resources at Oklahoma State University, January, 2005.

[b] Research Assistant and Associate Professor, respectively, Dept. of Agricultural Economics, Oklahoma State University, Stillwater, OK 74077.

[c] Corresponding authors. Dr. Arthur Stoecker, Phone:405-744-6165, Fax:405-744-8210, Email:astoker@okstate.edu. Yi-Hung Lin, Phone:405-744-5547, Email:yihung.lin@okstate.edu.

1. Introduction

Swine production has experienced both rapid growth and substantial structure changes over the last decade in Oklahoma. The total number of pigs in Oklahoma during 2002 was 2,240,000 head, a dramatic increase from the 215,000 head in 1990 (Oklahoma Agricultural Statistics Service). In addition, the 40 largest farms produced 89 percent of all the pigs marketed in Oklahoma during 2002. The market share of all small farms (less than 500 head per year) was only 2 percent a significant drop from 35 percent in 1993. Swine manure could be an economical source of plant nutrients and a valuable soil amendment to improve soil quality and maintain soil pH as long as land application abides by appropriate agronomic principles. However, it is a challenge to manage manure in environmentally sound manner for intensive and specialized hog production operations with limited applicable cropland.

Research on economic diet optimization for swine has shown the possibility of manipulating animal growth response by nutritional means (Fawcett *et al*., 1978; Glen, 1983). Although greater efficiency may be achieved by using the concepts of diminishing returns (Fuller *et al*., 1993; Gahl *et al*. 1995), and the relative feedstuff values in ration formulation, the implications for manure management were generally ignored. Furthermore, there are few studies where these relationships are quantified econometrically, though the relationship between diet manipulation and nutrient excretion has been studied. An integrated economic analysis of nutrient management with manure management in which the optimal decisions on collection methods, storage methods, and application methods were dependent on the amount and composition of manure is, therefore, much needed for addressing the issue in the waste management of geographic concentration of hog feeding operations.

2. Literature Review

Feed ration management is an important component in the Comprehensive Nutrient Management Plans (CNMPs) due to its direct effects on hog production and other components of manure management. Both the nutrient content of manure and the rate of gain are highly related with the nutrient content in diets. This study adopted a simulation model from *Nutrient requirements of Swine* (NRC, 1998), upon which a profit maximization problem will be built. The NRC assumed pig performance level is jointly determined by genetic, nutritional, and thermal factors. In the model, a mechanism that considers genotype, temperature and nutritional effects is used to determine the amount of protein accretion generated by available digestible energy in diets. For the amount of digestible energy intake (Mcal per day) above the 55 percent of that needed for maintenance, the daily whole body protein gain (grams per day), WBPG_t, can be calculated by the following equation, which is a modification of the equation of Black *et al*. (1986):

$$\begin{aligned}\mathrm{WBPG}_t\ (g) = {} & (17.5 \times e^{-0.0192\mathrm{BW}_t} + 16.25) \times (\mathrm{MPAR} / 125) \times \\ & (1 + 0.015 \times (20 - \mathrm{T})) \times \\ & (\mathrm{DE\ intake} - 0.55 \times \mathrm{DEM}), \qquad (1)\end{aligned}$$

where protein accretion rate for a particular day, WBPG_t, is expressed in grams per Mcal digestible energy intake (DE) above 55 percent of maintenance; BW is body weight in kg. MPAR expressed in grams per day is the mean whole body protein accretion rate for the growing-finishing period. T is the effective ambient temperature in degree centigrade. DEM is the digestible energy requirement for maintenance in kcal per day.

The carcass fat free lean weight in grams at the marketing day then is the sum of the initial carcass fat-free lean weight of the feeder pig and the accumulation of daily carcass fat free lean gain over the growing-finishing period:

$$\mathrm{FFL}\,(g) = \mathrm{IFFL} + \sum_{1}^{T} \mathrm{CFFLG}_t\ , \qquad (2)$$

where IFFL is the initial carcass fat-free lean weight of the feeder pig (gram), which can be estimated by the following formula:

$$\mathrm{IFFL}\,(g) = 453.59 \times 0.95 \times \left[-3.65 + (0.418 \times \text{live weight, lb})\right], \qquad (3)$$

and the carcass fat free lean gain rate (grams per day), CFFLG_t, can be converted from whole-body protein growth rate, WBPG_t, by the following formula provided by the NRC:

$$\mathrm{CFFLG}_t\,(g) = 2.55 \times \mathrm{WBPG}_t\ . \qquad (4)$$

The whole body protein gain, WBPG_t, can be converted to the protein tissue gain in grams per day, PTG_t by a coefficient of 0.23;

$$\mathrm{PTG}_t\,(g) = \mathrm{WBPG}_t / 0.23\ . \qquad (5)$$

The metabolizable energy available each day for fat synthesis is the amount of ME intake minus that required for protein synthesis and maintenance; that is,

$$0.96 \times \mathrm{DE} - 10.6 \times \mathrm{WBPG}_t - 106 \times \mathrm{BW}^{0.75} . \tag{6}$$

The NRC assumed that one gram of fat can be synthesized with 12.5 kcal of metabolizable energy. The daily fat synthesized in grams was obtained by dividing the metabolizable energy available for fat synthesis by 12.5.

$$\mathrm{FSY}_t = (0.96 \times \mathrm{DE} - 10.6 \times \mathrm{WBPG}_t - 106 \times \mathrm{BW}^{0.75}) / 12.5 . \tag{7}$$

Since fat concentration in fat tissue is 90%. The fat tissue gain in grams per day was obtained by transforming synthesized fat with a coefficient of 0.9.

$$\mathrm{FTG}_t(\mathrm{g}) = \mathrm{FSY}_t / 0.9 . \tag{8}$$

The daily body weight gain (grams per day), DBWG_t, is then the sum of daily protein tissue gain and daily fat tissue gain divided by 0.94 to account for the other parts of body weight gain, such as bone and skin.

$$\mathrm{DBWG}_t(g) = (\mathrm{PTG}_t + \mathrm{FTG}_t) / 0.94 . \tag{9}$$

In the above model, the protein content can be only expressed in terms of the total body weight. As lean meat content in carcasses is used as a measure of hog quality by the industry, the protein content is not immediately meaningful to market participants, even expressed in term of carcass weight. However, protein accretion is closely related to the gains of carcass fat free lean meat; the carcass fat free lean meat rate can be converted from protein accretion rate using equation (4). The ratio of carcass weight to animal body weight provided by the Swine Contract Library (GIPSA, USDA) makes allowances for calculation of carcass weight given a final body weight. The modified NRC simulation can model thus be used to determine the optimal feeding policy for the specified final body weight and carcass composition.

The biological functions that describe the relationship between growth rate and nutrient requirement can be used to predict the nutritional requirements given specific growth rates. The lysine required for whole-body protein accretion each day (LysineG) was estimated using data from a wider range of experiments as follows:

lysine for gain (LysineG, g/day) = $0.12 \times \mathrm{WBPG}_t$, (10) where lysine for gain in grams is the amount of true ileal digestible lysine needed for daily whole body protein synthesis. The true ileal digestible lysine required for maintenance (LysineM) expressed in grams per day at any body weight is

$$\text{Lysine for maintenance (LysineM, g/day)} = 0.036 \times BW_t^{0.75} \tag{11}$$

The requirements of the essential amino acids other than lysine for protein deposition can also be calculated using the ideal protein system (*Nutrient Requirements of Swine*, NRC 1998), in which requirements for each of the other amino acids are expressed relative to the lysine requirement for protein accretion.

For phosphorus, an average retention of 6 g phosphorus per kg of weight gain was assumed for all types of pigs (INRA, 1989). However, it is also possible to estimate the actual digestible P requirements according to body weight and expected body weight gain for growing pigs. The average daily phosphorus (APHR, kgs/day) and calcium (ACR, kgs/day) retention can be described as follows (Jongbloed, 1987):

$$\text{APHR (kg/day)}=0.003467BW^{-0.025}ADG$$

$$\text{ACR (kg/day)}=0.007996BW^{-0.005}ADG\ . \tag{12}$$

In the growth model of Fawcett and Whittemore (1976), the utilization of digestible energy and protein components of the feed intake were partitioned into live body gain, urinary loss and heat loss. This provides a basis to manipulate the protein growth rate and body composition of pigs of particular genetic potential by nutritional means. In the framework of this analysis, protein growth rate could be determined by the nutrient composition of feed intake and maintenance requirements given initial body weight. The daily protein retention function was then estimated with the daily digestible energy intake and daily digestible amino acid intake. The chemical value, defined by Fawcett *et al.* as the minimum value obtained when the concentration of each essential amino acid in the feed is divided by the corresponding value in the preferred profile is regarded as the factors determining the conversion ratio of protein intake to retention.

3. Experimental Data and Regression Analysis

Nine experiments were conducted at Oklahoma State University (1999, 2000, 2003) to investigate the effect of crude protein (CP) or phosphorus (P) content in diets during the grower phase on growth performance, nitrogen and phosphorus excretion, and carcass traits in pigs. Some experiments, however,

Table 1. Summary of Experimental Diets (Carter *et al*., 1999, 2000, 2003)

	Dietary Treatment			
Exp 1/ Ingredient[a], %	CS&Caesin	Corn+CS&Caesin	CS&Caesin+SBM	Corn&SBM
Cornstarch	79.17	17.90	61.27	--
Casein	11.70	10.21	1.49	--
Corn	--	60.51	--	60.51
SBM-48	--	--	27.78	27.78
Exp 2/ Ingredient, %	CS&SBM	CS&SBMH	CS&SPC	CS&SPI
Cornstarch	65.19	60.38	76.44	79.23
Soybean meal, 48%	29.52	28.75	--	--
Soybean hulls	--	4.11	--	--
Soy protein concentrate	--	--	19.26	--
Soy protein isolate	--	--	--	16.29
Exp 3/ Ingredients, %	Corn&SBM	LPAA	Corn&SBMH	Corn&SBMP
Corn, dent grain	71.12	72.22	71.56	71.63
SBM, dehulled	25.94	14.40	14.42	14.41
Soybean hulls	--	--	10.00	--
Beet pulp	--	--	--	10.00
Cornstarch	--	10.00	--	--
Exp 4/ Ingredient, %	Corn&SBM	LPAA	Corn&SPC	Corn&SPI
Corn	67.01	77.9	83.44	86.09
Soybean meal, 48%	29.00	17.5	--	--
Soy protein concentrate	--	--	12.59	--
Soy protein isolate	--	--	--	9.37
Exp 5/ Ingredient, %	CS&Casein	Corn&SBM	LPAA	Corn&SPC
Cornstarch	79.17	--	--	--
Casein	11.70	--	--	--
Corn	--	65.19	75.63	80.99
SBM-48	--	30.3	18.8	--
Soybean protein concentrate	--	--	--	13.85
Exp 6/ Ingredient, %	Normal Corn A	High-oil Corn B	Normal Corn C	Normal Corn D
Corn	90.48	90.48	90.48	90.48
Casein, dried	5.04	5.04	5.04	5.04
Exp 7/ Ingredient, %	Hybrid A Corn	Hybrid B Corn	Hybrid C Corn	Hybrid D Corn
Corn	90.48	90.48	90.48	90.48
Casein, dried	5.04	5.04	5.04	5.04

Table 1. Summary of Experimental Diets (Carter *et al*., 1999, 2000, 2003)   (continued)

	Dietary Treatment			
Exp 8/ Ingredient, %	Corn&Caesin	RS[b]&Caesin	WS[c]&Caesin	--
Corn, or sorghum	90.00	90.00	90.00	--
Casein, dried	6.14	6.14	6.14	--
Exp 9/ Ingredient, %	Corn&SBM	CS1+Corn&SBM[b]	CS2+Corn&SBM[b]	Corn&SBM+HI[c]
Ground corn	66.65	66.65	66.65	66.65
Soybean meal, dehulled	30.68	30.68	30.68	30.68

[a] Synthetic amino acids, vitamins and minerals were added to met or exceeded NRC (1998) requirements.

[b] RS refers to red sorghum used in the experiment.

[c] WS refers to white sorghum used in the experiment.

[d] Cornstarch was added to the daily rations to provide 100 or 200 kcal/kg ME in Diets 2 and 3.

[e] Hemicell® replaced cornstarch in Diet 4 and provided 89 million IU/ton.

Source: Oklahoma Agricultural Experiment Station, 1999, 2000, 2003.

were designed to determine the energy and nitrogen balance of different corn hybrids, or grains. The goals of diet formulation and feeding strategy in these experiments are to achieve maximal animal performance. Pigs were housed individually in an environmentally controlled room in metabolism chambers, which allowed the separate, but total collection of urine, feces, and refused feed. The room temperature was maintained at 24^0 Celsius to achieve optimal animal performance. In each experiment, pigs of same littermate were allotted randomly to different dietary treatments. The ingredient composition of each diet was shows in Table 1.

The performance variables analyzed in this study were average daily gain (ADG, in grams), average daily feed intake (ADFI, in grams/day), average daily body protein retention (APR, in grams/day), average daily phosphorus retention (APHR, in grams/day), and the efficiency of feed utilization (G:F, ADG/ADFI) in a certain feeding period. Some equations presented in the NRC simulation model contain conversion coefficients of chemical and physical components, and parameters of nutritional requirements, which are less sensitive to the nutrient contents in the diets. The deductive and flexible nature of the body protein generating equation in predicting animal growth, in contrast, make it more variable as the nutrient contents in the diets change. Thus, the parameters of the whole body protein generating equation and the maximum DE intake equation will be tested and re-estimated with experimental data (Carter *et al*., 1999, 2003). To best estiamte the parameters of the simulation model with experimental results, pig's genotype, and temperature in the simulation model were specified at the same levels as the experiments. The equation to calculate daily APR during the growing-finishing period from average feed intake, given an average body weight, a certain mean lean growth rate, and $24^0\mathrm{C}$ ambient temperature is:

$$\text{APR (g/day)} = (17.5\times e^{-0.0192\mathrm{BW}_t}+16.25)\times(\mathrm{MFFL}/318.75)\times\ (1+0.015\times(20\text{-}24))\times$$

$$\text{(MxDE intake-}\ 0.55\times\mathrm{DE}\ \text{requirement for maintenance).} \qquad (13)$$

or

$$\text{APR (g/day)} = (17.5\cdot e^{-0.0192\mathrm{BW}_t}+16.25)\times(0.003137\cdot\mathrm{MFFL})\times\ 0.94\ \cdot$$

$$\text{(MxDE intake-}\ 0.55\times\mathrm{DE}\ \text{requirement for maintenance),} \qquad (14)$$

where the effect of temperature on whole body protein accretion rate in equation (3-1), $1+0.015\times(20\text{-}24)$, was simplified to 0.94, and works as the parameter of DE intake above 55% of DE requirement for maintanence. To relate pig genotype (generally expressed as mean fat-free lean growth rate during the feeding period) to its whole body protein accretion rate, the mean fat-free carcass lean accretion rate (MFFL) entered the model as a random effect variable linearly.

In the regression analysis, the data set used to estimate model consists of D cross-sectional units (dietary treatments), denoted $d=1,\ldots\ldots,D$, observed at each of R_d pig replicates, $r=1,\ldots\ldots,R_d$. MFFL appearing in the equation above as random effects was assumed that follows a normal distribution with mean of 350 gram per day, and a constant variance σ_{ur}^2 that is homoscedastic for the same littermate pigs, and hereroscedatis across various littermates. That is,

$$\mathrm{MFFL}_r \sim \text{iid } N(350,\ \sigma_{ur}^2) \qquad (15)$$

The variation in the predictability of NRC simulation model may be attributed to two possible reasons. First, the coefficients of the NRC model may not adequately measure the dynamic growth function. Second, growth variables may be affected by dietray treatments. To investigate the dynamic growth relationship in the daily nitrogen retention equation, we assume that the parameter vector $\mathbf{b}_i$ is the same for all d. The average daily body protein retention (APR) in the simulation model can be converted to the average daily nitrogen retention (ADNR, gram/day) by dividing it with a coefficient, 6.25. The nonlinear mixed model specifies that

$$\mathbf{ADNR}_d = 1/6.25 \times (\mathbf{b}_1 e^{\mathbf{b}_2 \mathbf{BW}_d} + \mathbf{b}_3) \times \mathbf{b}_4 \mathbf{MFFL}_d \times \mathbf{b}_5 \mathbf{ADE}_d + \boldsymbol{\varepsilon}_d \qquad d=1,\ldots\ldots,D$$

$$= h(\mathbf{BW}_d, \mathbf{MFFL}_d, \mathbf{ADE}_d, \mathbf{b}_d) + \boldsymbol{\varepsilon}_d$$

$$E[\varepsilon_{dr}]=0 ,$$

$$\mathrm{Var}[\varepsilon_{dr}]=\sigma_r^{\ 2} ,$$

$$\mathrm{Var}[\varepsilon_{dr},\varepsilon_{fj}]=\sigma_{rj} , \qquad \text{if } i=j , \tag{16}$$

where each cross-sectional vector, $\mathbf{BW}_d$, $\mathbf{MFFL}_d$, and $\mathbf{ADE}_d$ has R_d observations, and $\mathbf{ADE}_d$ is digestible energy intake (DE) above 55 percent of maintenance, expressed in grams per Mcal.

Under the framework of analysis that allows disturbance variances differ and correlate across littermates with constant **b** for all dietary treatments, The genralized ordinary least squares estimator can be obtained by stacking the data in the pooled regression model. The experimental data for daily nitrogen retention consist of series of numerous replicate observations for 26 diets. By pooling all 240 observations and estimating the coefficients by nonlinear ordinary least squares, the pooled maximum likelihood estimators were shown on Table 2 (PROC NLMIXED, SAS).

Table 2. The ML estimators of the simulation model using experimental data conducted by Carter *et al.* (1999, 2000, 2003).

Coef.	b_1	b_2	b_3	b_4	b_5	σ^2_{ur}	σ^2_{ed}
Est.	14.05 (Infty)[a]	-13.05 (Infty)	-0.00002 (-15.31)	0.03451 (-14.76)	139.37 (Infty)	3313.14 (Infty)	0.8504 (629706)
p-Val	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001

[a] Estimated t-values for the parameter estimates are shown in parentheses

Hypotheses tests were conducted to determine whether the original NRC nitrogen retention equation is applicable to the experimental data using the parameters re-estimated by the experimental data of Carter *et al.* For hypothesis testing and confidence intervals in a nonlinear regression model, the usual procedures can be used, with the proviso that all results are only asymptotic (Green, 1991). Since all the factors in the equation jointly determine the value of daily nitrogen retention, the sorts of hypotheses will invole systematic linear restrictions. The tests of the validity of the coefficients must be carried out by imposing all the constraints of the hypothesis on estimators. That is,

$$H_0\!:\mathrm{b}_1=17.5,\ \mathrm{b}_2=-0.0192,\ \mathrm{b}_3=16.25,\ \mathrm{b}_4=0.003137,\ \text{and}\ \mathrm{b}_5=0.94.$$

For testing the hypothesis that b_i is indifferent from the NRC values in the nonlinear model, an asymptotic F test, based on the approximate chi-squared distributions, is carried out. From the SAS output, F= 726×10^{190} with p-value<0.0001. This is extremely larger than the critical values for the 5 percent significance level, and the parameter values suggested by NRC were thus rejected in favor of the re-estimation values.

In the experiments characterized by the longitudinal data, a plausible assumption is that parameters vary across 26 dietary treatments (i.e., across the cross-sectional units). However, if dietary treatments have no effect on growth variables, the same set of parameters should enter all of the equations across the cross-sectional units. Considerable efficiency will be gained by estimating the equations jointly; otherwsie estimating the equations separately will waste the information that the same set of parameters appears in all of the equations. To determine whether the parameter vector was the same for all dietary treatments, it is useful to ascertain which particular observations are especially influential in the results obtained. If the observation for particular diet conforms to the model that is estimated with the other observations, this standardized residual should be small. Otherwise, the particular diet may deserve different parameters as perhaps not conforming to the model.

To find out influential data points, each residual was standized by dividing by the appropriate standard error for that residual. The appropriate variance suggested by Belsley *et al.* is the variance of the modified residual, calculated by the least squares coefficient with the ith observation being omitted. Examiniation of the standardized residual suggests that the disturbance terms are quite small for observations across dietary treatments. The hypothesis that the disturbances of all observations were significantly different than 0 was strongly rejected at the 5 percent significance level. Since no individual effect of cross-sectional units are observed for the diets with reduced crude protein and phosphorus content, in principle, a pooled regression model of (16) can be applied to all data sets of experiments conductd by Carter *et al.*

4. The Profit Maximum Problem

This study will use profit maximization as an optimization goal. The goal is to maximize profit from a sequence of continuous hog production cycles. The dynamic system simulation model in which some important equations was re-estimated in section 3 by the experimental data over a wide range of nitrogen and phosphorus ratios diets will be used to select the feedstuffs that give the optimal daily growth, while simultaneously meeting daily nutrient requirements. The main idea is to build a profit-maximizing problem upon a well-established mathematical programming model to determine optimal dietary regimes and then to explicitly add waste management costs to the optimization.

The swine feeding operator is assumed to choose length of each feeding period, and daily amount and type of each feed that maximizes discounted profits over the life of the feeding facility. The price the grower receives is assumed to consist of a base price with a net carcass quality premium (discount) rate expressed as the percentage of base hog price for desirable (undesirable) carcass traits. The cost structure of pig production operations includes a fixed cost, c_f, and a daily variable feed cost, c_t. A constrained profit maximization problem with daily adjustment on nutrient requirements for the growing to finishing pig feeding operator has been formulated in GAMS 2.5 using the MINOS solver as follows.

MAX

$$T, y_{jt}, BW_t \qquad Z=\Psi\times[(Pb\times U\times FBW)/(1+d)^{T-1}-\sum_1^T C_t/(1+d)^{T-1}-C_f] \qquad (3\text{-}1)$$

capital recovery factor × (pork basis price × carcass merit system index × final body weight/discount factor less total discounted feed costs less fixed cost)

Subject to

$$\sum_1^J E_j\times Y_{jt}\geq DEI_t \qquad (3\text{-}I1)$$

(The DE content in the rations)

$$1250+188\times BW_t-1.4\times BW_t^2+0.0044\times BW_t^3\geq DEI_t \qquad (3\text{-}I2)$$

(The upper bound of DE intake)

$$110\times BW_t^{0.7}\leq DEI_t \qquad (3\text{-}I3)$$

(The lower bound of DE intake)

$$\sum_1^J A(i,j)\times B(i,j)\times Y_{jt}\geq 0.036\times BW_t^{0.7}\times AAm(i)+0.12\times WBPG_t\times AAp(i) \qquad (3\text{-}I4)$$

(The amino acid content in the ration must be at least equal to what is required)

$$\Sigma_1^J O(j)\times H(j)\times Y_{jt} \geq (EXP(-0.0557 - 0.416 \times \ln BW_t + 0.005 \times \ln BW_t^2)/100) \times (1250 + 188 \times BW_t - 1.4 \times BW_t^2 + 0.0044 \times BW_t^3)/3.4 \quad \text{(3-I5)}$$

(The phosphorus content in the rations must be at least equal to what is required)

$$\Sigma_1^J CA(j)\times Y_{jt} \geq (EXP(-0.0658 - 0.1023 \times \ln BW_t - 0.0185 \times \ln BW_t^2)/100) \times (1250 + 188 \times BW_t - 1.4 \times BW_t^2 + 0.0044 \times BW_t^3)/3.4 \quad \text{(3-I6)}$$

(The calcium content in the rations must be at least equal to what is required)

$$\Sigma_1^J O(j)\times H(j)\times Y_{jt}/\Sigma_1^J CA(j)\times Y_{jt} = 1.9 \quad \text{(3-I7)}$$

(The ideal ratio of phosphorus to calcium in the ration)

$$C_t = \Sigma_1^J P_j \times Y_{jt} \quad \text{(3-I8)}$$

(The feed cost)

$$WBPG_t = (14.05 \times e^{-13.05BW_t} - 0.00002) \times (0.03451 \times MPAR) \times 139.37 \times (DEI_t - 0.55 \times 110 \times BW_t^{0.75}) \quad \text{(3-II1)}$$

(The whole body protein generating equation)

$$PTG_t(g) = WBPG_t / 0.23 \quad \text{(3-II2)}$$

(The daily protein tissue gain)

$$LP = (IFFL + \sum_1^T 2.55 \times WBPG_t)/(1000 \times FBW / 1.35) \quad \text{(3-II3)}$$

(The lean percent in the carcass)

$$FSY_t = (0.96 \times DE - 10.6 \times WBPG_t - 106 \times BW^{0.75})/12.5 \quad \text{(3-II4)}$$

(The daily lipid synthesis from energy intake)

$$FTG_t = FSY_t / 0.9 \quad \text{(3-II5)}$$

(The daily fat tissue gain)

$$DBWG_t = (PTG_t + FTG_t)/0.94 \quad \text{(3-II6)}$$

(The daily body weight gain)

$$BW_{t+1}=BW_t+DBWG_t \tag{3-II7}$$

(The body weight accretion equation)

$$FBW=20+\sum_1^T DBWG_t \tag{3-II8}$$

(The body weight at the marketing day)

where C_t is the daily cost of feed ingredients; P_b is the base hog price per kg; $U(\cdot)$ is the net carcass quality premiums (discounts) rates expressed as the percentage of base hog price for desirable (undesirable) carcass traits, such as final body weight and lean percent (LP); C_f is the fixed cost; A(i, j) is the *i*th essential amino acid content in feed ingredient j; B(i, j) is the coefficient for true digestibility of amino acid i in feed ingredient j; O(j) is the coefficient for bioavailability of Phosphorus in feed ingredient j; H(j) is the phosphorus content in the *j*th feed ingredient; CA(j) is the calcium content in feed ingredient j; P_j is the price of feed ingredient j. AAm(i) and AAp(i) are twelve-element vectors containing the essential amino acid profile for maintenance, and growth, respectively. DEI_t is the digestible energy intake at day t. Ψ is the approximate capital recovery factor;

$$\Psi=(1+d)^T/\left[(1+d)^T-1\right]. \tag{17}$$

Equations (3-I1) to (3-I7) were presented as the constraints regarding nutritional requirements and the associated feeding cost. Equation (3-I1) specifies the total energy values contributed by feed ingredients in the diets. However, under profit maximizing growth, controlled (restricted) digestible energy consumption must satisfy equations (3-I2) (the upper limit of daily DE), and (3-I3) (the minimum requirements of daily DE). Equation (3-I4) requires that the sum across ingredient contributions of each essential amino acid in the diet must be greater than or equal to the requirements for that amino acid. Equations (3-I5) and (3-I6) state that the amount of phosphorus and calcium in the diet must be at least equal to what is required. Equation (3-I7) specifies the ideal ratio of phosphorus to calcium in the diet. Equation (3-I8) is the sum of total cost. (3-II1) to (3-II8) are equations regarding pig's growth. The equations describing the growth variables and specifying the nutrient requirements were expressed on a daily basis. Detailed description of the growth model and nutritional requirements were presented above. Price data used in profit maximizing model will also be collected from various U.S. government agencies and private companies.

Table 3. Prices of Feed Ingredients ($/g) and Feeder Pigs ($/head), and Pork Base Prices ($/kg),

Item	Price	Item	Price
L-tryptophan	0.034	Sorghum	0.00017995
DL-methionine	0.00269	Barley	0.00008809
L-lysine	0.00604	Oats	0.000095
L-threonine	0.00325	Wheat	0.00007964
DicalciumPhosphate	0.00039648	GroundedLimestone	0.00002756
Corn	0.00009348	SBM	0.00020013
Feeder Pig	36.85	Base Price, P_b	0.731858

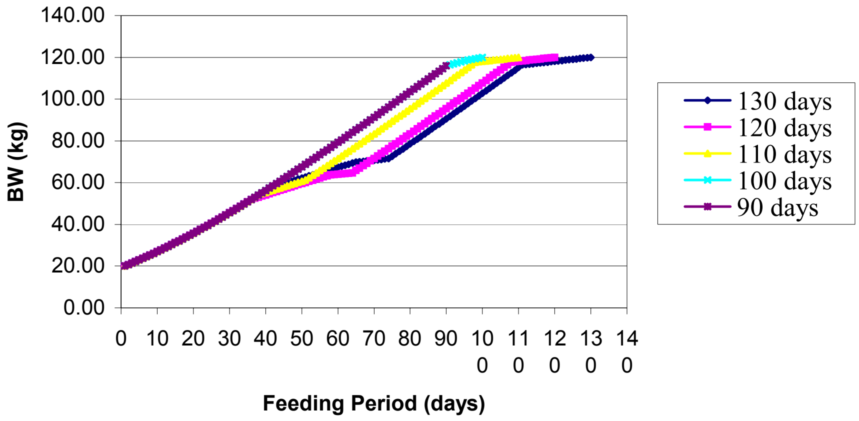
Source: 1. Heartland Lysine, Inc. (Chicago, IL). 2. Feed Outlook Report, USDA-Economic Research Service. 3. Agricultural Prices Monthly, USDA - National Agricultural Statistics Service.

This step consists of two major control decisions available to the grower: choose the daily profit-maximizing body-weight gain trajectory, and choose least cost rations that meet the changing nutritional requirements along the optimal growth path. Since growth rates, nutrient requirements, and the related nutrient excretion changes, as pigs grow each day, the method of phase feeding with daily production stage provides more flexible dietary regime, and accurate nutrient requirement. The advantage of daily changes in diet formulation is to meet the nutrient needs more efficiently at the lowest cost, while maintains pig growth performance at the optimal level.

The optimal length of feeding period can not be directly determined by the mathematical programming model formulated in GAMS, in which T is an exogenous parameter with all decision variables being simulated at daily intervals. A line search to maximize equation (3-1) was performed by repeated runs of profit maximization model using the MINOS solver with the feeding period lying in the interval $90 \leq T \leq 130$. The estimated economic returns for the standard runs of the model with the various feeding periods, T= 90,……, 125, and 130 are shown in Table 4. The corresponding optimal growth paths for T = 90, 100, 110, 120, and 130 days are given in figure 1.

As days fed increased, either final body weight or carcass lean percent increased. Table 4 shows that before pigs reach 120 kg, the final body weight constraint, marketing weight increased as days fed increased, while carcass lean percent was not altered. As final body weight constraint 120 kg was binding, days on feed were generally used to accumulate lean percent in body weight. The curves in figure 1 show that the extent to which feeding is restricted also increases with days fed. Carcass lean percent is expected to increase so as to receive premiums for higher carcass quality as days fed increased. Note that restricted feeding for the profit maximization model with carcass weight and merit- pricing program occurs in the latter part of the growth path. This result seems to be consistent with the hypothesis suggested by the National Research Council that younger pigs have greater growth efficiency of lean. Profit maximizing operators would maximize pig growth in the early stages of feeding so as to obtain the maximum gain of lean meat at least cost. Under the carcass merit- pricing program that the premium/discount rates are dependent on the lean percent in carcass, hog feeding operators then restrict pig growth in the later stage of growth to reduce animal body weight, and thus increase the lean percent in the carcasses.

Figure 1. The Optimal Growth Paths for Various Feeding Periods



The length of feeding period is a crucial factor in determining profitability of hog feeding operations that market pigs on a carcass basis. Figure 2 demonstrates the effect of T on the optimal constrained infinite period profit given by equation (3-1). The shape of the curve shows the importance of final body weight as well as carcass lean percent in determining profitability of hog feeding operation. The optimal feeding period, T^*, is at 100 days. Marketing too early would increase discounts for inadequate carcass quality and light carcass weights.

The length of feeding period is a crucial factor in determining profitability of hog feeding operations that market pigs on a carcass basis. Figure 2 demonstrates the effect of T on the optimal constrained infinite period profit given by equation (3-1). The shape of the curve shows the importance of final body weight as well as carcass lean percent in determining profitability of hog feeding operation. The optimal feeding

period, T^*, is at 100 days. Marketing too early would increase discounts for inadequate carcass quality and light carcass weights.

Table 4. The Results of Simulated Profit Maximization Model

Feeding Period (d)	Profit ($/head)	FBW (kg)	Lean Percent (%)
90	419.7	115.9	48.0
91	427.3	117.1	48.0
92	433.2	118.4	48.0
93	437.5	119.6	48.0
94	437.4	120.0	48.0
95	436.1	120.0	48.0
96	435.3	120.0	48.0
97	434.0	120.0	48.1
98	435.5	120.0	48.1
99	443.7	120.0	48.3
100	444.7	120.0	48.3
101	435.8	120.0	48.3
102	431.8	120.0	48.3
103	428.5	120.0	48.3
104	437.2	120.0	48.4
105	435.0	120.0	48.5
106	427.9	120.0	48.4
107	427.6	120.0	48.4
108	422.8	120.0	48.4
109	429.2	120.0	48.6
110	439.2	120.0	48.7
115	430.9	120.0	48.9
120	431.2	120.0	49.1
125	433.3	120.0	49.3
130	433.2	120.0	49.6

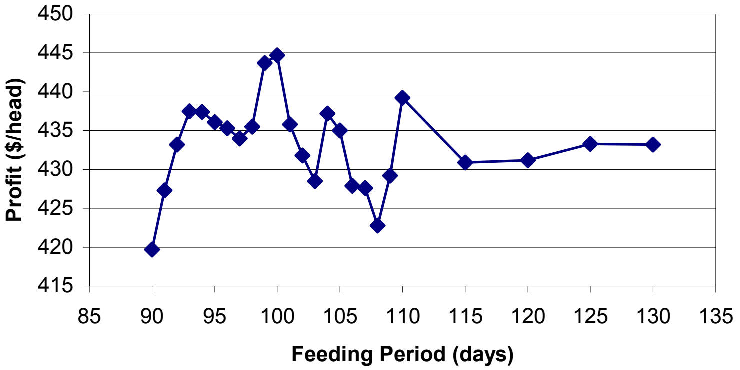


Figure 2. The Optimal Feeding Period for the Profit Maximization Model

Diets were formulated using linear programming (L.P.) in this study to achieve a particular daily weight gain, and a particular composition of that gain at least cost. Table 5 shows the amount and percentage of each ingredient that was in the optimal ration on the 1st , 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th, and 100th days. Among the energy-supplying ingredients, only wheat was included in the optimal rations. This result is consistent with the recommendation made by Oklahoma Cooperative Extension Service that wheat contains high protein and lysine, and is an excellent swine feed when it is competitively priced (Fact Sheet-3500, Oklahoma Cooperative Extension Service). Comparision with the works of Fawcett *et al*., the overall efficiency of pig production can be achieved by manipulating both the body weight gains and carcass composition of pigs at the whole animal level over feeding periods.

Table 5. The Optimal Ration Composition of Profit Maximization Model for Pigs with High-Medium Lean Growth Rate

	Wheat		SBM		LimstonG		
D (days)	Amount (g)	Percent (%)	Amount (g)	Percent (%)	Amount (g)	Percent (%)	FI (g)
1	1083.13	75.59	330.83	23.09	18.86	1.32	1432.82
10	1354.09	78.42	349.24	20.22	23.46	1.36	1726.79
20	1675.01	81.44	352.78	17.15	28.88	1.40	2056.67
30	1998.06	84.25	339.33	14.31	34.31	1.45	2371.70
40	2305.12	86.74	312.87	11.77	39.45	1.48	2657.44
50	2583.94	88.89	278.77	9.59	44.09	1.52	2906.80
60	2830.38	90.70	242.01	7.76	48.19	1.54	3120.58
70	3047.93	92.19	206.33	6.24	51.80	1.57	3306.06
80	3245.96	93.41	174.04	5.01	55.08	1.58	3475.08
90	1981.00	98.34	0.00	0.00	33.43	1.66	2014.43
100	3502.44	94.65	138.45	3.74	59.35	1.60	3700.24

Since the point corresponding to the most economic gain generally occur before the maximum growth (Gahl *et al*. 1995), diets formulated for maximum economic returns provide less overall nutrients and result in smaller sizes of animals and shorter feeding period than those for maximum growth. Problems associated with the over-supplementation of diets with nutrients to ensure maximum performance could be alleviated by profit diet formulation, which provides only necessary nutrients and reduces excess amounts of excreted nutrients in feces and urine. The advantage of profit maximizing diet formulation increases as number of pigs increases . With limited cropland available for application of manure, the large quantities of nutrient laden manure increase the waste management costs, and reduce the net returns of hog production. Given the increasing large and intensive pig feeding operations in modern pig production, the profit maximization application of the simulation model is expected to produce relatively more satisfactory results.

4. Comprehensive Profit Maximizing Diet Formulation

The NRC growth model does not directly provide excretion estimates. To maximize the overall profit of swine feeding operation, the relationship between nutrient intake and the amount and form of nutrients excreted will be quantified econometrically by the data sets of swine feeding trials conducted by Carter *et al*. (1999; 2000; 2003).

This objective will be accomplished by modifying an existing swine waste management model (Stoecker, 1998; Carreira, 2000) to calculate the effect of diet/growth manipulation, and the amount and form of nitrogen and phosphorus excreted on the waste management costs. The Decision Support System (the swine spreadsheet) is a tool that will be used to calculate waste management costs, in which the construction costs of manure treatment facilities, and the fertilizer value of manure are two major components. The estimated amount and form of nitrogen, dry matter, and phosphorus excretion will be used to determine the economic implications of the dietary modifications on the fertilizer value of manure and on the utilization of swine production facilities. In particular, the relationship between increases in soluble phosphorus concentration in the runoff and phytase modified diets will be examined. The implied costs from related changes in manure management and/or modifications to lagoons or other treatment facilities due to changes in nutrient content of manure will also be determined with the swine waste management spreadsheet (Stoecker *et al*., 2002).

This program estimates manure management system specifications and costs based on the size, type, and geographic location of a swine production unit. The analysis will be conducted with finishing operations of 2000, 4000, and 8000 pigs in both semi-arid and humid locations. The cost structure incorporated in profit-maximizing feeding program is comprehensive and can be used to determine the overall optimal growth trajectory that considers waste management costs in addition to feed cost.

Reference:

Black, J. L., R. G. Campbell, I. H. Williams, K. J. James, and G. T. Davies. "Simulation of Energy and Amino Acid Utilization in the Pig.", *Research and Development in Agriculture*, 3(1986):121-45.

Boland, Michael, Kenneth A. Foster, and Paul V. Preckel, "Nutrition and the Economics of Swine management.", *Journal of Agricultural and Applied Economics*, 31(1999):83-96.

Carrieira, R.I., "Dynamic Spreadsheet Programming to Compare the Effect of Geographic Location and Economies of Size on Hog Manure Handling Systems in Oklahoma.", Oklahoma State University, Master Thesis, May 2000.

Carreira R.I., and A.L. Stoecker, "Dynamic Spreadsheet Programming to Select the Most Cost Efficient Manure Handling System.", Paper Presented at Western Agricultural Economics Association Annual Meeting, Vancouver, British Columbia, June 29-July 1, 2000.

Fawcett, R.H. "Toward a Dynamic Production Function." *Journal of Agricultural Economics*, 24(1973):543-55.

Fawcett, R.H., C.T. Whittemore, and C.M. Rowland "Toward the Optimal Nutrition of Fattening Pigs: Part I-Isoquants and Isocomposition Functions." *Journal of Agricultural Economics*, 29(1978):165-73.

Fawcett, R.H., C.T. Whittemore, and C.M. Rowland "Toward the Optimal Nutrition of Fattening Pigs: Part II-Least Cost Growth and the Use of Chemical Value in Diet Formulation." *Journal of Agricultural Economics*, 29(1978):524-35.

Gahl M. J., T. D. Grenshaw, and N.J. Benevenga. "Diminishing Returns in Weight, Nitrogen, and Lysine Gain of Pigs Fed Six Levels of Lysine from Three Supplemental Sources." *Journal of Animal Science*, 73(1995):3177-3187.

Kim, Change-Gil "An Integrated Decision Model for Evaluating Alternative Swine Waste Management System under Environmental Constraints in Oklahoma." Unpublished Ph.D. Dissertation, Stillwater: Oklahoma State University, Stillwater, Oklahoma.

Luce G. William, and Charles V. Maxwell. “Swine Nutrition.” Fact Sheet-3500, Oklahoma Cooperative Extension Service.

National Research Council. *Nutrient Requirements of Swine*. National Research Council. Tenth Revised Edition. National Academy Press. Washington DC, 1998.

Senne, B.W., S.D. Carter, L. A. Petty, and J. A. Shriver., “Nitrogen and Phosphorus Excretion from Pigs Fed Different Soybean Fractions.”, *Animal Science Research Report*, (2000):129-35, Department of Animal Science, Oklahoma State University.

Senne, B.W., S.D. Carter, L. A. Petty, and J. A. Shriver., “Effects of Corn and (OR) Soybean Meal on Nitrogen and Phosphorus Excretion of Growing Pigs.”, *Animal Science Research Report*, (1999):280-286, Department of Animal Science, Oklahoma State University.

Shriver, J.A., S.D. Carter, A.L. Sutton, B.T. Richert, B.W. Senne, and L.A. Pettey., “Effects of Adding Fiber Sources to Low Crude Protein, Amino Acid Supplemented Diets on Nitrogen Excretion, Growth Performance and Carcass Traits of Finishing Pigs.”, *Journal of Animal Science*, 81(2003):492-502.

Snedecor, G. W., and William G. Cochran. *Statistical methods*. Sixth Edition. Iowa State University Press. Ames Iowa, 1967.

Stoecker, A.L., C.D. Fullhage, J.A. Hoehne, R.E. Massey, J.A. Lory, D.W. Hamilton, J. Williams. “Spreadsheet for Design and Economic Analysis of Swine Production and Waste Management Systems.”, Animal Production Systems and the Environment-An International Conference on Order, Water Quality, Nutrient management and Socioeconomic Issues, Proceeding Vol. I: 431-37, Ames IA: Iowa State University Press, 1998.

U.S. Department of Agriculture, the Grain Inspection Packers and Stockyards Administration (GIPSA), Swine Contract Library: http://scl.gipsa.usda.gov/. Accessed 08/05/2004.

Zhang, Hailin. “Animal Manure Can Raise Soil pH.” *Production Technology*. Oklahoma Cooperative Extension Service. February, 1998.

Zhang, Hailin. “Comprehensive Nutrient Management Plan (CNMP).” *Production Technology*. Oklahoma Cooperative Extension Service. January, 2003.

Zhang, Hailin. “Animal Manure and Soil Quality.” *Production Technology*. Oklahoma Cooperative Extension Service. February, 1998.