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Analysis of Laying Hen Egg Population Model Using a Lefkovitch Matrix Model

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ABSTRACT

The poultry industry plays an important role in food security and economic stability in Indonesia, with eggs serving as one of the main sources of animal protein. This study aims to analyze the population dynamics and egg production of a single-cohort layer chicken population at UD Faoji Farm, Kembangan–Bukateja, Indoneisa, using the Lefkovitch matrix model. The population was classified into three productivity-based stages: young layers, productive layers, and older layers. Primary data were obtained from historical farm records and interviews, including initial population size, weekly surviving population, mortality, and egg production data from week 16 to week 100 (October 2023–June 2025). The model was constructed using stage-specific survival probabilities and transition probabilities to form a transition matrix for population projection.

The results show that the young-layer population declined rapidly due to a high transition rate into the productive stage, while the productive-layer stage reached peak population around 35 weeks of age before gradually declining. Meanwhile, the older-layer stage continuously increased and eventually dominated the total population. Population projection results indicate a gradual decrease in the total population from 3,675 to 3,353 chickens by the end of the observation period. Furthermore, dominant eigenvalue analysis produced $\lambda = 0.9989$, indicating a slow long-term population decline of approximately 0.11% per week. Despite this decline, the value being close to 1 reflects efficient mortality management and stable production performance. The Lefkovitch matrix model therefore provides an effective quantitative framework for evaluating population dynamics and supporting sustainable production management in layer chicken farming.

Keywords: Lefkovitch matrix, stage-structured model, layer chicken, population dynamics, egg production, dominant eigenvalue

INTRODUCTION

The poultry industry is one of the key pillars of global food security, including in Indonesia. This sector plays a strategic role not only in fulfilling the demand for animal protein but also in supporting national economic stability. According to the Director General of Livestock and Animal Health, Agung Suganda, the poultry sector contributes approximately 60% to the livestock Gross Domestic Product (GDP), employs around 10% of the national workforce, and has an economic value reaching IDR 700 trillion [1]. Furthermore, poultry products, including chicken meat and eggs, account for nearly two-thirds of the total protein consumption of the Indonesian population. This figure highlights that the availability and sustainability of poultry production are crucial determinants of dietary patterns, nutritional quality, and long-term food security.

Compared to meat, eggs offer distinct advantages as a source of protein. Eggs are widely consumed due to their ease of processing, affordability, and rich nutritional content, particularly high-quality protein. Based on data on the average weekly consumption of chicken eggs, the population in Purbalingga Regency has shown an increasing consumption trend from 2020 to 2024, with a growth rate of 5.30% [2]. This increase not only reflects a high level of public preference for eggs as a primary food source but also indicates the strengthening role of eggs in meeting daily nutritional needs.

The dominance of egg consumption over other animal protein sources makes the layer poultry farming industry a promising and relatively stable business sector. The high demand has encouraged the emergence of small-scale production enterprises, typically managed by households or independent farmers with limited flock sizes. However, this potential is closely linked to the importance of effective operational management, particularly in maintaining a consistent egg supply. Supply instability can lead to significant challenges, as egg prices are highly sensitive to fluctuations due to the relatively inelastic nature of demand.

In practice, the production dynamics of layer chickens are influenced by several factors, including age, productivity levels, and culling policies [3]. Productivity generally increases until reaching a peak at a certain age, followed by a gradual decline as the chickens grow older. Therefore, understanding changes in population structure and egg production at each stage of the chickens' lifecycle is essential for efficient production planning.

To systematically analyze these changes, a mathematical approach is required that can describe population dynamics based on productivity stages rather than solely on age. One relevant approach is the Lefkovitch matrix model, which allows populations to be classified into several stages according to their productivity levels [4]. The Lefkovitch matrix model was first introduced by Lefkovitch in 1965 in his work "The Study of Population Growth in Organisms Grouped by Stage" published in the journal Biometrics, extending the Leslie matrix model by grouping individuals based on developmental stages instead of age alone [5]. This model can be used to project the number of individuals at each stage over time and relate it to production outputs.

In this study, the production dynamics of a single cohort of layer chickens at UD Faoji Farm, Kembangan–Bukateja, are analyzed using the Lefkovitch matrix model. This approach is expected to provide a quantitative description of changes in chicken population and weekly egg production, thereby serving as a basis for evaluation and the development of more effective and sustainable production management strategies.

LITERATURE REVIEW

A. Population

A population is defined as the entire set of objects, individuals, or entities belonging to the same species occupying a specific area that serves as the scope of a study [6]. According to population ecology principles, changes in the number of female individuals are generally influenced by factors such as birth, death, and migration [7]. In the context of a single-cohort layer chicken population, observations focus on a group of female individuals originating from the same age group or hatching period. No new individuals are introduced during the observation period; therefore, population changes are solely driven by mortality and stage transitions rather than by birth or migration. This single-cohort approach enables a more focused analysis of population dynamics, including survival rates, productivity, and growth patterns over a given period.

B. Lefkovitch Matrix Model

The Lefkovitch matrix (stage-structured model) is a population modeling approach that classifies female individuals based on biological development stages rather than chronological age, as in the age-structured (Leslie) model [4]. This approach is motivated by the fact that age is not always an accurate indicator of an individual's condition or productivity. For example, in layer chickens, individuals of the same age may exhibit different egg production levels due to physiological, health, and environmental factors. Therefore, a stage-based approach provides a more realistic representation of population dynamics, particularly when development rates and stage durations vary among individuals [8].

The model was developed to address limitations of the Leslie matrix, introduced in 1945, which assumes that individuals always transition to the next age class at each time step [9]. In many biological systems, individuals may remain in the same stage for multiple periods or experience delayed transitions. To account for this, Lefkovitch (1965) proposed a stage-structured matrix model that allows individuals to remain in the same stage, transition to the next stage, and contribute to reproduction or production within a given stage [5].

The key difference between age-structured and stage-structured models lies in their classification basis. Age-structured models group individuals strictly by age, forcing transitions between classes at each time step, whereas stage-structured models group individuals by biological condition, allowing retention within the same stage over multiple periods [8], [10]. This flexibility makes stage-structured models more suitable for populations with heterogeneous development patterns, such as plants, fish, and layer chickens.

The Lefkovitch model is represented by a projection matrix $A \in \mathbb{R}^{n \times n}$, whose elements describe stage-specific demographic processes. These elements include the probability of survival in stage$-i$ (P_i), the probability of transitioning to from stage$-i$ to the next stage (G_i), and the average reproduction or production rate at stage$-i$ (F_i). Each row and column corresponds to a specific stage, capturing the dynamics of the population across stages over time. The general form of Lefkovitch matrix is such below:

$$A = \begin{bmatrix} P_1 + F_1 & F_2 & F_3 & \cdots & F_{n-1} & F_n \\ G_1 & P_2 & 0 & 0 & \cdots & 0 \\ 0 & G_2 & P_3 & 0 & \cdots & 0 \\ 0 & 0 & G_{i-1} & P_i & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & G_{n-1} & P_n \end{bmatrix}.$$

In general, the row index of matrix A represents the stage occupied by individuals at the next time step, while the column index represents the stage at the current time step. The main diagonal elements (P_i) denote the probability that female individuals remain in stage i, whereas the sub-diagonal elements (G_i) represent the probability of transitioning to the next stage. The first row contains the elements (F_i), which indicate the reproductive or production contributions of each stage to the addition of new individuals. These parameters form the core of the model, as the overall population dynamics depend on survival and transition patterns between stages [11].

In stage-structured models (Lefkovitch matrices), stages are typically defined as intervals representing specific age ranges or biological phases. Each stage i includes individuals within the interval from x_{i-1} to x_i. The classification of stages can be based on various criteria, such as chronological age, body size, reproductive maturity, or productivity level [4]. Table 2.1 presents a general example of stage classification within a given interval in the Lefkovitch matrix model.

Table 2.1 Classification and Interval of Each Stage

Stage	Interval of Each Stage
Stage 1	$[x_0, x_1)$
Stage 2	$[x_1, x_2)$
$\vdots$	$\vdots$
Stage $n-1$	$[x_{n-2}, x_{n-1})$
Stage n	$[x_{n-1}, x_n]$

MATERIALS & METHODS

A. Research Design

This study employs a quantitative descriptive approach, which aims to describe variables objectively as they are, supported by numerical data derived from actual farm conditions. The data used in this research consist of historical records and information obtained through interviews with the management of UD Faoji Farm, Kembangan-Bukateja, Indonesia.

B. Data Collection Method

This study utilizes primary data, defined as data collected directly by the author from the original source. In this case, the data were obtained from Mr. Muhammad Balyan, the manager of UD Faoji Farm, Kembangan-Bukateja, Indonesia on July – August 2025. The data were collected through historical farm records and interviews. The dataset includes:

1. Initial population data of chickens introduced into the farm
2. Egg production data from week 16 to week 100 (October 2023 – June 2025)
3. Weekly records of the number of surviving chickens from October 2023 to June 2025
4. Chicken mortality data from October 2023 to June 2025.

C. Data Processing Method

In this study, the data were processed through manual calculations followed by analytical interpretation to support management decisions at UD Faoji Farm, Kembangan-Bukateja, Indonesia. The analysis procedure consisted of the following steps:

1. Collecting data on initial population, egg production, and weekly mortality (October 2023–June 2025).
2. Defining stage intervals based on biological performance (mortality and production rates).
3. Grouping the population into three productivity-based stages and summarizing key variables (survival, mortality, and production).
4. Constructing the initial population vector and estimating weekly survival and transition probabilities, with no transition from the final stage.
5. Forming the Lefkovitch matrix and projecting the population vector over time.
6. Defining stage-specific production rates and calculating total weekly egg production.
7. Analyzing and visualizing population and production dynamics to identify peak production, population decline, stage contributions, and key influential parameters.

RESULT

Data obtained from interviews and historical records at UD Faoji Farm, Kembangan–Bukateja, include the initial population of layer chickens, weekly surviving population, weekly mortality, and weekly egg production data. The farm maintained 3,675-layer chickens originating from a single cohort, defined as a group of chickens introduced into the housing system at the same time. The initial population consisted of 16-week-old chickens that had entered the laying phase (production-ready stage). Based on historical farm records, culling was generally conducted at approximately 100 weeks of age. Within this age range, the layer chicken population was classified into three stages according to age and productivity level. The complete classification is presented in Table 4.1.

Table 4.1 Primary Data

No	Stage (Age in Weeks)	Initial Population ($N_i(0)$)	Average Weekly Surviving Chickens ($\overline{N_i}$)	Average Weekly Mortality (K_i)	Average Weekly Egg Production ($F_{prod,i}$)
1	[16,26)	3,675	3,659.5	3.1	2.15
2	[26,66)	0	3,563	4.1	4.9
3	[66,100]	0	3,417	3.74	4.55

From the data above, the initial distribution vector of the layer chicken population can be obtained as follows:

$$N(0) = \begin{bmatrix} N_1(0) \\ N_2(0) \\ N_3(0) \end{bmatrix} = \begin{bmatrix} 3{,}675 \\ 0 \\ 0 \end{bmatrix}.$$

The initial distribution vector $N(0)$ represents the population composition at $t = 0$ (week 16), which serves as the starting point of the modeling period. In this single-cohort system, only the first element is nonzero, $N_1(0) = 3675$, indicating that the entire population initially belongs to Stage 1. Meanwhile, $N_2(0)$ and $N_3(0)$ are equal to zero because, under the Lefkovitch matrix assumptions, all chickens at the beginning of the observation period are still classified as Stage 1 (young layers), with no individuals yet reaching or remaining in Stage 2 (productive layers) or Stage 3 (older layers). This vector serves as the initial condition that evolves over time through the transition process represented by matrix A.

Next, the stage development rate (γ_i) is determined to describe the probability that a surviving chicken successfully completes stage i and transitions to the next stage within one time interval:

$$\gamma_i = \frac{1}{D_i}$$

where D_i denotes the duration of stage i in weeks. The value of D_i is determined from the absolute age intervals defined using historical data. The model requires $0 < \gamma_i < 1$, indicating that each individual in stage i has a probability of progressing to the next stage. The development rates for each stage are presented in Table 4.2.

Table 4.2 Stage Duration and Development Rate

Stage (i)	**Age Interval (Weeks)**	**Stage Duration (D_i)**	**Development Rates ($\gamma_i = \frac{1}{D_i}$)**
1	[16,26)	10 weeks	0.1
2	[26,66)	40 weeks	0.025
3	[66,100]	34 weeks	0.000

Note: The development rate for Stage 3 (γ_3) is set to zero because this stage represents the final condition before culling; therefore, no subsequent stage exists.

Next, the probability of survival during one time interval (one week) at stage i is calculated. This probability is estimated from historical mortality data, where the survival probability (σ_i) is defined as the complement of the weekly mortality rate (μ_i), that is:

$$\sigma_i = 1 - \mu_i,$$

where the mortality rate (μ_i) is computed as the average ratio of weekly deaths to the average number of surviving chickens in each stage. The mortality and survival probabilities for each stage are presented in Table 4.3.

Table 4.3 Mortality and Survival Probability Rates

Stage (i)	**Age Interval (Weeks)**	**Mortality Rate ($\mu_i = \frac{1}{D_i}\sum_{t \in T_i} \mu_t$)**	**Survival Probabilities Rate (σ_i)**
1	[16,26)	0.000849546	0.999150454
2	[26,66)	0.001150917	0.998849083
3	[66,100]	0.001095496	0.998904504

The final step in constructing the transition matrix A is combining the survival probability (σ_i) and the stage development rate (γ_i) to obtain the final transition probabilities, namely the persistence probability (P_i) and the progression probability (G_i). The element P_i represents the probability that a layer chicken survives and remains in stage i during one time interval, whereas G_i represents the probability that a chicken survives and successfully progresses to the next stage. These probabilities are defined as follows:

$$P_i = \sigma_i(1 - \gamma_i)$$

$$G_i = \sigma_i\gamma_i$$

The resulting persistence and progression probabilities for each stage are presented in Table 4.4.

Table 4.4 Persistence and Progression Probability

Stage (i)	**Survival Probabilities Rate (σ_i)**	**Development Rate (γ_i)**	**Persistence Probability ($P_i = \sigma_i(1-\gamma_i)$**	**Progression Probability ($G_i = \sigma_i\gamma_i$)**
1	0.999150454	0.1	0.89924	0.09992
2	0.998849083	0.025	0.97388	0.02497
3	0.998904504	0.000	0.99890	0

Based on the persistence (P_i) and progression (G_i) probabilities presented in Table 4.4, the transition matrix A for the Lefkovitch matrix model of the layer chicken population with $n = 3$ stages is given by:

$$A = \begin{pmatrix} P_1 & 0 & 0 \\ G_1 & P_2 & 0 \\ 0 & G_2 & P_3 \end{pmatrix} = \begin{pmatrix} 0.89924 & 0 & 0 \\ 0.09992 & 0.97388 & 0 \\ 0 & 0.02497 & 0.99890 \end{pmatrix}.$$

After constructing the transition matrix A, the next step is to project the population dynamics of the layer chickens. The projection is performed by repeatedly applying the matrix to the initial distribution vector over 85-time intervals (from week 16 to week 100), expressed as:

$$N(t) = A^t N(0).$$

A summary of the projected population vectors $N(t)$ at four-week intervals is presented in Table 4.5.

Table 4.5 Summary of Projected Population Vectors

Age (Weeks)	**Time Period (t)**	$N_1(t)$	$N_2(t)$	$N_3(t)$
16	0	3675	0	0
20	4	2403.033422	1208.552797	50.44570857
24	8	1571.311464	1877.401393	199.0769503
28	12	1027.459582	2205.540931	399.7627088
32	16	671.8420996	2321.86647	623.5611822
36	20	439.3085769	2309.558642	852.6475313
40	24	287.250117	2222.016737	1076.355656
44	28	187.8341777	2093.266025	1288.601064
48	32	122.8222604	1944.752946	1486.205708
52	36	80.31183583	1789.779407	1667.811593
56	40	52.51483693	1636.3942	1833.17849
60	44	34.33875056	1489.276392	1982.731977
64	48	22.45365042	1350.960291	2117.274453
68	52	14.68214215	1222.630542	2237.802054
72	56	9.600456681	1104.636729	2345.390229
76	60	6.277610415	996.8251029	2441.123671
80	64	4.104845616	898.7511962	2526.054791
84	68	2.684103731	809.8149975	2601.180408
88	72	1.755099585	729.3458661	2667.429973
92	76	1.14763618	656.6549353	2725.660999
96	80	0.750423972	591.0665692	2776.658801
100	82	0.490692214	531.9364063	2821.139018

After obtaining the projected population vector $N(t)$, the economic output in the form of total weekly egg production $E(t)$ was calculated. This calculation requires the egg production rate vector (F_{prod}), which represents the average number of eggs produced per chicken per week at each stage, as presented in Table 4.1:

$$F_{prod} = \begin{bmatrix} 2.15 \\ 4.90 \\ 4.55 \end{bmatrix}$$

Thus, the total weekly egg production is obtained through the matrix multiplication $E(t) = N(t)^T \cdot F_{prod}$ and a summary of the results is presented in Table 4.6.

Table 4.6 Summary of Total Egg Production

Age (Weeks)	Total Population	Total Egg Production (F_{prod})
16	3.675	7901,25
20	3.662,031928	11.317,95854
24	3.647,789807	13.483,3866
28	3.632,763222	14.835,10899
32	3.617,269752	15.658,8096
36	3.601,51475	16.140,89705
40	3.585,62251	16.402,888
44	3.569,701267	16.523,98185
48	3.553,780914	16.555,59327
52	3.537,902836	16.531,13229
56	3.522,087527	16.472,20061
60	3.506,34712	16.392,71313
64	3.490,688394	16.301,57954
68	3.475,114738	16.204,45561
72	3.459,627415	16.104,8865
76	3.444,226384	16.005,05257
80	3.428,910833	15.906,25558
84	3.413,679509	15.809,23517
88	3.398,530939	15.714,37459
92	3.383,46357	15.621,83415
96	3.368,475794	15.531,63715
100	3.353,566117	15.443,72591

DISCUSSION

Table 4.5 shows that the young-layer stage (N_1) experiences the fastest population decline, decreasing from 3,675 chickens at week 16 to nearly zero by the end of the projection period. This decline is primarily caused by the relatively high development rate ($G_1 = 0.09992$), indicating that chickens quickly complete Stage 1 and transition to Stage 2 (productive layers).

The productive-layer stage (N_2) exhibits a significant increase, reaching its peak at approximately 35 weeks of age, when the inflow from N_1 balances the outflow toward N_3. After this peak, the N_2 population gradually declines due to transitions to Stage 3 ($G_2 = 0.02497$) and the survival dynamics within Stage 2.

Meanwhile, the older-layer stage (N_3) shows stable and continuous growth, eventually dominating the total population after approximately week 54. This accumulation occurs because Stage 3 is the final stage, with a progression probability of $G_3 = 0$; therefore, chickens entering this stage can only decrease through mortality.

Table 4.6 illustrates the population dynamics of the layer chickens during the projection period, where the total population gradually declines from 3,675 to 3,354 chickens by the end of the production cycle. The stage dynamics indicate a rapid transition from the young-layer stage to the productive-layer stage, which reaches its peak around week 48 and produces the highest weekly egg output of 16,556 eggs. After this point, the total production E(t) gradually decreases due to the declining population in the productive-layer stage and the increasing proportion of older-layer chickens. This analysis confirms that farm sustainability strongly depends on the efficiency of the transition probability G_1 and the survival persistence P_2.

Although the stage contribution analysis successfully identifies weekly production efficiency and peak egg production periods, it only describes short-term dynamics. To understand the long-term growth behavior and stability of the layer chicken population, the asymptotic population growth rate was evaluated using the dominant eigenvalue (λ). The resulting value can be used to assess the effectiveness of farm management and the sustainability of future production. Since fecundity values in matrix A were assumed to be zero, the transition matrix takes the form of a lower triangular matrix. According to the theorem from [12], the eigenvalues of a triangular matrix are given directly by its diagonal entries. Therefore, the eigenvalues of the transition matrix are:

$$\{P_1, P_2, P_3\}.$$

The dominant eigenvalue (λ) is defined as the eigenvalue with the largest absolute value:

$$\lambda = \max\{P_1, P_2, P_3\}.$$

If $\lambda > 1$, the population tends to grow; if $\lambda = 1$, the population remains stable; and if $\lambda < 1$, the population declines. From Table 4.4, the maximum persistence probability is

$$\lambda = \max\{0.89924, 0.97388, 0.99890\} = 0.99890.$$

Since $\lambda < 1$, the population is predicted to decline in the long term. Specifically, the single-cohort layer chicken population at UD Faoji Farm, Kembangan–Bukateja is expected to decrease by approximately 0.11% per week $(1 - 0.9989)$. This result also indicates that the older-layer stage has the highest survival persistence and therefore plays the dominant role in determining the overall population decline rate. The very small decline rate (close to 1.0) suggests highly efficient mortality management within the farm system.

CONCLUSION

This study demonstrates that the population dynamics and egg production of layer chickens at UD Faoji Farm, Kembangan–Bukateja, Indonesia can be effectively modeled using the Lefkovitch matrix approach, which classifies the population into three productivity-based stages. The resulting transition matrix describes the probabilities of chickens remaining in the same stage and transitioning to the next stage, providing a quantitative representation of population changes from week 16 to week 100.

The projection results indicate that the total population gradually declined from 3,675 to 3,353 chickens during the observation period. The young-layer stage experienced the fastest decrease due to high transition rates into the productive stage, while the older-layer stage eventually dominated the population because it represents the final stage before culling. In terms of production, weekly egg output increased as the productive-layer population grew, reaching a peak of 16,556 eggs around week 48, before gradually declining as the population shifted toward the older-layer stage.

Furthermore, dominant eigenvalue analysis produced $\lambda = 0.9989$, indicating a slow long-term population decline of approximately 0.11% per week. Despite this decline, the eigenvalue being close to 1 suggests efficient mortality management and relatively stable production performance throughout the production cycle. Overall, the Lefkovitch matrix model provides a useful framework for evaluating population dynamics and supporting sustainable management strategies in layer chicken farming.

Declaration by Authors

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