Mathematical Curves for the Description of Input and Output Variables of the Daily Production Process in Aviary Housing Systems for Laying Hens

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ABSTRACT The objectives of this study were 1) to compute appropriate mathematical curves that describe the daily production process by the input variables daily feed consumption, water consumption, ambient temperature, and output variables hen-day egg production, egg weight, second grade eggs, floor eggs, cumulative mortality, body weight, and flock uniformity; and 2) to obtain insights into the daily variations in these variables, in order to support the poultry farmer with an aviary housing system in his daily management. Literature and research data attained from six unmolted flocks that were housed in aviary systems were used to formulate the mathematical curves. The curves were a function of the number of days in the laying period. Curves for cumulative mortality, hen-day egg production, egg weight, body weight, and percentage of floor eggs described individual flock results well ($0.72 < R^2_{adj} < 1.00$). The coefficients of determination for feed consumption, water consumption, flock uniformity, and percentage of second grade eggs were in general low ($0.33 < R^2_{adj} < 0.54$), which implies that the form of the curve differs between flocks. Egg weight, body weight, cumulative mortality, and hen-day egg production had the lowest minimum coefficients of variation (0.8 to 1.9), followed by feed consumption, water consumption, and flock uniformity (2.8 to 3.6). Ambient temperature, percentage floor eggs, and percentage of second grade eggs had the highest minimum coefficients of variation (4.8 to 9.1).

(*Key words*: mathematical curve, egg production, aviary system, laying hen, variability)

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INTRODUCTION

Most laying hens are housed in battery cages with a maximum of 450 cm^2 floor area per hen (Anonymous, 1986). Cage systems have strong advantages over alternative housing systems, especially in terms of economics, pollution control, and working conditions (De Wit, 1992; Appleby *et al.*, 1994). In terms of welfare, some groups may prefer alternative housing systems (De Wit, 1992). Aviary housing systems were developed to provide such an alternative (Ehlhardt *et al.*, 1988; Amgarten and Mettler, 1989; Elson, 1989; Appleby *et al.*, 1992; Blokhuis and Metz, 1992; Hansen, 1994; Blokhuis and Metz, 1995). In aviary systems, hens have more space (approximately 1,000 cm^2 available area per hen) and freedom to move in all three dimensions of the house, they can scratch and dustbathe in the litter that is provided on the floor, and they can use laying nests and perches.

In the current state of development of alternative housing systems, production costs, labor requirements, required management skill, and required veterinary supervision are all higher than in cage systems (Van Horne, 1991; De Wit, 1992; Elson, 1992; Blokhuis and Metz, 1995). In floor-housed flocks, there is a higher risk of infectious diseases, endoparasites (round and flat worms), ectoparasites (mites), pathological conditions of the feet, and cannibalism (Appleby *et al.*, 1994). In cage systems, there is a higher risk for fatty livers and osteoporosis (Appleby *et al.*, 1994). To support the aviary farmer in his daily management, Lokhorst *et al.* (1995) suggested the development of computer-based tools to monitor and control the three main critical success factors (CSF): feed consumption, ambient temperature, and disease detection. An expert system prototype has been developed by Lokhorst (1995) to monitor the three CSF. The expert system prototype compares daily data on feed consumption, water consumption, hen-day egg production, second grade eggs, floor eggs, egg weight, body weight, flock uniformity, cumulative mortality, and ambient temperature with a standard. Deviations of different variables from the standard are used to detect aberrations in the three mentioned CSF (Lokhorst, 1995).

Available standards from breeding and feed companies only have weekly data on a limited number of variables; whereas, daily data for all mentioned variables are used by the expert system prototype to monitor the daily production process. Because the intention is to use the expert system on farms, it is necessary to have farm-specific standards, in which the farm-specific circumstances can be incorporated. Thus, for each

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TABLE 1. General data on the aviary flocks. TWF = Tiered wire floor system

Flock no.	Age of hens at the start in the laying house	Number of hens at the start of the laying cycle (age = 141 d)	Type of aviary system	Breed of hens
	(d)	(no.)		
1	119	20,866	TWF	Bovans
2	110	20,990	TWF	LSL
3	118	23,094	Multifloor	LSL
4	122	25,750	TWF	Bovans
5	122	15,956	Righs-Boleg	LSL
6	122	15,900	Righs-Boleg	LSL

variable that is used in the expert system prototype, a mathematical curve must be developed.

The production of eggs can be seen as a process with input variables (feed consumption, water consumption, and ambient temperature) and output variables [egg production (hen-day egg production, egg weight, second grade eggs, floor eggs), mortality, and growth (body weight, flock uniformity)]. The poultry farmer's management skills are used to manage this production process and he or she continually looks for deviations in that process. Despite good management skills, the production process is sometimes unpredictable. According to Deming (1986), two sources of variation can be distinguished: 1) normal process variation and 2) exceptional process variation. Normal process variation is inherent to the system and permanently present and its influence on the production process is small and unpredictable. Normal process variation, in general, cannot be assigned to one specific cause. Exceptional process variation has an external cause, occurs one at a time, is incidental and local, and has a large influence on the production process. In order to detect exceptional process variation, it is important to know the normal process variation of the production process. In other words, the manager should not be worried about normal variation in the production process.

The objectives of this study were 1) to formulate appropriate mathematical curves that describe the input and output variables of feed consumption, water consumption, ambient temperature, hen-day egg production, egg weight, second grade eggs, floor eggs, cumulative mortality, body weight, and flock uniformity; and 2) to obtain insight in the daily variation in these variables. The mathematical curves can function as a standard based on daily production data, and they can be used by the poultry farmer to detect aberrations (exceptional process variation) in the production process in aviary housing systems.

MATERIALS AND METHODS

Animals and Data Collection

Data from six unmolted flocks (Table 1) were used to fit the parameters for the mathematical curves for hen-day egg production, egg weight, feed consumption, water consumption, second grade eggs, floor eggs, body weight, flock uniformity, and cumulative mortality. The mean and standard deviation per flock were determined for the ambient temperature. Two flocks consisted of White Bovans and the other four flocks consisted of White Lohman (LSL) hens. All flocks were housed on farms with an aviary system. The Tiered Wire Floor (TWF), Multifloor, and Righs-Boleg aviary systems are described in Blokhuis and Metz (1995). Process computers were used to register the daily mean ambient temperature, feed consumption, and water consumption. During the first 50 d of the laying cycle of Flock 1, no feed and water consumption data were collected. The poultry farmers recorded daily the mortality and the number of first grade, second grade, and floor eggs. Average egg weight was determined by the poultry farmer once a week for Flocks 1 to 4 and daily for Flock 5 and 6 by weighing a stack of six egg trays with a total of 180 eggs. An automatic weighing system with four scales, placed in the middle of the feed tiers, was used to determine the daily body weight and flock uniformity in Flock 5 and 6. Body weight and flock uniformity data for the first 85 d of the laying period of Flock 6 were not available.

Mathematical Curves

Literature and research data obtained from the six flocks housed in aviary systems were used to formulate mathematical curves that describe the input and output variables of the production process. The variables feed consumption, water consumption, hen-day egg production, egg weight, second grade eggs, floor eggs, body weight, flock uniformity, and cumulative mortality are described as a function of age (t), where t represents the number of days in the laying period, which is presumed to start at an age of 141 d (Siplu, 1990). Cumulative mortality is based on the number of housed hens at the start of the laying period and the other functions are based on the number of hens present. The ambient temperature is presumed to be relatively constant during the whole laying period (Lokhorst *et al.*, 1995).

Statistical Analysis

The nonlinear regression method of the statistical program SPSS® (Norusis, 1992) was used to fit the parameters of the mathematical curves for the different variables. Fitting was done per flock. To get an overall fit of all flocks, data of the six flocks were combined into one data set. Because of the small number of flocks, no flock, housing system, or hen type effects were analyzed, and all the fitting results of the different flocks were given separately. The coefficient of determination (R^2_{adj}) and the variance (σ^2) were used as goodness of fit measurements. Starting values were determined by using simple mathematical methods, such as the determination of derivatives and the graphical determination of slopes and limits.

RESULTS

Mathematical Curve Formulation

Hen-Day Egg Production. The hen-day egg production is calculated as the number of eggs produced per day divided by the number of hens present. Cason and Britton (1988) compared 1) the model of Adams and Bell (1980) P $= 0.07(1/(0.01 + ar^{(x-b)}) - c(x - d))$, 2) the compartmental model of McMillan (McMillan, 1981; McMillan *et al.*, 1986; Yang *et al.*, 1989), $P = a(e^{-bx})(1 - e^{-c(x-d)})$, and 3) a logistic model developed by themselves (Cason and Britton, 1988) $P = a(e^{-bx})(1/(1 + e^{c+dx}))$. These three models describe the weekly egg production (P), where x is the age of the flocks in weeks, e is the base of natural logarithms and parameters a, b, c, and d are constants to be determined by a least squares error nonlinear curve-fitting program (Cason and Britton, 1988).

Adams and Bell (1980) modeled the egg production as the difference between a sigmoid increase (a logistic growth curve), and a linear decrease and they assumed a theoretical maximum egg production of 100%. The compartmental model of McMillan (1981) is divided into two components, the percentage of hens that start laying and the average egg production of these hens. Both components are functions of the age of the hens. A normal distribution is assumed for hens that start laying, which is described by a logistic curve representing sexual maturity. It is also assumed that egg production starts at a high level (for instance 80 or 90%), quickly rises to a maximum, and then gradually diminishes. Cason and Britton (1988) tried to combine the decreasing term of the compartmental model of McMillan (1981) and an increasing term representing a logistic growth curve similar to the increasing term of Adams and Bell (1980). The conclusion of Cason and Britton (1988) was that the Adams and Bell (1980) model provided the best fit for their data, followed by the logistic model, and the compartmental model.

For the mathematical curve that describes daily hen-day egg production in an aviary system, the following assumptions were made. A normal distribution was assumed for hens that start laying; therefore, a logistic growth curve, as described by Adams and Bell (1980), is used. Adams and Bell (1980) assumed a theoretical maximum production of 100% and a linear decrease of the egg production when hens become older, but this can be doubted, as suggested by Yang *et al.* (1989). Plots of our own data show a quick increase in hen-day egg production and a more or less stable production period, followed by a nonlinear decrease. Therefore, a second order polynomial is used to describe the gradual decrease in egg production. The notation for the hen-day egg production, thus becomes:

$$Y_{\text{hen-day-egg-production}}\ (\text{percentage}) = \frac{100}{1 + a \times r^t} - (b + C \times t + d \times t^2)$$

The logistic part is described with parameters a (a > 0) and r (0 < r < 1) and the second order polynomial is described with parameters b, c, and d. The hen-day egg production at the start of the laying period is determined by parameters a and b. The time between the start of the laying period and the day the maximum production is reached is influenced by parameter r. The results of the second order polynomial are subtracted from the asymptote of the logistic growth curve part, which represents the theoretical maximum hen-day egg production. The realized maximum hen-day egg production therefore depends on all parameters. The persistence of the hen-day egg production is described as a gradual decrease with parameters c and d.

Egg Weight. Egg weight is asymptotically related to age, and this can be described with a restricted growth curve (Adams and Bell, 1980; Minvielle *et al.*, 1994). Although the formula of Minvielle *et al.* (1994) is somewhat different from that of Adams and Bell, the basic principles are the same. The maximum egg weight is the asymptote and the initial egg weight is described with a parameter that is subtracted from the maximum egg weight. The growth rate is described with parameter r. Plots of our own data show the same pattern. Therefore, the next mathematical curve was used to model the daily egg weight in aviary systems for laying hens:

$$Y_{\text{egg-weight}}\ (\text{grams}) = a + b \times r^t$$

The parameter a in the formula expresses the asymptote of the maximum egg weight and b must be subtracted from a to determine the initial egg weight at the start of the laying period. Parameter r (0 < r < 1) is responsible for the growth rate.

Floor Eggs. No mathematical curve is found in the literature that describes the relation between age and the percentage of floor eggs. Plots of our own data show that the percentage of floor eggs starts at a relatively high level and that there are large differences between flocks (3 to 20%). At the start of the laying period, hens must adjust to the laying nests and egg production is also low. Right after the start of the laying period a quick decrease in the percentage of floor eggs was seen, which was sometimes followed by a gradual increase and sometimes remained stable. The percentage of floor eggs was modelled with a combination of an exponential decreasing component and a second order polynomial. The second order polynomial can be used to model different combinations of decreasing and increasing components. The mathematical curve for the percentage of floor eggs was expressed by the following formula:

$$Y_{\text{floor-eggs}}\ (\text{percentage}) = a \times e^{-b \times t} + c \times t + d \times t^2$$

The percentage of floor eggs at the start of the laying period is described with parameter a (a > 0). The initial fast exponential decrease of the percentage of floor eggs is described with parameter b. The combinations of gradual increase and decrease of the percentage of floor eggs are expressed by parameters c and d.

Second Grade Eggs. Adams and Bell (1980) and Van Horne *et al.* (1991) proposed a linear function for the quantification of the second grade eggs. Interpolation between an initial value and a value for the percentage of second grade eggs at the end of the laying period was used to calculate the percentage of second grade eggs. Sugimoto *et al.* (1986) propose a quadratic function for the percentage of second grade eggs. Our own data suggest a quadratic relationship between the age of the hens and the percentage of second grade eggs. This relationship can be described with a second order polynomial. The mathematical curve for the second grade eggs then becomes:

$$Y_{\text{second-grade-eggs}}\ (\text{percentage}) = a + b \times t + c \times t^2$$

The initial percentage of second grade eggs at the start of the laying cycle is represented by parameter a. The combinations of the gradual increase or decrease is described with parameters b and c.

Feed and Water Consumption. No appropriate mathematical curves were found in the literature to describe the relation between feed consumption and age or between water consumption and age. Van Horne *et al.* (1991) interpolates between six feed consumption data sets that are representative of the whole laying period. Our own daily data of feed and water consumption show much variation, but the main pattern for the two is the same. In the beginning of the laying period, feed and water consumption gradually increase, which can be represented by a restricted growth curve. After a while, the feed and water consumption per flock show different patterns. These patterns show a gradual increase or decrease or a combination of these, and can be described with a second order polynomial. The same mathematical curve was used to describe feed and water consumption, but separate fits were made because feed and water consumption were different variables. The mathematical curve to describe the daily feed and water consumption therefore became:

$$Y_{\text{feed-or-water}}\ (\text{grams or centiliters}) = \frac{a}{1 + b \times e^{-a \times c \times t}} + d \times t + e \times t^2$$

The first part of the formula represents the restricted growth curve and the second part of the function represents the second order polynomial. Parameter a represents the horizontal asymptote of the restricted growth curve. Parameter b represents, together with parameter a, the feed or water consumption at the start of the laying period ($Y_0 = a/(1 + b)$) and parameter c, together with parameter a, represents the speed of the increase in feed and water consumption in the restricted growth phase. Parameters d and e determine whether feed and water consumption gradually increase or decrease during the rest of the laying period.

Body Weight. Graphs of the body weight of different breeds of laying hens showed, like feed and water consumption, a logistic growth curve and a linear increase. Our own data show the same growth. Therefore, the next mathematical curve was used to represent the daily body weight of the hens:

$$Y_{\text{body-weight}}\ (\text{grams}) = \frac{a}{1 + b \times e^{-a \times c \times t}} + d \times t$$

Flock Uniformity. No mathematical curve was found in the literature that represents flock uniformity. Our own data suggest a quadratic relationship between the age of the hens and flock uniformity. This relationship can be described with a second order polynomial. Therefore, the mathematical curve for the daily flock uniformity became:

$$Y_{\text{flock-uniformity}}\ (\text{percentage}) = a + b \times t + c \times t^2$$

The flock uniformity at the start of the laying period is represented by parameter a. The gradual increase or decrease in flock uniformity during the rest of the laying period is determined by parameters b and c.

Cumulative Mortality. Adams and Bell (1980) and Van Horne *et al.* (1991) calculated the cumulative mortality by interpolating data of the first and last week of the laying period. Based on our own data, a quadratic increase in the cumulative mortality seems more suitable. If the number of hens at the start of the laying period is known, the number of hens present on a certain day in the laying period can be calculated with the next mathematical curve for the cumulative mortality:

$$Y_{\text{cumulative-mortality}}\ (\text{percentage}) = a \times t + b \times t^2$$

The parameters a and b, respectively, express the linear and quadratic increase in the cumulative mortality of the hens during the laying period.

RESULTS

Mathematical Curve Fitting Results

Figures 1 and 2 show the graphical representation of the mathematical curves. The parameter fits for each mathematical curve are presented in Tables 2 to 9. The

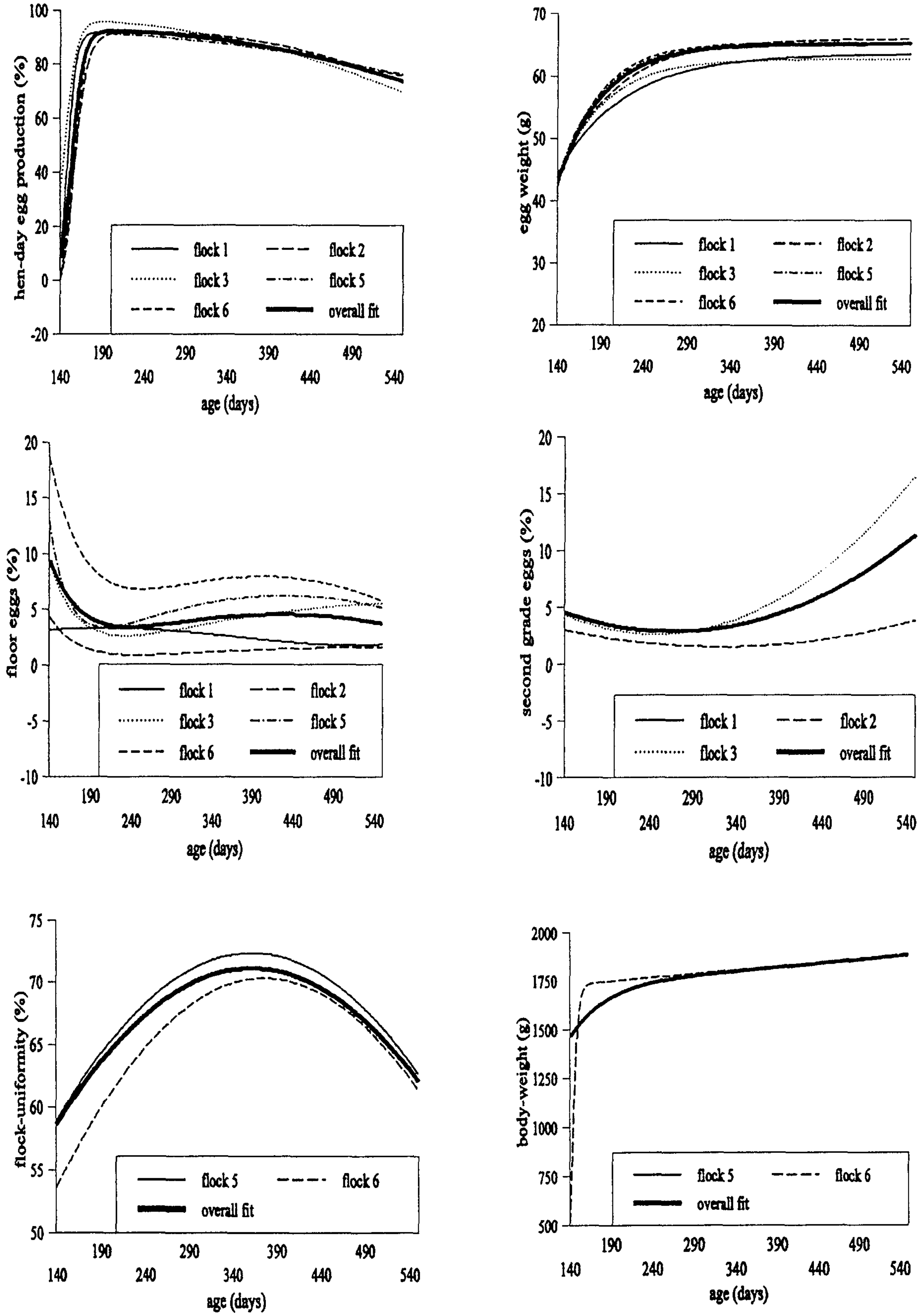

FIGURE 1. Mathematical curves for the hen-day egg production, egg weight, floor eggs, second grade eggs, flock uniformity, and body weight as a function of age for different flocks that are housed in an aviary system for laying hens.

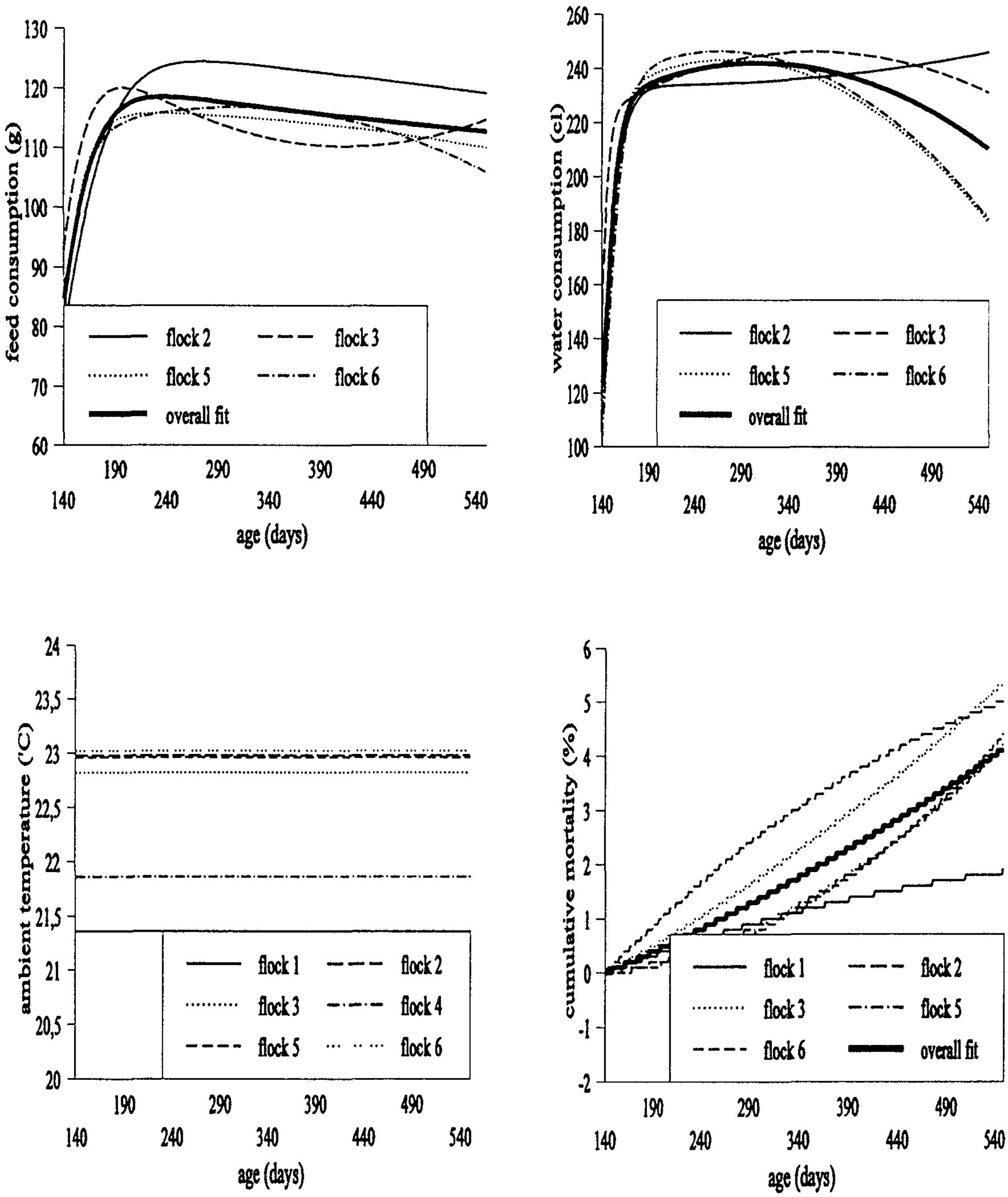

FIGURE 2. Mathematical curves for feed consumption, water consumption, ambient temperature, and cumulative mortality as a function of age for different flocks that are housed in an aviary system for laying hens.

results of Flock 4 are excluded from the overall fit, because a major aberration in the production process occurred at an age of 203 d. This aberration had a temporary effect on feed and water consumption and a permanent effect on the hen-day egg production.

Table 2 shows the parameter fits for the hen-day egg production for six flocks and for the overall fit of the flocks. From variance values in Table 2, one can see that there is not only variation within flocks, with a maximum of 11.631 for Flock 1, but there is also great variation between flocks (24.012). The coefficients of determination per flock are high ($R^2_{adj} > 0.9$), except for Flock 4, which can be explained by the aberration that occurred.

Table 3 shows the parameter fits for the egg weight for six flocks and for the overall fit of the flocks. The coefficients of determination per flock and for the overall fit are greater than 0.9. Variation in Flocks 1 to 4 is lower than variation in Flocks 5 and 6. Probably, this difference is caused by the interval in which the data were gathered. Egg weight data for Flocks 1 to 4 were gathered only once a week, whereas egg weight data for Flocks 5 and 6 were gathered daily.

TABLE 2. Parameter fits for the hen-day egg production (percentage) for six separate aviary flocks and the overall fit of the flocks with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number					
Parameters		ASE	1	2	3	4[2]	5	6
a, %	5.274	0.247	4.480	7.858	1.864	0.761	10.218	13.458
r, ln%/lnd	0.871	0.003	0.832	0.882	0.872	0.794	0.847	0.859
b, %	7.506	0.522	8.241	10.365	3.631	13.638	7.944	6.784
c, %/d	−0.005	0.006	−0.007	−0.041	0.006	−0.052	0.011	0.011
d, %/d²	1.252E-4	1.317E-5	1.260E-4	1.976E-4	1.443E-4	3.273E-4	6.722E-5	7.816E-5
R^2adj	0.866		0.907	0.989	0.964	0.806	0.973	0.969
σ^2	24.012		11.631	2.640	2.933	19.888	5.515	7.653

[1]$Y_{\text{hen-day-egg-production}} = \dfrac{100}{1 + a \times r^t} - (b + c \times t + d \times t^2)$.

[2]Excluded from the overall fit.

TABLE 3. Parameter fits for the egg weight (grams) for six aviary flocks and the overall fit of the flocks with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number					
Parameters		ASE	1	. 2	3	4	5	6
a, g	65.277	0.070	63.665	66.104	62.844	61.828	65.510	65.507
b, g	−21.938	0.264	−19.303	−22.200	−19.782	−18.581	−21.647	−23.241
r	0.981	3.896E-4	0.987	0.985	0.981	0.991	0.981	0.979
R^2adj	0.919		0.985	0.987	0.951	0.967	0.948	0.943
σ^2	2.036		0.266	0.362	0.965	0.818	1.274	1.506

[1]$Y_{\text{egg-weight}} = a + b \times r^t$.

[2]Excluded from the overall fit.

TABLE 4. Parameter fits for floor eggs (percentage) for six separate aviary flocks and the overall fit with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number					
Parameters		ASE	1	2	3	4	5	6
a, %	9.390	0.391	3.183	4.449	9.329	21.678	12.852	18.672
b, %/d	0.025	1.709E-3	−4.185E-3	0.029	2.863E-2	1.967E-2	4.075E-2	2.190E-2
c, %/d	3.187E-2	1.374E-3	−7.682E-3	7.682E-3	2.364E-2	4.546E-2	4.304E-2	5.905E-2
d, %/d²	−5.573E-5	4.511E-6	−7.485E-5	−9.020E-6	−2.479E-5	−1.155E-4	−7.440E-5	−1.100E-4
R^2adj	0.106		0.826	0.843	0.806	0.903	0.716	0.809
σ^2	6.598		0.068	0.058	0.276	1.748	0.796	0.955

[1]$Y_{\text{floor-eggs}} = a \times e^{-b \times t} + c \times t + d \times t^2$.

[b]Excluded from the overall fit.

TABLE 5. Parameter fits for second grade eggs (percentage) for four aviary flocks and for the overall fit with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number			
Parameters		ASE	1	2	3	4[2]
a, %	4.527	0.242	6.455	2.985	4.314	10.360
b, %/d	−0.027	0.003	−0.034	−0.016	−0.032	−0.074
c, %/d²	1.056E-4	7.351E-6	1.216E-4	4.396E-5	1.507E-4	1.775E-4
R_{adj}^2	0.337		0.462	0.533	0.863	0.376
σ^2	7.077		5.077	0.205	1.594	7.036

[1]$Y_{\text{second-grade-eggs}} = a + b \times t + c \times t^2$.

[2]Excluded from the overall fit.

TABLE 6. Parameter fits for feed consumption (grams) and water consumption (cl) for five separate aviary flocks and for the overall fit with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number				
Parameters		ASE	2	3	4[2]	5	6
Feed consumption							
a, g	121.513	1.434	127.844	128.938	104.942	116.064	111.905
b	0.434	0.022	0.633	0.390	0.259	0.431	0.390
c, $(g{\cdot}d)^{-1}$	4.027E-4	3.653E-5	2.894E-4	4.494E-4	9.101E-4	5.903E-4	6.499E-4
d, g/d	−0.028	0.013	−0.022	−0.137	−3.767E-2	3.833E-4	5.861E-2
e, g/d^2	1.617E-5	2.768E-5	1.625E-6	2.494E-4	1.054E-4	−3.726E-5	−1.789E-4
R_{adj}^2	0.422		0.677	0.584	0.089	0.693	0.538
σ^2	37.435		34.804	11.473	59.812	10.472	27.116
Water consumption							
a, cl	227.126	1.675	234.295	223.626	228.093	228.651	233.882
b	0.854	0.058	0.780	0.467	0.407	1.065	1.242
c, $(cl{\cdot}d)^{-1}$	5.480E-4	4.172E-5	3.876E-4	9.441E-4	1.446E-4	5.549E-4	4.112E-4
d, cl/d	0.180	0.018	−1.053E-2	0.202	−0.113	0.218	0.198
e, cl/d^2	−5.418E-4	4.225E-5	9.639E-5	−4.481E-4	2.260E-5	−8.057E-4	−7.791E-4
R_{adj}^2	0.543		0.765	0.496	0.644	0.769	0.814
σ^2	192.983		69.289	101.182	56.521	114.267	119.053

[1] $Y_{\text{feed-or-water}} = \dfrac{a}{1 + b \times e^{-a \times c \times t}} + d \times t + e \times t^2.$

[2] Excluded from the overall fit.

Table 4 shows the results for the floor eggs. The initial percentage of floor eggs varied between 3.2 and 18.7%. The coefficients of determination per flock were between 0.7 and 0.9, which means that the chosen mathematical curve described the percentage of floor eggs reasonably well. The overall fit, however, showed a very poor coefficient of determination. This low coefficient means that each flock had its own curve that described the percentage of floor eggs. There was much daily variation within and between flocks.

Data to fit the parameters for the mathematical curve that describes the percentage of second grade eggs were present from four flocks. The results are shown in Table 5. As with the percentage of floor eggs, the initial percentage of second grade eggs differed between flocks. The coefficients of determination per flock ranges from 0.4 to 0.9. This result implies that the chosen mathematical curve was better than using the mean, but that it is difficult to give just one mathematical curve that can be used for all flocks. Daily variation within flocks also showed a broad range, from 0.2 to 5.1.

The parameter fits for the curves for feed and water consumption are shown in Table 6. The coefficients of determination for feed consumption varied between 0.5 and 0.7 and for water consumption between 0.5 and 0.8. The overall fits for feed consumption and water consumption, respectively, are 0.4 and 0.5. Per flock, the mathematical curves differ, so it is difficult to give just one overall fit for feed and water consumption. Variance for feed consumption was between 10.5 and 34.8 per flock, whereas the overall variance for feed consumption was 37.4. This result means that besides the variation between flocks there was also a lot of daily variation within a flock. The same can be seen for water consumption, although there was relatively more variation between flocks.

For the statistical analysis of body weight and flock uniformity, only two data sets were present. Also, from Flock 6, data from the first 85 d are missing, which makes it difficult to fit the data well. The parameter fits for body weight and flock uniformity are shown in Tables 7 and 8, respectively.

TABLE 7. Parameter fits for body weight (grams) for aviary flocks and the overall fit with their asymptotic standard error (ASE)[1]

	Overall fit		Flock number	
Parameters		ASE	5	6
a, g	1722.439	3.952	1717.037	1727.881
b	0.175	0.012	0.170	2.389
c, $(g{\cdot}d)^{-1}$	1.52E-5	1.25E-6	1.57E-5	1.64E-4
d, g/d	0.390	0.013	0.392	0.389
R^2_{adj}	0.919		0.933	0.798
σ^2	346.503		348.323	264.400

[1] $Y_{\text{body-weight}} = \dfrac{a}{1 + b \times e^{-a \times c \times t}} + d \times t.$

[2] Excluded from the overall fit.

TABLE 8. Parameter fits for flock uniformity (percentage) for two aviary flocks and for the overall fit with their asymptotic standard error (ASE)[1]

Parameters	Overall fit			Flock number	
			ASE	5	6
a, %	58.563		0.557	58.883	53.615
b, %/d	0.113		5.447E-3	0.121	0.141
c, %/d²	−2.550E-4		1.176E-5	−2.728E-4	−2.983E-4
R_{adj}^2		0.420		0.614	0.327
σ^2		10.782		6.065	14.828

[1]$Y_{flock\text{-}uniformity} = a + b \times t + c \times t^2$.

The coefficients of determination per flock and for the overall flock are good. The lower coefficient of determination for Flock 6 can be explained by the missing data at the beginning of the laying period. The coefficients of variation differ between the two flocks, which means that the curves have a different form. The low coefficient of variation of Flock 6 probably is caused by the large amount of missing data.

The parameter values for the mathematical curve that describes cumulative mortality are given in Table 9. Cumulative mortality in Flock 4 showed much more variation than the other flocks, which probably was related to the aberration in the production process.

The coefficients of determination per flock were greater than 0.9, which means that the chosen mathematical curve fits well the data of the separate flocks. The coefficient of determination for the overall fit is somewhat lower, which means that there were differences between flocks. Variance of the overall fit is also much higher than the variance within flocks, which means there were large differences between flocks.

The mean and the standard deviations of the ambient temperatures of the six flocks are shown in Table 10. The mean ambient temperature varied between 21.36 and 23.02 C, and the standard deviation between 1.13 and 2.31. Thus, within flocks there was more daily variation than between flocks.

Table 11 summarizes the overall fitting results of the mathematical curves. The coefficients of variation are given with the expected means. The coefficients of variation give information on the daily variations, relative to their means, of the production variables.

DISCUSSION

Mathematical Curves

The suggested mathematical curves for the description of the daily production process are better than using mean values of the production variables, but they are not all equally successful in describing the daily production of laying hens in an aviary system.

The minimum and maximum values of the coefficients of determination per flock of the mathematical curves for cumulative mortality, hen-day egg production, egg weight, body weight, and percentage of floor eggs vary between 0.72 and 1.00 (Table 11), which implies that these mathematical curves fit the individual flocks very well. The coefficients of determination of the overall fits for hen-day egg production, egg weight, and body weight are also high, which means that there is not much variation between flocks. This relationship can also be seen in Figures 1 and 2. The implication is that these mathematical curves may also give reasonable estimations for the parameters of other flocks; however, it is always possible to do some fine tuning, by regularly fitting the curves with the collected data, during the laying period. The general curves are then adjusted to the specific flock circumstances.

The low overall coefficients of determination for cumulative mortality and percentage of floor eggs implies that there is great variation between flocks. This variation makes it difficult to estimate the parameters of these mathematical curves in advance. Once a flock has started the laying period, the parameters can be adjusted to the specific situation of the flock. From then on, it is expected

TABLE 9. Parameter fits of the cumulative mortality (percentage) for six separate aviary flocks and the overall fit with their standard error[1]

Parameters	Overall fit			Flock number					
			SE	1	2	3	4[2]	5	6
a, %/d	7.563E-3		3.080E-4	6.732E-3	0.018	9.519E-3	8.507E-4	2.483E-3	1.205E-3
b, %/d²	6.183E-6		1.042E-6	−5.394E-6	−1.412E-5	8.608E-6	2.971E-5	1.876E-5	2.306E-5
R_{adj}^2		0.675		0.943	0.978	0.999	0.885	0.991	0.977
σ^2		0.549		0.012	0.042	2.968E-3	0.225	0.011	0.028

[1]$Y_{cumulative\text{-}mortality} = a \times t + b \times t^2$.

[2]Excluded from the overall fit.

TABLE 10. Mean and standard deviation ambient temperature (Celsius) for six flocks that are housed in an aviary system

	Flock number					
Parameter	1	2	3	4	5	6
Mean	21.36	22.98	22.82	21.86	22.96	23.02
SD	2.096	1.752	1.542	2.312	1.125	1.188

that the parameters give a reasonable fit for a specific flock.

The coefficients of determination per flock for the mathematical curves that describe feed consumption, water consumption, flock uniformity, and percentage of second grade eggs are, in general, low (Table 11). Within a flock, there is great daily variation, which influences the coefficients of determination. This daily variation can partly be explained by the fact that the poultry farmer influences the input variables feed and water consumption. Based on the results of the output variables of the production process the farmer actively influences the input variables. Naturally, the coefficients of determination for the overall fits of these mathematical curves are also low; especially the curves of feed and water consumption that show different curve forms between flocks (Figures 1 and 2). This result leads to the conclusion that it is very difficult to estimate the parameters for these mathematical curves for other flocks. Once a flock has started the laying period, the estimation parameters should become better, but the mathematical curves should be fitted regularly to the data during the laying period.

Mathematical curves can be used in monitoring the production process. The mathematical curves can act as a reference value for real production results. From our analysis, it becomes clear that if the mathematical curves are used as reference value, they must be fitted more or less regularly to flock-specific circumstances; then, the predicted values are closest to the real production results. The parameter fits presented in this paper can serve as good starting points for the proper setting of the parameters.

Normal Daily Process Variation

In order to detect aberrations or exceptional process variations in the production process, it is important to know the normal production variation (Deming, 1986). According to the minimum coefficients of variation of the flocks, the production variables can be separated into three classes. The first class, with minimum coefficients of variation between 0.8 and 1.9 (Table 11), consists of egg weight, body weight, cumulative mortality, and hen-day egg production. These variables also have the lowest maximum coefficients of variation (1.1 to 4.0), except for cumulative mortality. The second class, with a minimum coefficient of variation between 2.8 and 3.6 and a maximum coefficient of variation between 4.8 and 5.7, consists of the variables feed consumption, water consumption, and flock uniformity. The third class, with minimum coefficients of variation between 4.8 and 9.1 and maximum coefficients of variation between 10.6 and 45.1, consists of the variables ambient temperature, percentage floor eggs, and percentage of second grade eggs.

It can be concluded from the results of Table 11 that the daily percentages of second and floor eggs show so much variation that they are difficult to use as management parameters to monitor the daily production process. The ambient temperature also shows a great deal of variation between days (4.9 to 10.6), which was not expected

TABLE 11. Overall coefficients of determination (R^2_{adj}) and standard deviation and minimum and maximum coefficients of determination, standard deviations, coefficients of variation, and expected means (μ) per flock for the mathematical curves

	Overall		Per flock						
			R^2_{adj}		SD			CV	
Parameter	R^2_{adj}	SD	Minimum	Maximum	Minimum	Maximum	μ	Minimum	Maximum
								(%)	
Input									
Feed consumption, g	0.42	6.12	0.54	0.69	3.24	5.90	115	2.8	5.2
Water consumption, g	0.54	13.89	0.50	0.81	8.32	10.91	230	3.6	4.8
Ambient temperature, cL					1.13	2.31	23	4.9	10.6
Output									
Cumulative mortality, %	0.68	0.74	0.94	1.00	0.05	0.20	3	1.7	6.7
Hen-day egg production, %	0.87	4.90	0.91	0.99	1.62	3.41	85	1.9	4.0
Egg weight, g	0.92	1.43	0.94	0.99	0.52	1.23	62	0.8	2.0
Body weight, g	0.92	18.61	0.80	0.93	16.26	18.66	1700	1.0	1.1
Flock uniformity, %	0.42	3.28	0.33	0.61	2.46	3.85	68	3.6	5.7
Second grade eggs, %	0.34	2.66	0.46	0.87	0.45	2.25	5	9.1	45.1
Floor eggs, %	0.11	2.57	0.72	0.84	0.24	0.98	5	4.8	19.5

because the temperature was controlled by climate computers. This daily variation in ambient temperature has an effect on daily feed and water consumption. According to Luiting (1990), 54% of the gross energy consumption is used for heat production loss, which consists of heat production for maintenance and heat increment of production. The daily variation in feed and water consumption is between 2.8 and 5.2. Therefore, most of the variation in the daily variation of the ambient temperature is compensated for by the daily variation in feed and water consumption. Another part of the daily variation in ambient temperature has its effect on the egg production (hen-day egg production between 1.9 and 4.0 and egg weight between 0.8 and 2.0) and body weight gain. The mean daily body weight shows less variation (1.0 to 1.1) than does flock uniformity (3.6 to 5.7). Probably, competition for feed and water affected flock uniformity.

To monitor the daily production process in an aviary system for laying hens, the poultry farmer should look primarily at ambient temperature, feed consumption, water consumption, hen-day egg production, egg weight, body weight, and flock uniformity. Cumulative mortality can also be used to monitor the daily production process. To control the production process, it is important that the poultry farmer try to reduce the daily variation in the ambient temperature. By concentrating on exceptional variation and not looking at normal process variation, the poultry farmer can control better the three CSF on feed consumption, ambient temperature, and the timely detection of disease.

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