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Article

# Technical-economic optimization in the fattening of turkeys from commercial genetic lines in Temascaltepec, Mexico

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**Abstract:**

The objective of the study was to develop a combined approach of deterministic modeling and Monte Carlo simulation to establish the optimal technical-economic level for fattening commercial genetic lines of turkeys in the municipality of Temascaltepec, Mexico. Data from 42 turkeys of the double-breasted diamond genetic variety, with an average age of three weeks and an initial body weight of 1.077 ± 0.132 kg, were analyzed. In order to model the relationship between feed consumption and final weight of the turkeys, a quadratic production function was fitted using nonlinear regression along with a Monte Carlo simulation analysis to evaluate the risk associated with fluctuations in feed costs and the selling price of turkeys. The deterministic analysis identified that economic profitability is maximized when turkeys consume 26.81 kg of feed and reach a live weight of 11.30 kg. The Monte Carlo simulation confirmed the validity of these results under scenarios of uncertainty in sales prices and feed costs, estimating an average net profit of

$379.29 per bird in the economic optimum, compared to $325.39 in the technical optimum, representing a 16.56 % increase in profitability per turkey. These findings confirm that integrating deterministic modeling with stochastic simulation constitutes an effective methodological tool for production decision-making under conditions of variability and uncertainty. It is recommended that this approach be validated in other agricultural contexts to strengthen its practical applicability.

**Keywords:** Economic analysis, Feed consumption, Nonlinear regression, Optimal economic level, Stochastic simulation.

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# Introduction

In Mexico, turkey (*Meleagris gallopavo*) breeding with commercial genetic lines (meleagriculture) is considered one of the most traditional livestock activities(1). This productive system is developed throughout the national territory, mainly concentrated in indigenous communities(2), where small production units operate and implement animal husbandry practices adapted to the farmers' conditions(3). Turkey production in Mexico is carried out under three well-defined systems: technified, semi-technified, and small producers who raise turkeys in backyard settings in a traditional way(4), each system with different characteristics and technological levels(5,6).

Since domestication, several varieties or genetic lines of the wild turkey have been developed, the most commercially important of which include the large white turkey and the double-breasted bronze(7). These commercial lines are raised mainly in intensive systems and are selected for their rapid growth, feed efficiency, carcass yield and larger breast size(8). Despite the diversity of turkey production systems, poultry farming in Mexico faces significant challenges to meet the growing domestic demand for turkey meat, which has led to a considerable increase in imports. In 2017, the country ranked as the third largest importer of turkey meat with 7.2 million tons of frozen meat and 85 thousand tons of fresh chilled meat(9).

A determining factor for improving turkey production is technical and economic efficiency and the optimal use of productive factors (labor, capital, and raw materials) (1), especially feed, which represents one of the most relevant inputs in this production system (1,10). Animal growth in this context can be accurately modeled by mathematical functions describing the evolution of live weight, allowing the estimation of maximum growth values and optimal ages to maximize productivity and economic benefit [11,12]. To evaluate the technical efficiency in production Bates and Ocelli [13] propose two approaches; the deterministic and the probabilistic. This study focuses on the probabilistic model by applying a quadratic production function with a nonlinear regression approach, complemented with a Monte Carlo simulation analysis.

Although some previous studies in the Mexican agricultural sector have implemented production functions to evaluate the impact of feed on animal weight gain, the results of these studies are not yet available[14-17], there is a lack of work focused on meleagriculture with commercial genetic lines to determine the optimal slaughter ages to maximize economic profitability in this production system, particularly considering that feed represents more than 70 % of the total costs in turkey production[10,18,19]. Therefore, the objective of the present study was to develop a combined approach of deterministic modeling and Monte Carlo simulation to determine the optimal technical-economic level in the fattening of commercial genetic lines of turkeys, incorporating dietary variables and the impact of the cost of the diets used in the municipality of Temascaltepec, Mexico.

# Material and methods

## Study area

The experiment was conducted at the poultry fattening farm of the zootechnical post at the UAEM Temascaltepec University Center. The farm is located between parallels 18°49'58.9'' and 19°08' 37.0'' N, and between meridians 99°51'17.9'' and 100°36.0' 46.2" W. The climate of the zone is semi-warm sub-humid with summer rains. The average annual temperature is 20.3 °C, with precipitation of 1,158 mm[20].

## Animal handling and facility preparation

The fattening house used in the experiment has dimensions of 9 m in length, 6 m in width, and 3.5 m in height. Individual corrals made of 3/8" rods covered with hexagonal mesh were installed inside, having a length of 100 cm, a width of 50 cm, and a height of 70 cm. These pens were designed to prevent contact between turkeys from different flocks and to ensure adequate ventilation during the fattening cycle. Prior to the start of the experiment, the facilities underwent a cleaning process using soap and water, followed by disinfection with a creoline solution (13.33 ml/L) 48 h before the arrival of the animals.

Each pen was equipped with a lighting system using 40-watt fluorescent bulbs, a 30 cm long feed through with a capacity of 1.2 kg of feed, and a 40-watt fluorescent bulb system. To ensure adequate ventilation control, adjustable plastic curtains were installed throughout the house. During the first four days of the experiment, the curtains remained completely closed to avoid drafts. From the fifth day onwards, progressive adjustments were started, lowering them by 25 cm each day, until, from the seventh day onwards, they remained open between 8:00 and 20:00.

## Reception and handling of turkeys

Prior to the arrival of the turkeys, a biosecurity protocol was implemented by placing a sanitary mat at the entrance of the shed, which was soaked with a solution of 2 L of water and 5 ml of creoline to prevent the introduction of external pathogens.

## Biological material and feeding

The study used 42 turkeys of the double-breasted diamond genetic variety, with an average age of three weeks and an initial body weight of 1.077 ± 0.132 kg. The turkeys were randomly distributed, one turkey assigned to each pen, and were managed under an *ad libitum* feeding regime (Figure 1). During the first two hours after their arrival, they received no feed so that they could adapt. Subsequently, the amount of feed to be provided was calculated based on the heaviest turkey, adding 10 % of its body weight to ensure adequate feed intake.

**Figure 1:** Traditional feeding system in the broiler poultry farm of the zootechnical post of the UAEM Temascaltepec University Center

In this study, three nutritional phases were employed: starting turkeys, growing turkeys, and finishing turkeys, according to the nutritional plan of the commercial feed used in the research, which integrates the growth and development phases into a single stage referred to as growing turkeys. During the initial phase, which lasted from the arrival of the turkeys until d 23, they were fed a diet containing 27 % crude protein. The transition to the growth diet was carried out gradually over 3 d, with decreasing proportions of the initial diet (75-25 %, 50-50 %, and 25-75 %). The turkeys consumed this growth diet between d 27 and 55 (Table 1). Subsequently, they transitioned to the finishing diet, which they were given until the end of the experiment (84 d).

**Table 1:** Nutritional composition of the diets fed to turkeys at different growth phases (%)

| Phases | Crude protein | Crude fat | Crude fiber | Ashes | Moisture | NFE |
|---|---|---|---|---|---|---|
| Starting | 27.00 | 3.50 | 4.50 | 7.50 | 12.00 | 45. 50 |
| Growing | 23.00 | 4.50 | 5.00 | 7.00 | 12.00 | 48.50 |
| Finishing | 20.00 | 4.50 | 5.00 | 6.00 | 12.00 | 52.50 |

NFE= nitrogen free extract by difference.

Source: Productores Agropecuarios Tepexpan, S.A. de C.V, 2023.

## Response variables

The initial live weight of the turkeys was recorded individually at the time of reception, using a scale with a capacity of 40 kg. Live weight was monitored every 8 d, according to the procedure described by Rodriguez-Licea *et al*[1], who demonstrated that this interval is adequate to capture significant changes in the growth of turkeys under similar conditions. Feed was offered twice daily, at 0900 and 1800 h. At the latter time, the rejected feed was collected from each feeder, stored in bags identified by lot, and weighed to record waste before the next feeding. During the first day after their arrival, the turkeys were given water with a solution of RuViOtic (0.6 g/L) to ensure hydration; thereafter, from the second day until the end of the experiment, water was provided *ad libitum*.

The daily feed consumption was calculated as the total feed offered minus the feed rejected each day. Based on this information, weekly consumption was estimated by adding the daily values for each turkey. The weekly weight gain was determined by subtracting the final weight recorded in each week from the initial weight at the corresponding phase (start, growth, and finish). Feed conversion was estimated by dividing the total feed consumption by the final weight minus the initial weight of the turkeys. Data were recorded in a field logbook during the entire experimental period. The information was then organized in a Microsoft Excel spreadsheet, which served as the basis for statistical processing and subsequent modeling.

## Statistical model

To evaluate the relationship between feed intake and final weight of the turkeys, a production function represented by a nonlinear quadratic regression model was used. In this model, the total feed consumption (A) at each stage of production was used as the independent variable, while the live weight (P) expressed in kilograms was considered as the dependent variable. This nonlinear approach was chosen due to the biological nature of animal growth, where the decreasing marginal return on feed intake has been widely documented in the literature(16,17,21). The regression model was determined by evaluating both the statistical significance and the consistency in the biological and economic hypotheses, considering the magnitude and sign of the coefficients in each parameter(12). The model specification was as follows:

$$P = \alpha + \beta_1 A + \beta_2 A^2 + \varepsilon$$

Where P= live weight of each turkey in kilograms; α= intercept of the function; β1 and β2= are the estimated coefficients that capture the linear and quadratic effect of feed consumption; A= is the amount of feed supplied to each turkey (kg); ε= random error.

## Analysis of technical and economic efficiency

The technical-economic efficiency was estimated using the methods proposed by various authors(1,12,14). These authors calculate the optimum technical level (OTL) from the first partial derivative of the production function with respect to the independent variable "A". The equalization of the first derivative to zero gives the amount of feed with which the rate of weight gain reaches its maximum value. The value derived from "A" is then substituted into the production function to determine the weight with the maximum biological yield.

To determine the optimum economic level (OEL), the first partial derivative of the production function is used and equals the ratio between the price of the input (feed), divided by the selling price of the live turkey. This approach allows the integration of economic criteria into the model and, by deriving it, the amount of feed and live weight that maximizes economic profitability is obtained(16). During the study period, the cost per kilogram of feed was $11.63, while the selling price per kilogram of live weight was $73 per kilogram.

## Monte Carlo simulation

The OTL and OEL were determined through a traditional optimization analysis, which is based on calculations that assume constant conditions. However, to address the uncertainty in the selling price and feed cost, a Monte Carlo simulation analysis was performed; this approach allows modeling the uncertainty of these variables, generating a distribution of potential results that complement the traditional analysis. The Monte Carlo simulation provided a detailed view of the impact of fluctuations in the price of feed and sale of the turkeys on the monetary benefits associated with optimal levels, allowing a more robust assessment of risk and economic gains.

To perform the Monte Carlo simulation analysis, the parameters associated with the price per kilogram of feed and the sales price of turkey were adjusted using 15 yr (2008-2022) of historical data. The historical sales price of turkey was obtained from the statistical portal of the Agrifood and Fisheries Information System (Sistema de Información Agroalimentaria y Pesquera)(22), while the historical price per kilogram of feed was determined using an inflation-adjusted methodology, as there is no source of accurate historical price data in Mexico. The adjustment for inflation was made using annual inflation rates consulted on Banco de México's website(23) with a base price of $11.63 per kg of feed for the year 2023. The following formula was used for this adjustment:

$$adjusted\ P = \frac{current\ P}{1 + inflation}$$

$_{ajusted}$P is the adjusted price of the previous year, $_{current}$P is the base price for the year 2023 ($11.63). This adjustment enabled the creation of a time series of historical feed prices (2008-2022), adjusted to constant values of the base year, ensuring a consistent comparison throughout the study period.

A Monte Carlo simulation was performed with 10,000 iterations to assess the variability in turkey sales prices and feed costs. The initial parameters for the simulation were defined based on historical data on the price per kilo of turkey feed and sales. The feed cost was modeled with a mean = $8.18 and variance of $1.46, while the sales price of turkey included a mean of $57.11 and standard deviation = 14.01 pesos.

For each iteration, total revenue and total cost were calculated at the OTL and the OEL. The total revenue was obtained by multiplying the sales price by the weight of the turkey, while the total cost was calculated by multiplying the feed cost by the consumption. The net profit was determined by subtracting the total cost from the revenue. To ensure the accuracy and robustness of the simulation, a convergence and cross-validation test was performed.

The convergence assessment was carried out through an analysis with different numbers of iterations (1,000, 5,000, and 10,000) to obtain the mean, standard deviation and the 5, 50 and 95 % percentiles of the net gains at each optimal level. Cross validation was performed using five folds to check the consistency of the results. This process involved splitting the simulations into different subsets and combining the results to check whether the estimates in net gain for each optimum were consistent with the data partitions. The optimization analysis and Monte Carlo simulation were carried out using the R software (version 4.4.1)[24].

## Results

Table 2 shows the weight gain of the turkeys from the third week of age, of 1.08 kg, until wk 12, when they reached an average weight of 12.45 kg. The total feed consumption per turkey was 34.74 kg during the finishing phase, with an FC of 3.05 kg of feed per kg of weight gained.

**Table 2:** Productive variables in the fattening of double-breasted diamond turkey poults

| Variable | Values |
|---|---|
| Number of turkeys | 42.00 |
| Average initial weight per turkey, kg | 1.08 |
| Average final weight per turkey, kg | 12.45 |
| Total average feed consumption per turkey, kg | 34.74 |
| Average feed conversion per turkey | 3.05 |

The F value of the model (1,167.97; $P$<0.001), indicates that the predictor variables (A and $A^2$) have a significant impact on the weight gain of the turkeys. The coefficient of determination indicates that 99.57 % of the variability in weight is explained by the predictors. The predicted $R^2$ (0.9876) confirms that the model has high predictive power and can be applied to practical scenarios under various dietary conditions. The positive coefficient of "A" shows that for each additional kilogram of feed consumed, the average weight gain of the turkeys increases by 0.58 kg, while the negative coefficient of "$A^2$" indicates the presence of decreasing marginal yields. This behavior shows that the increase in feed consumption was not proportional to the weight of the turkeys (Table 3).

**Table 3:** Regression model results for predicting weight gain in turkey poults

| | **Estimated parameters** | **Standard error** | **t statistic** | ***P*-value** |
|---|---|---|---|---|
| Intercept | 1.41419 | 0.15220 | 9.29 | <.0001 |
| Variable A | 0.57806 | 0.02512 | 23.01 | <.0001 |
| Variable $A^2$ | -0.00781 | 0.00074 | -10.55 | <.0001 |
| $R^2$ of the model | 0.99570 | | | |
| Predicted $R^2$ of the model | 0.98769 | | | |
| F of the model | 1,167.97 | | | <.0001 |

## Optimal technical level in the production of turkey poults

The OTL was obtained by equalizing the first derivative of the production function to zero, which corresponds to the point where the turkeys reach their maximum biological production or maximum *in vivo* weight[12,21].

For the estimated production function: P1.41419+0.57806A-0.00781$A^2$, by deriving P with respect to A and equating it to zero, was obtained the following result:

$$\frac{\mathrm{dy}}{\mathrm{dx}} = 0.57806 - 0.01562\mathrm{A} = 0$$

Solving for A generates the value of the variable input, which represents the total amount of feed that the turkeys need to reach their maximum production weight or maximum in vivo weight.

$$-0.01562A = -0.57806$$

$$A = \frac{-0.57806}{-0.01562}$$

$A = 37.01$ kilograms of feed

Turkeys require 37.01 kg of feed to reach their maximum production weight. Substituting this value of A in the production function gives the maximum live weight of the turkeys.

$P1.41419 + 0.57806(37.01) - 0.00781(37.01)^2 =$ 12.11 kilograms of weight.

## Optimal economic level in the production of turkey poults

The OEL was determined by equating the first derivative of the production function to the ratio between the price of one kilogram of feed (Px) and the selling price of one kilogram of turkey (Py). This analysis establishes the optimal amount of feed to be consumed by the turkeys to maximize economic benefit[12,21].

$$\frac{dP}{dA} = \frac{Px}{Py} = 0.57806 - 0.01562A = \frac{11.63}{73}$$

Solving for A:

$$0.57806 - 0.01562A = 0.15936$$
$$-0.01562A = -0.4187$$

$A = \frac{-0.4187}{-0.01562} = 26.81$ kg of feed

Turkeys require 26.81 kg of feed to reach the maximum economic benefit. Substituting this value of A in the production function gives the live weight that maximizes income.

$P1.41419 + 0.57806(26.81) - 0.00781(26.81)^2 =$ 11.30 kilograms of live weight

Table 4 shows that the OEL generates a higher profit per turkey ($513.10) than the OTL ($413.60). The reduction in feed consumption for the OEL generates a reduction in the total cost, which translates into an increase in the benefit/cost ratio for each peso invested.

**Table 4:** Comparison of monetary gains at the optimal technical and the economic level

| **Parameter** | **Optimum technical level** | **Optimal economic level** |
|---|---|---|
| Feed intake, kg | 37.01 | 26.81 |
| Weight of turkey, kg | 12.11 | 11.30 |
| Total income, $ | 844.03 | 824.90 |
| Total cost, $ | 430.43 | 311.80 |
| Profit, $ | 413.60 | 513.10 |
| Benefit/cost ratio, $ | 1.96 | 2.65 |

## Monte Carlo simulation

The Monte Carlo simulation results indicate that the average net gain at the OEL was higher than that at the OTL. As the number of simulations increased, it was observed that both the mean gain and the values at the 5th and 95th percentiles stabilized after 1,000 interactions. Cross-validation confirmed the precision of these estimates with values very close to those obtained by the convergence method. The standard deviation for both optima remained constant, indicating a stable variability in net gain regardless of sample size. The behavior of the percentiles indicated that the central values remained consistent, which reinforces the stability of the estimates and the robustness of the results. However, the extremes of the distribution revealed greater variability in average gain for the OEL, which may be associated with higher risk under adverse conditions compared to the OTL (Table 5).

**Table 5:** Evaluation of net profit with Monte Carlo simulation for the optimal technical and economic level

| | **Optimum technical level** | | | **Optimal economical level** | | |
|---|---|---|---|---|---|---|
| **Number of simulations** | **Profit ($)** | **Standard deviation ($)** | **Percentiles** | **Profit ($)** | **Standard deviation ($)** | **Percentiles** |
| 1,000 | 334.14 | 182.79 | 5%: 35.86<br>50%:338.04<br>95%: 621.55 | 387.73 | 164.98 | 5%: 119.88<br>50%: 393.90<br>95%: 656.86 |
| 5,000 | 330.4 | 182.75 | 5%: 32.85<br>50%:326.64<br>95%: 629.40 | 383.82 | 165.98 | 5%: 112.41<br>50%:383.33<br>95%: 657.83 |
| 10,000 | 325.39 | 181.51 | 5%: 30.40<br>50%:324.09<br>95%: 624.83 | 379.29 | 164.95 | 5%:111.49,<br>50%: 378.40<br>95%: 652.50 |
| Parameter: | | | | | | |
| Cross-validation | 329.25 | 180.88 | 5%: 30.32<br>50%:328.59<br>95%: 626.42 | 383.01 | 164.15 | 5%: 109.13,<br>50%: 381.75<br>95%: 651.61 |

# Discussion

The final weight of the turkeys at 12 wk of life in this study (12.45 kg) was similar to that reported by Santos-Ricalde *et al*[25] in turkeys of the Convertible genetic line. Similar results have been reported in Nigeria, where turkeys fed commercial diets showed weight gains comparable to those in this study[26]. The feed conversion observed in this study was 3.05 kg, higher than the 2.46 kg recorded for turkeys of the Nicholas 700 line in a similar fattening period[27]. This difference can be attributed to variations in diet and management used in each investigation, factors that directly impact feed efficiency. On the other hand, a study conducted in Nigeria reported a higher feed conversion ratio of 3.53 kg[26], which highlights the influence of management and feeding conditions on the productive performance of turkey poults.

The average final weight of the turkeys in this study (12.45 kg, after 12 wk of fattening) was higher than that reported in backyard and semi-technified production systems, where the average weights at 15 wk were 3.19 and 4.76 kg, respectively[1]. The standard error analysis confirmed the validity of this behavior, showing that all assumptions associated with the distribution of variables A and $A^2$ are satisfied[12]. This ensures that the estimates of the effects of the variables on the production of turkey poults are reliable and not susceptible to variations in the sample data.

The t statistic associated with variables A and $A^2$ showed statistical significance in the regression model, confirming their significant influence on turkey production[1]. In addition, the value of $R^2$ in the model was consistent with that reported by Rodríguez-Licea *et a*[1], who found that the feed input explained 99.55, 98.76, and 99.34 % of the weight attained by turkeys in technified, semi-technified, and backyard systems, respectively. These results align with other studies, which highlight feed input as a critical factor in turkey production[26] and reinforce the importance of diet in feed conversion and growth [27].

According to microeconomic theory[28], the negative sign of parameter $A^2$ in the production function indicates the presence of a quadratic model with diminishing marginal returns. This behavior implies that as the feed input is progressively increased, the increase in the weight of the turkeys begins to decrease[1]. Consequently, there is a decrease in the economic gain at the time of sale.

Maximum live weight production in turkeys does not imply maximum monetary gain[1]. This is explained by the fact that, at high levels of feed intake, a proportion of the weight gained is transformed into fat instead of meat, reducing the technical efficiency and increasing production costs[12,14,29]. This study confirmed that the monetary gain was higher in the OEL, a performance that can be attributed, among other variables, to the inverse relationship between the economic optimum and the price of the feed[16], which highlights the importance of optimizing feed costs to maximize the profitability of the production system.

The results of the Monte Carlo simulation reveal clear differences in the net gains obtained for the optimal levels, with OEL showing higher gains in all the simulations performed. This behavior highlights the importance of optimizing production costs to maximize economic benefits. Furthermore, the stabilization of the average earnings and the 5th and 95th percentiles after 1,000 iterations validates the sufficiency of the model in obtaining reliable estimates, which agrees with previous studies that have demonstrated the effectiveness of the Monte Carlo method in estimating economic variables under uncertainty[30,31].

A relevant result is the lower standard deviation observed in the OEL compared to the OTL, which suggests greater stability of economic gains when costs are optimized. However, the extreme percentiles (5th and 95th percentiles) show greater variability in the gains associated with OEL, which could imply a higher risk under adverse conditions. This performance is relevant for small producers, who may face greater difficulties in scenarios of economic uncertainty or fluctuations in the market price of feed inputs.

Cross-validation reinforces the robustness of the results obtained by demonstrating consistency with the values derived by the convergence method. This finding indicates that the model used is reliable for projecting economic scenarios in turkey production under conditions similar to those of this research. The stability observed in the central percentiles for both optimum levels is an indicator that the estimates obtained are not only accurate but also highly reproducible across different simulated scenarios.

## Conclusions and implications

The deterministic analysis identified that the economic profitability is maximized when turkeys consume 26.81 kg of feed and reach a live weight of 11.30 kg. The Monte Carlo simulation confirmed the validity of these results under scenarios of uncertainty in sales prices and feed cost, estimating an average net profit of $379.29 per bird in the economic optimum, compared to $325.39 in the technical optimum, which represents a 16.56 % increase in profitability per turkey. These findings confirm that integrating deterministic modeling with stochastic simulation constitutes an effective methodological tool for making production decisions under conditions of variability and uncertainty. It is recommended that this approach be validated in other agricultural contexts to strengthen its practical applicability.

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### Conflict of interest

The authors of this paper declare that they have no conflict of interest.

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