# Active Control of the Growth Trajectory of Broiler Chickens Based on Online Animal Responses

J.-M. Aerts,*,[1] S. Van Buggenhout,* E. Vranken,* M. Lippens,† J. Buyse,‡ E. Decuypere,‡ and D. Berckmans*

**Laboratory for Agricultural Buildings Research, Department of Agro-engineering and -Economics, Catholic University of Leuven, Kasteelpark Arenberg 30, B-3001 Leuven, Belgium; †Ministry of the Flemish Community, Agricultural Research Centre—Ghent, Department Animal Nutrition and Husbandry—Small Stock Husbandry, Burg. Van Gansberghelaan 92, B-9820 Merelbeke, Belgium; and ‡Laboratory for Physiology and Immunology of Domestic Animals, Department of Animal Production, Catholic University of Leuven, Kasteelpark Arenberg 30, B-3001 Leuven, Belgium*

**ABSTRACT** The objective of the research reported here was to control the growth trajectory of broiler chickens during the production process based on an adaptive compact dynamic process model. More specifically, the daily feed supply was calculated, based on a model-based control algorithm, with the aim of following a previously defined target growth trajectory as close as possible. For the modeling of the dynamic growth response of broiler chickens to the control input, feed supply, an online parameter estimation was used.

The developed control algorithm was able to grow the birds according to different target trajectories ranging from restricted (final BW of 1,800 g and 1,945 g in experiments 1 and 3, respectively) to compensatory growth trajectories (final BW of 2,400 g and 2,100 g in experiments 2 and 4, respectively). The mean relative error (MRE) between the different predefined target growth trajectories and the realized growth trajectories ranged from 3.7% to 6.0%. With a few exceptions, the numerical values of feed conversion ratio and mortality after wk 1 were lower and the values of uniformity index were higher in the controlled groups compared with animals fed ad libitum. As a conclusion, it can be stated that integration of dynamic data-based modeling approaches with new hardware and sensing techniques to measure information from the animals should make it possible to control broiler growth trajectories.

(*Key words*: bioresponse, broiler, growth control, online modeling, prediction)

2003 Poultry Science 82:1853–1862

## INTRODUCTION

Genetic selection and improved nutrition have led to a reduction of the commercial slaughter age in broiler chickens. However, this evolution has also resulted in several negative growth responses. Problems with this "fast growing strategy" are, among others, increased body fat deposition, decreased reproduction capacity of the breeder stock, metabolic diseases such as ascites and sudden death syndrome, and greater incidence of skeletal diseases (Plavnik et al., 1986; Leeson and Summers, 1988; Zubair and Leeson, 1994; Lippens et al., 2000).

Some of these negatively correlated growth responses related to fast growing can be alleviated by altering the growth trajectory in such a way that initial growth is reduced, followed by accelerated growth or compensatory growth (Zubair and Leeson, 1996). Early feed restriction programs have been extensively studied from physiological and nutritional points of view and have demonstrated the possible benefits of compensatory growth on animal welfare and production performance (Auckland and Morris, 1971; Plavnik and Hurwitz, 1985, 1988, 1991; Jones and Farrell, 1992a,b; Buyse et al., 1996). To apply such altered growth trajectories in practice in an efficient way, it is important that the growth trajectory be monitored during the process in order to compare the real trajectory of the broilers with the desired (target) trajectory so that, in case of deviations, the growth trajectory can be adjusted. In order to make such adjustments, it should be known how the growth trajectory can be altered by means of the process inputs (e.g., feed supply). Or, using the terminology of control theory, a process (e.g., growth process) can only be controlled in an efficient way provided that there is continuous feedback of the process output to be controlled and that at every moment an accurate mathematical model is available that predicts the response of the process output to variations in the process input(s) (Golten and Verwer, 1991; Camacho and Bordons, 1999).



Received for publication February 3, 2003.

Accepted for publication August 11, 2003.

[1]To whom correspondence should be addressed: daniel.berckmans@agr.kuleuven.ac.be.

**Abbreviation Key:** CF = cumulative feed intake; MPC = model predictive control; MRE = mean relative error.

Although modern control theory has been applied with success to control a variety of processes (e.g., chemical reactors, robotic movement, navigation of airplanes, etc.), it has little been used to control biological processes. This is mainly due to the fact that for years the appropriate sensors and measuring devices for feedback information from the living organisms in practice have been lacking (or were too expensive), and also because the existing mathematical models in literature, describing (parts of) biological production processes, were too complex for control purposes (Bridges et al., 1995). Because of the complexity, time-dependency, and specificity of the response of living organisms, an online dynamic model with a recursive estimation of the model parameters is needed.

The (r)evolution in modern hardware techniques (price, computational power, reliability, compact dimensions) and software makes it possible today to measure information on living organisms on-line at low cost and to use advanced mathematical identification techniques for modeling complex processes (Bakker et al., 1980; Young, 1984; Åström, 1985; Berckmans and Goedseels, 1986; Ljung, 1987; Oltjen and Owens, 1987; Roush et al., 1992; Xin et al., 1992; Aerts et al., 2000). These mathematical identification techniques estimate the model parameters of a mathematical model structure based on online measurements of the process inputs and outputs. The estimation of the model parameters can be performed recursively during the process, resulting in a dynamic model that can cope with the time-variant aspects of bioprocesses (Goodwin and Sin, 1984; Ljung, 1987). Aerts et al. (2003) demonstrated the possibility of modeling the growth response to the control input feed intake.

The objective of this research was to explore whether the growth trajectory of broiler chickens in practice could be controlled on-line with feed supply as control input, by making use of modern control theory. Feed supply was chosen as control input because it is one of the most important inputs in growth processes from an energetic as well as an economic point of view (Beyerly, 1967; Parkhurst, 1967; Fitzhugh, 1976; Ingelaat, 1997; Filmer, 2001).

## MATERIALS AND METHODS

### Model Predictive Growth Control

The term model predictive control (MPC) does not designate a specific control strategy. Instead a range of control methods is used such that they use continuous feedback of the process output(s), as in other control strategies, and also make explicit use of a dynamic model of the process to predict the process response, which is used to calculate the control signal by minimizing an objective function (Soeterboek, 1990; Camacho and Bordons, 1999). The various MPC algorithms propose different objective functions for obtaining the control law. The general aim is that the future output (y) on the considered horizon should follow a determined reference or target signal (r), and at the same time, the control effort ($\Delta$u) necessary for doing so should be penalized. The general expression for such an objective function is (Camacho and Bordons, 1999)

$$J(N_1,\ N_2,\ N_u) = \sum_{F=N_1}^{N_2} \delta(F)[\hat{y}(t+F \mid t) - r(t+F)]^2 + \sum_{F=1}^{N_u} \lambda(F)[\Delta u(t+F-1)]^2 \quad [1]$$

where $N_1$ = the minimum cost horizon; $N_2$ = the maximum cost horizon; $N_u$ = the control horizon, $\hat{y}(t + F \mid t)$ = the predicted value of the process output y at time $t$, $F$ time steps in the future; $r(t+F)$ = the value of the reference or target trajectory at moment $t$+$F$; $\Delta$u($t$+$F$-1) = the change of control input at moment $t$+$F$-1; and $\delta(F)$, $\lambda(F)$ = weighing coefficients.

More specifically in this application, the objective function was written as

$$J(1,4,4) = \sum_{j=1}^{4}[\hat{W}(t+F \mid t) - r(t+F)]^2 + \sum_{j=1}^{4} \lambda(F)[\Delta CF(t+F-1)]^2, \quad [2]$$

where $\hat{W}(t + F \mid t)$ = the predicted weight of the animals, CF = the cumulative feed supply, and $r$ = the target weight trajectory. The MPC method uses the principle of receding horizon. This means that after calculation of the optimal sequence of the control input over the control horizon $N_u$, only the first value of the calculated control input is applied, then the horizon is moved with one measuring unit and subsequently the procedure of optimization is repeated with new measured information.

The methodology of MPC controllers is characterized by the following strategy (Camacho and Bordons, 1999): (1) MPC control theory makes explicit use of a model to predict the process output at future time instants. The future process outputs for a determined horizon $N_2$, called the prediction horizon, are predicted at each instant $t$ using the process model. These predicted[2] outputs $\hat{y}(t + k \mid t)$ for $k = 1 \ldots N$ depend on the known values up to instant $t$ (past inputs and outputs) and on the future control signals $u(t + k \mid t)$, $k = 0 \ldots N$-1, which are those sent to the system and to be calculated. (2) The set of future control signals is calculated by optimizing a determined criterion in order to keep the actual process outputs as close as possible to the desired process output or target trajectory $r(t + k)$. The criterion usually takes the form of a quadratic function of the errors between the predicted output signal and the reference trajectory. In most cases, the control effort is included in an objective function. (3) MPC uses a receding strategy so that at each instant the

[2]The notation indicates the value of the variable at the instant $t + k$ calculated at instant $t$.

horizon is displaced toward the future, which involves the application of the first control signal of the sequence calculated at each step. The control signal $u(t \mid k)$ is sent to the process, but the next control signals are rejected, because at the next sampling instant $y(t + 1)$ is already known. Step (1) is repeated with this new value, and all the sequences are brought up to date (i.e., receding horizon principle).

The predictive model is the corner stone of MPC. In this research, a model was used that predicts BW of broiler chickens (process output) to the process (control) input cumulative feed supply by applying a time-variant parameter estimation method. For more details about the used modeling technique, the reader is referred to Aerts et al. (2003). The control algorithm was programmed in Matlab.[3]

## Birds and Housing

The ethical commission of the Catholic University of Leuven approved the performed experiments. All the experiments were conducted with Ross 308 broilers, mixed-sex, obtained from a local hatchery[4] (female broiler breeders were about 45 wk old). In the hatchery the chicks were vaccinated against Newcastle disease.[5]

In experiments 1 and 2, chicks were vaccinated via the drinking water against infectious bursal disease (NOBILIS D78)[6] at d 10. Birds were kept in 2 temperature-controlled rooms with 4 floor pens each. In each pen, 50 birds were housed (stocking density of 16 birds per $m^2$) on wood shavings. The testing facility was equipped with an automatic weighing system[7] consisting of eight weighing platforms (1 platform/pen) and a weighing computer to measure the average BW of the flock per pen every 24 h. Feed consumed was recorded daily for all pens. A conventional lighting schedule of 23L:1D was used. Mean air temperature was set at 32°C during d 1. Every 2 d temperature was decreased 1°C until the constant temperature of 21°C was reached at d 23. Water was freely available to all birds. The testing facility used in experiments 1 and 2 was situated in the Zootechnical Centre of the Catholic University of Leuven (Belgium).

In experiments 3 and 4, birds were treated at arrival against infectious bronchitis (NOBILIS 1B H120)[6] followed by a booster vaccination (NOBILIS, ND CLONE 3C)[6] at d 15 against Newcastle disease. Birds were kept in 2 compartments on chopped straw with 2,900 birds per compartment (stocking density of 16 birds per $m^2$). A conventional lighting schedule of 23L:1D was used. Mean air temperature was 30°C during d 1 to 3. From d 3, room temperature was set at 28°C and then decreased 1°C every 3 d until a constant temperature of 21°C was reached at d 21. Water was freely available to all birds. All growth trials were carried out during 42 d. Each compartment was equipped with 4 weighing platforms connected to a weighing computer[7] for measuring the average weight of the flock animals every 24 h. Feed consumption was recorded daily in both compartments. One compartment was equipped with an automatic feeding system.[8] In the other compartment, feed had to be administered manually. The testing facility used in experiments 3 and 4 was situated in a broiler house of the Agricultural Research Centre, Ghent, Belgium.

## Diets

The broilers were given a commercial starter feed followed by a grower feed. In experiments 1 and 2, a starter diet with 220 g/kg CP and 2,890 kcal $AME_n$/kg was given until 12 d of age. From d 13 until d 42, a grower diet with 205 g/kg CP and 3,028 kcal $AME_n$/kg was offered. In experiments 3 and 4, a starter diet with 211 g/kg CP and 2,960 kcal $AME_n$/kg was given until 10 d of age. From d 11 until d 42, a grower diet with 209 g/kg CP and 3,060 kcal $AME_n$/kg was offered.

## Experimental Design

Animals were weighed manually every week in order to check the accuracy of the automatic weighing systems: in experiments 1 and 2, all birds per pen were weighed manually; in experiments 3 and 4, each week a random sample of 200 birds was taken for weighing in both compartments.

Because the presence of other parameters (transport, breeding conditions, etc.) that influence mortality especially during the first week, the mortality rate in all experiments was evaluated starting from d 7. By doing so, the impact of controlling the growth on the mortality could be investigated.

In experiments 1 and 2, each of the 2 temperature-controlled rooms had 2 reference groups and 2 experimental growth-controlled groups. The reference groups were fed ad libitum. The amount of feed of the growth-controlled groups was calculated based on the control algorithm (cf. Procedure [below]). In experiment 1, the target weight trajectory that had to be followed by the controlled groups was defined as a restricted growth curve with a final BW of 1,800 g at 42 d. In experiment 2, the target trajectory was defined as a “strong” compensatory growth trajectory with a final BW of 2,400 g at d 42. The target growth trajectories of experiments 1 and 2 are given in Table 1.

During the 2 trials of experiment 3 and the 2 trials of experiment 4, animals were fed ad libitum (reference group) in 1 compartment, and in the other compartment the feed supply was calculated based on the control algorithm (controlled group). Because the 2 compartments were not identical, the controlled group and the ad libitum fed group were changed among the compartments during the successive trials. In experiments 3 and 4, the

[3]Matlab, Version 5.3.0, The MathWorks Inc., Natick, MA.
[4]Willem Spoormans N.V., Arendonk, Belgium.
[5]ND Hitchner G149, Antec International Ltd., Sudbury, UK.
[6]Intervet International b.v., Boxmeer, The Netherlands.
[7]747 version A1, Fancom b.v., Panningen, The Netherlands.
[8]Minimax®, Roxell n.v., 9990 Maldegem, Belgium.

**TABLE 1. The target growth trajectories used in the different experiments**

| | Target growth trajectory (g) | | | |
|---|---|---|---|---|
| Day | Experiment 1 | Experiment 2 | Experiment 3 | Experiment 4 |
| 1 | 45 | 45 | 44 | 50 |
| 2 | 55 | 55 | 55 | 61 |
| 3 | 67 | 67 | 67 | 73 |
| 4 | 81 | 81 | 81 | 87 |
| 5 | 88 | 88 | 88 | 94 |
| 6 | 100 | 100 | 100 | 106 |
| 7 | 113 | 113 | 113 | 119 |
| 8 | 129 | 129 | 129 | 135 |
| 9 | 152 | 130 | 152 | 153 |
| 10 | 177 | 150 | 177 | 172 |
| 11 | 204 | 175 | 204 | 193 |
| 12 | 233 | 205 | 233 | 217 |
| 13 | 263 | 235 | 263 | 242 |
| 14 | 295 | 265 | 295 | 269 |
| 15 | 328 | 295 | 328 | 303 |
| 16 | 362 | 330 | 362 | 340 |
| 17 | 397 | 380 | 397 | 379 |
| 18 | 435 | 430 | 435 | 420 |
| 19 | 473 | 490 | 473 | 464 |
| 20 | 513 | 550 | 513 | 511 |
| 21 | 555 | 620 | 555 | 560 |
| 22 | 597 | 690 | 597 | 616 |
| 23 | 642 | 760 | 642 | 675 |
| 24 | 688 | 830 | 688 | 737 |
| 25 | 735 | 905 | 735 | 801 |
| 26 | 783 | 980 | 783 | 868 |
| 27 | 832 | 1,060 | 832 | 937 |
| 28 | 886 | 1,140 | 886 | 1,008 |
| 29 | 948 | 1,220 | 948 | 1,081 |
| 30 | 1,015 | 1,305 | 1,015 | 1,156 |
| 31 | 1,080 | 1,390 | 1,085 | 1,232 |
| 32 | 1,146 | 1,480 | 1,155 | 1,309 |
| 33 | 1,211 | 1,570 | 1,226 | 1,386 |
| 34 | 1,277 | 1,665 | 1,298 | 1,464 |
| 35 | 1,342 | 1,760 | 1,371 | 1,542 |
| 36 | 1,408 | 1,855 | 1,452 | 1,621 |
| 37 | 1,473 | 1,950 | 1,533 | 1,700 |
| 38 | 1,538 | 2,045 | 1,615 | 1,780 |
| 39 | 1,604 | 2,140 | 1,698 | 1,860 |
| 40 | 1,669 | 2,235 | 1,781 | 1,941 |
| 41 | 1,735 | 2,320 | 1,863 | 2,022 |
| 42 | 1,800 | 2,400 | 1,945 | 2,100 |

controlled group was housed in the compartment with the automatic feeding system during the first trial and in the compartment with manual feeding during the second trial. In experiment 3, the birds were controlled in order to follow a restricted growth curve with a final BW of 1,945 g at d 42. In experiment 4, the target trajectory was defined as a "moderate" compensatory growth trajectory with a final BW of 2,100 g at d 42. The applied target growth trajectories are given in Table 1.

## Procedure

Every day at 0900, the average weight of the feed-controlled groups was read from the display of the weighing computer, and the feed consumed during the last 24 h was determined for all experiments. In experiments 1 and 2, the weight and feed consumption data for the 2 controlled groups were averaged per room. In all the experiments, these average values of weight and feed consumption were imported as inputs into the control algorithm. Subsequently, the control algorithm calculated the amount of feed that had to be administered to the feed-controlled animals the next 24 h in order to follow the previously defined target growth trajectory. In experiments 1 and 2, these calculations were performed per room so that per room the 2 controlled groups received the same amount of feed per bird. In experiments 3 and 4, these calculations were carried out for the compartment with the controlled birds. The calculated amounts of feed were administered all at once. All of the birds (the reference groups as well as the controlled groups) were fed ad libitum during the first 3 d. The daily amount of feed calculated by the control algorithm was supplied to the controlled groups from d 4 on, because the algorithm needed data of weight and feed intake of at least 3 d to perform reliable parameter estimation.

## Statistical Analysis

The performance of the control algorithm corresponds to the relative deviance of target growth trajectory during the whole growth trial. It was quantified by means of the mean relative error (MRE), which was defined as

$$MRE = \frac{1}{N}\sum_{t=1}^{N}\sqrt{\left(\frac{W(t)-r(t)}{r(t)}\right)^2} \times 100 \qquad [3]$$

where MRE = the mean relative error (%), $N$ = the number of samples, $W(t)$ = the weight measured with the automatic weighing systems at time $t$ (kg), and $r(t)$ = the target weight trajectory at time $t$ (kg).

In experiments 1 and 2, the significance of the differences in average values of feed conversion ratio, uniformity index, and mortality between the controlled groups and ad libitum fed reference groups were analyzed by means of Student's $t$-test. Because the trials in experiments 3 and 4 were confounded in 2 nonidentical compartments with only 1 duplication in time, no statistical analysis was applied to the observed differences in feed conversion ratio, uniformity index, and mortality.

## RESULTS AND DISCUSSION

Graphical results of the model predictive growth control are presented in Figures 1 to 4. For each experiment, 1 representative figure is shown. In each figure, 2 graphs are displayed, namely 1 graph with the growth trajectory of the feed controlled animals, the target trajectory, and the trajectory of the animals fed ad libitum and another graph with the feed consumed by the feed controlled animals, the animals fed ad libitum, and the feed supply calculated by the control algorithm.

In experiment 1, the animals were restricted during the entire growing period (final BW of 1,800 g on d 42). In both rooms, the animals were able to realize the target growth trajectory (Figure 1). The MRE of the controlled weight trajectory of the restricted group in the second room was slightly larger than in the first room (4.1 vs. 3.7%). This finding could be explained by the fact that the weight trajectory of the controlled group in the second room oscillated more (with larger amplitude) around the desired reference growth trajectory, especially during wk 5 and 6. The period of these oscillations is influenced by the weighing factor $\lambda$ in the objective function. Values for $\lambda$ vary between zero and one. The closer to zero, the faster the controller tends to minimize the error between the process output and the target trajectory, and the closer to 1, the slower this error will be minimized (Camacho and Bordons, 1999). In this research, the value of $\lambda$ was set to 0.8 in order to avoid large variations in daily feed supply, resulting in slow oscillations around the target. In the second graph in Figure 1, it is apparent that, with the exception of a few days, the daily amount of feed calculated by the control algorithm was entirely consumed by the broilers and ranged from 35 to 100% of the feed intake of the ad libitum-fed birds.

Some causal mechanisms responsible for the improved performance (lower feed conversions, low mortality due to metabolic diseases, reduced fat deposition) of broilers

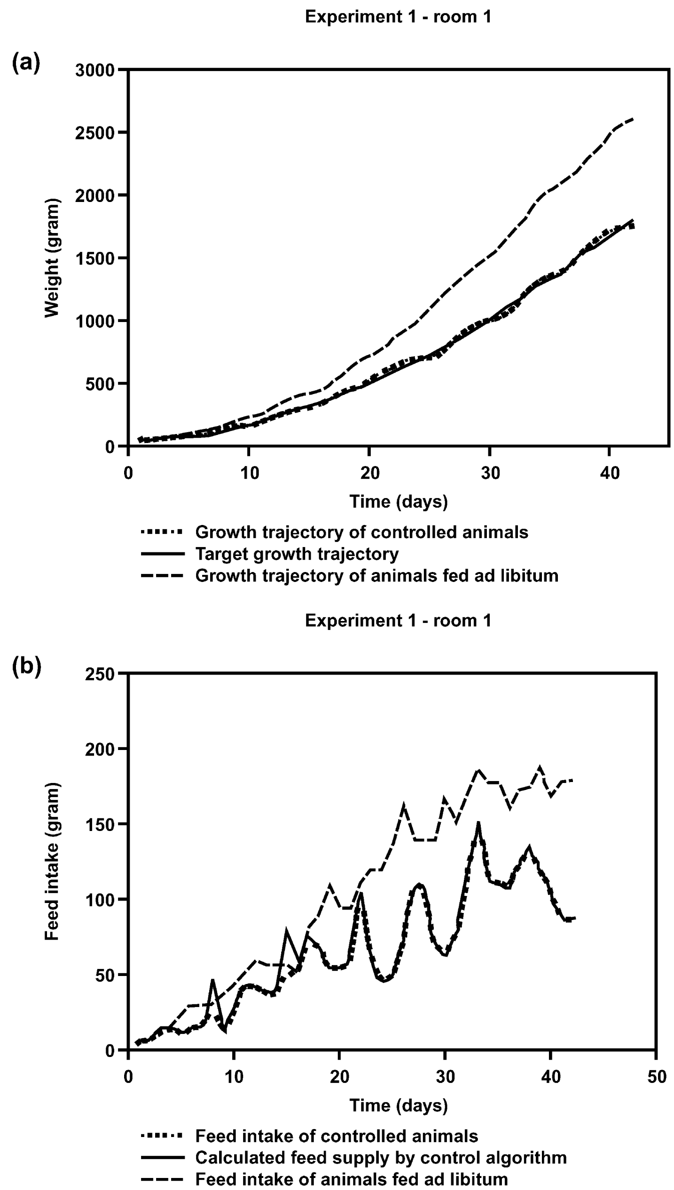


**FIGURE 1.** Controlled growth trajectory, target growth trajectory, and growth trajectory of the ad libitum group as a function of time (a) and feed intake of the animals fed ad libitum, feed-controlled animals, and calculated feed supply by the control algorithm (b) for experiment 1. The control target was a restricted growth trajectory with a final BW of 1,800 g.

following a changed growth trajectory (initial growth rate reduction followed by compensatory growth) are discussed elsewhere (Buyse et al., 1996).

The cumulative feed conversion ratio was 1.56 for the controlled group and 1.52 for the ad libitum-fed group (Table 2). In the second room, the feed conversion rate was 1.58 for the controlled group and 1.60 for the ad libitum-fed group. The differences between the average values (Table 2) were not statistically significant. The numerical value of the uniformity index of the controlled animals at d 42 was higher than the animals fed ad libitum (63.3 vs. 55.3% for room 1 and 59.6 vs. 51.2% for room 2). The uniformity index was calculated as the percentage of birds that were within 10% of the mean BW of all the

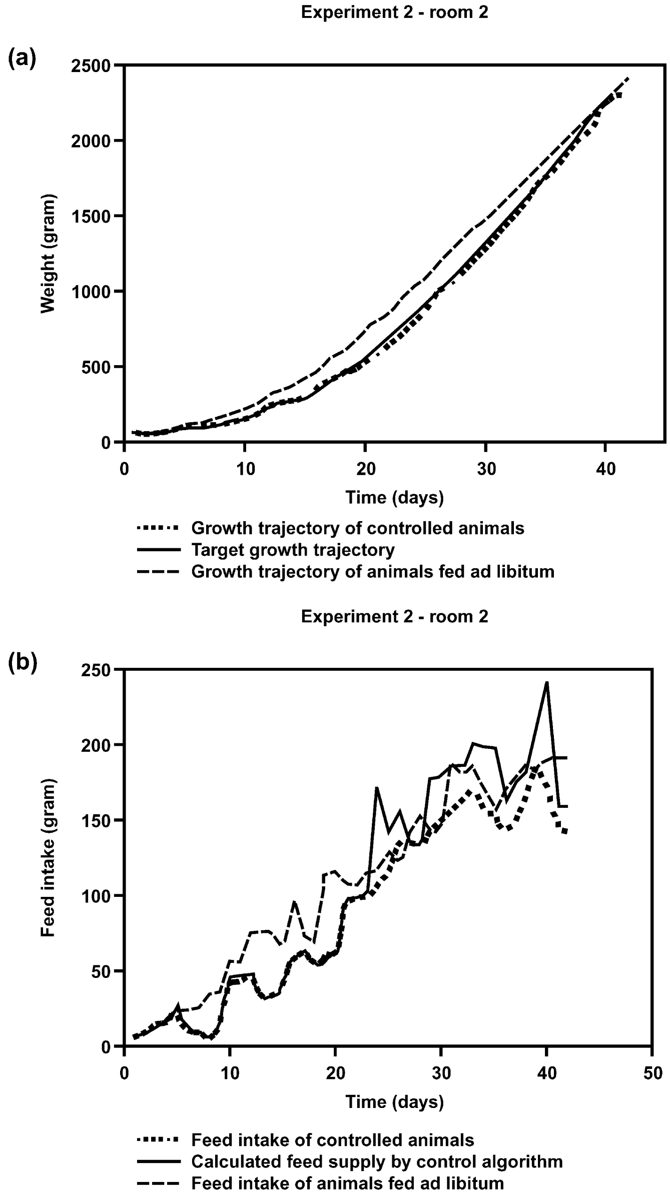


**FIGURE 2.** Controlled growth trajectory, target growth trajectory, and growth trajectory of the ad libitum group as a function of time (a) and feed intake of the animals fed ad libitum, feed-controlled animals, and calculated feed supply by the control algorithm (b) for experiment 2. The control target was a pronounced compensatory growth trajectory with a final BW of 2,400 g.

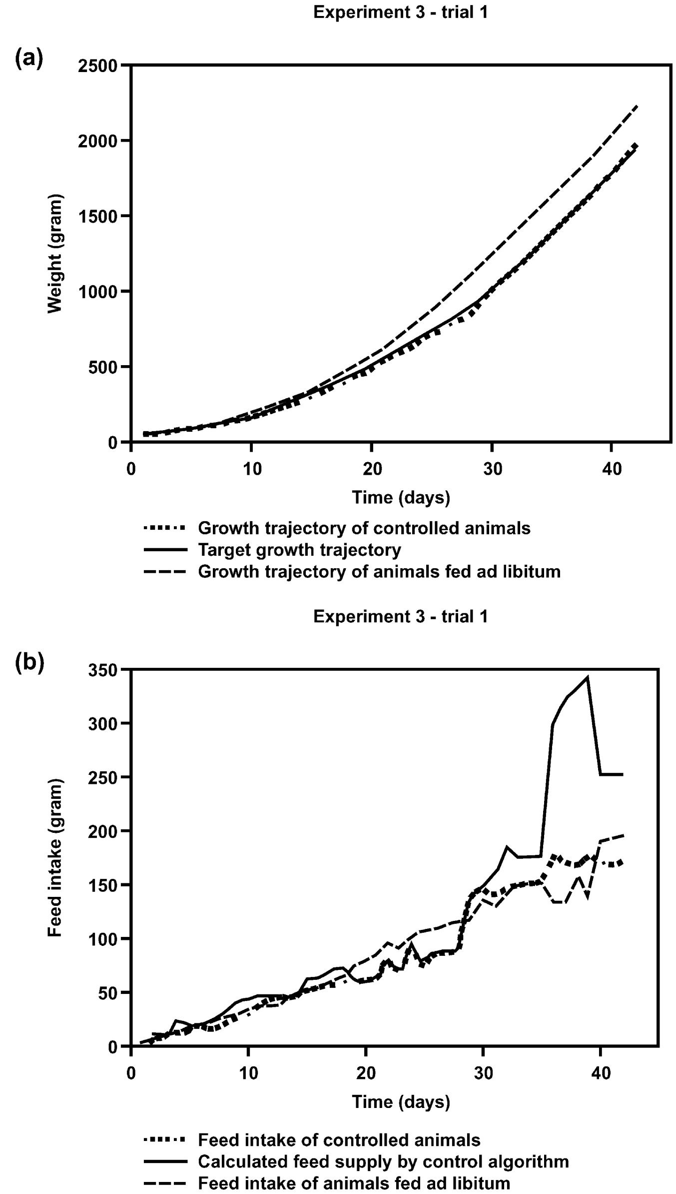


**FIGURE 3.** Controlled growth trajectory, target growth trajectory, and growth trajectory of the ad libitum group as a function of time (a) and feed intake of the animals fed ad libitum, feed-controlled animals, and calculated feed supply by the control algorithm (b) for experiment 3. The control target was a restricted growth trajectory with a final BW of 1,945 g.

birds of the group (Petitte et al., 1981; Zhang et al., 1999). The numerical value of the mortality of the controlled (restricted) groups was lower (but not statistically significant) than that of the ad libitum-fed groups (0.0 vs. 5.0% and 3.0 vs. 6.0%), which is in agreement with findings reported in the literature (e.g., Urdaneta-Rincon and Leeson, 2002).

In experiment 2, a strong compensatory growth trajectory (initial lowered growth followed by an accelerated growth) was set as target trajectory. In both climate-controlled rooms, the model predictive control algorithm was able to let the birds follow the target trajectory. In both rooms, the controlled group realized a full compensatory growth in comparison with the animals fed ad libitum (see Figure 2). The MRE was 4.6% in room 1 and 5.3% in room 2. In the lower graph in Figure 2, it is apparent that during the first half of the growing period (from d 1 up to d 22) the daily amount of feed calculated by the control algorithm was completely consumed, indicating that the birds were restricted. During the second half of the growing period, the amount of feed calculated by the control algorithm exceeded the amount consumed by the birds, indicating ad libitum feed consumption. The numerical values of the feed conversion ratio of the feed-controlled animals, that were restricted during early age, were lower than those of the animals fed ad libitum (1.45 vs. 1.64 for room 1 and 1.65 vs. 1.69 for room 2). This result is in agreement with the results of Plavnik and Hurwitz (1985,

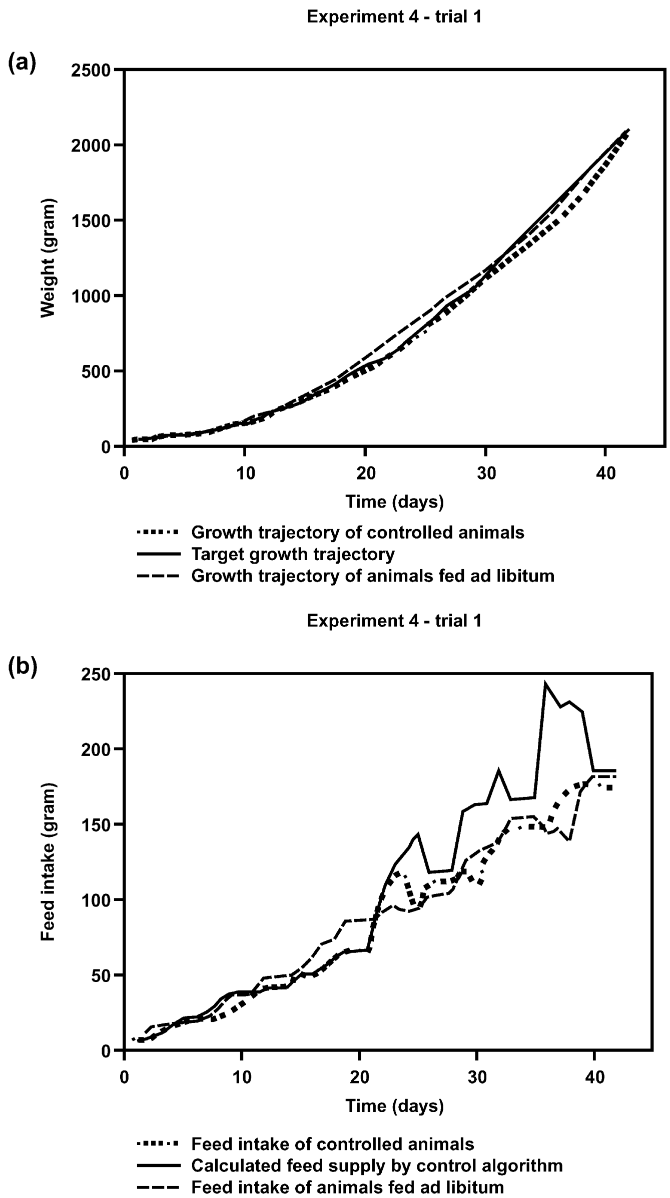


**FIGURE 4.** Controlled growth trajectory, target growth trajectory, and growth trajectory of the ad libitum group as a function of time (a) and feed intake of the animals fed ad libitum, feed-controlled animals, and calculated feed supply by the control algorithm (b) for experiment 4. The control target was a moderate compensatory growth trajectory with a final BW of 2,104 g.

1989) and Lee and Leeson (2001). The numerical values of the uniformity index at d 42 was higher for the feed-controlled animals than for the animals fed ad libitum in room 2 (67.1 vs. 47.1%), but lower in room 1 (51.3 vs. 56.3%). As in experiment 1, mortality after wk 1 of the birds following a compensatory growth trajectory (controlled groups) (compensatory growth) was lower than for the ad libitum fed groups (1.1 vs. 3.3% and 1.3 vs. 3.0%), which is in agreement with work of Blair et al. (1993) and Urdaneta-Rincon and Leeson (2002). The results are summarized in Table 2. Except for the mortality, no significant differences between average values were observed in experiment 2 (Table 2).

In experiment 3, a moderate restricted growth curve was chosen as target trajectory. In general, the control algorithm succeeded in growing the birds according to the previously defined target trajectory. As apparent in Table 2, the MRE was 4.0% for trial 1 and 3.7% for trial 2. The fact that the control performance in trial 1 was slightly less accurate than in trial 2 could mainly be explained by an accuracy problem of the weighing system. Indeed, during wk 5 and 6 of the growing period, the average weight of the animals in trial 1 was strongly underestimated by the weighing system (up to 12% at d 42). As a result, the deviation between the reference weight and the actual weight was overestimated, and consequently the daily amount of feed calculated by the control algorithm (and administered to the birds) was too large. This result explains why the actual weights of the birds rose above the target trajectory during the last 2 wk, as shown in Figure 3. From the lower graph in Figure 3, it is shown that during the first 2 wk intake by controlled animals equalled more or less the feed intake of the animals fed ad libitum. During wk 3 and 4, the feed supply calculated by the control algorithm was 15 to 30% lower than the feed intake of the animals fed ad libitum, indicating growth restriction. During the last 2 wk, feed intake increased again (relative to animals fed ad libitum) due to overfeeding, as explained above. The numerical value of the feed conversion ratio was lower for the controlled group in trial 2 compared with that of the animals fed ad libitum (1.65 vs. 1.74), but higher in trial 1 (1.83 vs. 1.61). In both trials, the BW of the controlled groups was more uniform than that of the animals fed ad libitum at d 42 (uniformity index of 57.7 vs. 56.5% and 57.0 vs. 40.0%). The numerical values of mortality after wk 1 of the controlled group was lower in trial 1 (2.1 vs. 4.1%), but higher in trial 2 (2.8 vs. 2.2%) than those of the ad libitum fed birds.

In experiment 4, the target growth trajectory that the growth-controlled birds had to follow was a moderate compensatory growth curve (final BW of 2,104 g at d 42). The MRE for trial 1 was 4.8% and for trial 2, 5.9%. In Figure 4 the results of trial 1 are shown. During the first 3 wk of the growing period, the controlled animals could keep up with the moderate compensatory growth trajectory. From d 21 on, the realized growth trajectory of the controlled group deviated from the reference trajectory with a maximum of 7.4% at d 35 but approached the target trajectory again during the last week (deviation of 2.0% at d 42). The daily feed supply calculated by the control algorithm was (nearly) completely consumed by the controlled group during the first 3 wk (period of reduced growth) and was on average 85% of the feed intake of the animals fed ad libitum. During the last 3 wk, the feed intake of the controlled animals equalled on average the feed intake of the animals fed ad libitum. As shown in Figure 4, the feed supply calculated by the control algorithm exceeded the actual feed intake during that period, indicating ad libitum feed intake of the controlled group. In trial 2, the controlled birds were able to follow the target growth trajectory during the first 4 wk,

**TABLE 2. Results of the control algorithm for different target growth trajectories and the resulting performance of the broiler chickens**

| Experiment | MRE[1] (%) | Body weight at d 42 (g) | | Feed conversion ratio[4] (kg feed/kg weight gain) | | Uniformity index (%) | | Mortality after wk 1 (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | C group | A group | C group | A group | C group | A group | C group | A group |
| Experiment 1 | | | | | | | | | |
| Room 1 | 3.7 | 1,757 | 2,603 | 1.56 | 1.52 | 63.3 | 55.3 | 0.0 | 5.0 |
| Room 2 | 4.1 | 1,697 | 2,674 | 1.58 | 1.60 | 59.6 | 51.2 | 3.0 | 6.0 |
| | | | | 1.57 (±0.01)[5] | 1.56 (±0.06)[5] | 61.5 (±2.6)[5] | 53.4 (±2.9)[5] | 1.5 (±2.1)[5] | 5.5 (±0.7)[5] |
| Experiment 2 | | | | | | | | | |
| Room 1 | 4.6 | 2,296 | 2,473 | 1.45 | 1.64 | 51.3 | 56.3 | 1.1 | 3.3 |
| Room 2 | 5.3 | 2,278 | 2,480 | 1.65 | 1.69 | 67.1 | 47.1 | 1.3 | 3.0 |
| | | | | 1.55 (±0.14)[5] | 1.67 (±0.04)[5] | 59.2 (±11.2)[5] | 51.7 (±6.5)[5] | 1.2 (±0.1)[*,5] | 3.2 (±0.2)[5] |
| Experiment 3 | | | | | | | | | |
| Trial 1 | 4.0[2] | 1,964 | 2,219 | 1.83 | 1.61 | 57.7 | 56.5 | 2.1 | 4.1 |
| Trial 2 | 3.7[3] | 1,935 | 1,993 | 1.65 | 1.74 | 57.0 | 40.0 | 2.8 | 2.2 |
| Experiment 4 | | | | | | | | | |
| Trial 1 | 4.8[2] | 2,061 | 2,078 | 1.77 | 1.81 | 47.0 | 55.0 | 3.8 | 4.5 |
| Trial 2 | 6.0[3] | 1,907 | 1,748 | 1.70 | 1.80 | 56.3 | 50.1 | 4.7 | 5.2 |

[1]MRE = mean relative error; C group = controlled-fed animals; A group = animals fed ad libitum.

[2]Controlled-fed animals housed in compartment with automatic feeding.

[3]Controlled-fed animals housed in compartment with manual feeding.

[4]Feed conversion ratios are adjusted in order to compare C group and A group at the same BW.

[5]: $\bar{x} \pm$ SE; n = 2.

*Significant difference between C group and A group ($P \leq 0.1$).

but during wk 5 and 6 their growth deviated more and more from the target trajectory explaining the rather large RME of 6.0%. This finding might be caused by a problem of bird quality or an infection in the poultry house, because the ad libitum fed group in trial 2 had a final BW of only 1,748 g, which was even 159 g less than the controlled group (final BW of 1,907 g). In both trials, the numerical values of the feed conversion ratio of the controlled group were lower than those of the ad libitum fed birds (1.77 vs. 1.81 and 1.70 vs. 1.80). The uniformity index of the controlled group was higher than that of the ad libitum fed group in trial 2 (56.3 vs. 50.1%) but lower in trial 1 (47.0 vs. 55.0%). A lower mortality rate after wk 1 was observed for the controlled groups in both trials (trial 1: 3.8 vs. 4.5%; trial 2: 4.7 vs. 5.2%).

Filmer (2001) described a system for controlling broiler growth based on measurements of feed intake and BW of the flock. The main control inputs used in this system were feed composition and feed amount. The feed composition was calculated based on a superimposed ideal protein curve describing the protein content of the feed as a function of age. Recently, Stacey et al. (2002) developed a controller for broiler growth that was tested in practice in combination with the system described by Filmer (2001). In the performed trials, standard practice growth trajectories were used as reference or target trajectories. Birds were fed ad libitum and the blend ratio of the feed was used as control input. Growth was modeled with a semi-mechanistic growth model. This model was adaptive in a sense that one of the model parameters that could be interpreted as the metabolic efficiency, was estimated daily, based on measured weight and feed data of the past 14 d. Birds that were grown by the controller had similar feed conversion ratios to those of birds grown manually by the manager of the poultry house (1.75 vs. 1.73 on average). The birds started deviating from the target growth trajectory after 4 wk. Neither birds grown manually nor birds grown by the controller achieved the set target at d 41 in these trials (deviations in the order of magnitude of 150 g for both groups).

Comparing the controller as described by Stacey et al. (2002) with the growth control approach in this research, it could be observed that both approaches made use of an adaptive model as a basis for calculating the control actions. The model used in the MPC approach was a very compact recursive linear data-based model (no a priori knowledge needed; Aerts et al., 2003), whereas the model of Stacey et al. (2002) was semimechanistic and thus more complex. The controller of these authors used a genetic algorithm for calculating the optimal control inputs to the growth process. The disadvantages of the genetic algorithm, as indicated by the authors, were its slow working performance (due to iterative processing) and its stochastic nature, meaning that results were not precisely repeatable. In the presented research, the MPC control algorithm made use of a quadratic cost function (equation 2), which had the advantage that its minimum was an explicit function of past inputs and outputs and the target trajectory and could be calculated analytically.

The results of Stacey et al. (2002), as well as the results in the reported research, demonstrate that it is possible to control the growth of broiler chickens by applying modern control theory. To the authors' knowledge, no other examples can be found of this approach applied to birds.

Although the reported results were very promising, some remarks should be made. First of all, because the application of control theory is only possible when continuous process information is available, the accuracy of the sensors and measuring systems used is very important. As observed in the first trial of experiment 3, feeding back inaccurate information on average flock weight resulted in a deviation of the realized growth trajectory from the target growth trajectory.

Secondly, no economic optimization has been done. Because feed accounts for about two-thirds of total broiler production costs, feeding optimization is necessary for successful commercial operation. To this end, least-cost rationing with linear programming models has been widely used to optimize livestock feeding (e.g. Talpaz et al., 1986; Roush et al., 1994). Although the MPC algorithm in this research used only feed quantity as the control input, it could be extended to feed composition, and linear programming routines for calculating least-cost rations over time could be added. With regard to economic aspects, Plavnik and Hurwitz (1985) demonstrated that compensatory growth curves (as in trials 2 and 4) are beneficial not only for the welfare of the birds, but also for the producer since more concave growth curves resulted in better cumulative feed efficiency, due to a reduction in maintenance energy. On the other hand, it must be recognized that the obtained final (mean) slaughter weight of previously restricted broiler chickens is in many cases somewhat lower than that of their ad libitum fed counterparts. Furthermore, the effect of a temporary restriction on abdominal fat content or total body lipid content is highly variable between studies as lower, equal or even higher fat contents were observed in restricted broilers compared to ad libitum fed chickens (e.g., Summers et al., 1990; Deaton, 1995; Lippens et al., 2000).

Finally, it should be noted that there are also constraints in controlling growth trajectories. Birds can be grown following previously defined growth trajectories as long as the target trajectory is biologically feasible. Even realistic target trajectories can be hard to follow as, for example, in the second trial of experiment 4 or in the growth trials of Stacey et al. (2002). This can be caused by several factors, such as quality of the 1-d-old chick, environmental conditions, health problems, feed quality, etc. In the reported research, control was limited to 1 control input, namely, feed quantity. By introducing more control inputs, such as feed composition, feeding frequency, temperature and light schedule, etc., better control performances could be expected, but this would require a more complex process model and control algorithm.

In conclusion, in this research it is demonstrated that the combination of on-line measured weight of broilers during the growth process with compact dynamic data-based models can be used to control growth trajectories by applying modern control theory. The developed control algorithm was able to grow the birds according to different target trajectories ranging from restricted (final BW of 1,800 g and 1,945 g in experiments 1 and 3, respectively) to compensatory growth trajectories (final BW of 2,400 g and 2,100 g in experiments 2 and 4, respectively). The mean relative error (MRE) between the previously target growth trajectories and the realized growth trajectories ranged from 3.7% up to 6.0%. With a few exceptions, the numerical values of feed conversion ratio and mortality after wk 1 were lower and the values of uniformity index were higher in the controlled groups compared with the animals fed ad libitum. The fact that biological systems are much more complex than mechanical systems makes the process control more challenging.

## ACKNOWLEDGMENTS

We wish to thank the Belgian Ministry of Small Enterprises and Agriculture—Research and Development and Fancom b.v. for funding this research.

## REFERENCES

Aerts, J.-M., D. Berckmans, P. Saevels, E. Decuypere, and J. Buyse. 2000. Modeling the static and dynamic response of total heat production of broiler chickens to step changes in air temperature and light intensity. Br. Poult. Sci. 41:651–659.

Aerts, J.-M., M. Lippens, G. De Groote, J. Buyse, E. Decuypere, E. Vranken, and D. Berckmans. 2003. Recursive prediction of broiler growth response to feed intake by using a time-variant parameter estimation method. Poult. Sci. 82:40–49.

Åström, K. J. 1985. Process control—past, present and future. IEEE Control Syst. Mag. 5:3–10.

Auckland, J. N., and T. R. Morris. 1971. Compensatory growth in turkeys: Effect of under-nutrition on subsequent protein requirements. Br. Poult. Sci. 12:41–48.

Bakker, H. K., R. S. Struikenkamp, and G. H. De Vries. 1980. Dynamics of ventilation, heart rate and gas exchange: Sinusoidal and impulse work loads in man. J. Appl. Physiol. 48:289–301.

Berckmans, D., and V. Goedseels. 1986. Development of new control techniques for the heating and ventilation of livestock buildings. J. Agric. Engng. Res. 33:1–12.

Beyerly, T. C. 1967. Efficiency of food conversion. Science 157:890–895.

Blair, R. 1993. Effects of lighting pattern and dietary tryptophan supplementation on growth and mortality in broilers. Poult. Sci. 72:495–502.

Bridges, T. C., R. S. Gates, K. L. Chao, L. W. Turner, and H. Minagawa. 1995. Techniques for development of swine performance response surfaces. Trans. ASAE 38:1505–1511.

Buyse, J., P. C. M. Simons, F. M. G. Boshouwers, and E. Decuypere. 1996. Effect of intermittent lighting, light intensity and source on the performance and welfare of broilers. World's Poult. Sci. J. 52:121–130.

Camacho, E. F., and C. Bordons. 1999. Model Predictive Control. Springer-Verlag, Berlin.

Deaton, J. W. 1995. The effect of early feed restriction on broiler performance. Poult. Sci. 74:1280–1286.

Filmer, D. 2001. Nutritional management of meat poultry. Pages 133–146 in Integrated Management Systems for Livestock. Occasional Publication No. 28. British Society of Animal Science, Edinburgh.

Fitzhugh, H. A. 1976. Analysis of growth curves and strategies for altering shape. J. Anim. Sci. 42:1036–1051.

Golten, J., and A. Verwer. 1991. Control System Design and Simulation. McGraw-Hill, New York

Goodwin, G. C., and K. S. Sin. 1984. Adaptive Filtering, Prediction and Control. Prentice-Hall, New York.

Ingelaat, F. 1997. Nieuwe kostprijsschema's voor de kuikenvleessector. Pluimveehouderij 27:9–11.

Jones, G. P. D., and D. J. Farrell. 1992a. Early life food restriction of chicken: I. Method of application, amino acid supplementation and the age at which restriction should commence. Br. Poult. Sci. 33:579–587.

Jones, G. P. D., and D. J. Farrell. 1992b. Early life food restriction of chicken: II. Effect of food restriction on the development of fat tissue. Br. Poult. Sci. 33:589–601.

Lee, K. H., and S. Leeson. 2001. Performance of broilers fed limited quantities of feed nutrients during seven to fourteen days of age. Poult. Sci. 80:446–454.

Leeson, S., and J. D. Summers. 1988. Some nutritional implications of leg problems with poultry. Br. Vet. J. 144:81–92.

Lippens M., G. Room, G. De Groote, E. Decuypere. 2000. Early and temporary quantitative food restriction of broiler chickens. 1. Effects on performance characteristics, mortality and meat quality. Br. Poult. Sci. 41:343–354.

Ljung, L. 1987. System Identification. Theory for the User. Prentice Hall, New York.

Oltjen, J. W., and F. N. Owens. 1987. Beef cattle food intake and growth: Empirical Bayes derivation of the Kalman filter applied to a nonlinear dynamic model. J. Anim. Sci. 65:1362–1370.

Parkhurst, R. T. 1967. Commercial broiler production. Agricultural Handbook 320. Government Printing Office, Washington, DC.

Petitte, J. N., R. O. Hawes, and R. W. Gerry. 1981. Control of flock uniformity of broiler breeder pullets through segregation according to body-weight. Poult. Sci. 60:2395–2400.

Plavnik, I., and S. Hurwitz. 1985. The performance of broiler chicks during and following a severe food restriction at an early age. Poult. Sci. 64:348–355.

Plavnik, I., and S. Hurwitz. 1988. Early food restriction in male turkeys: Growth pattern, food efficiency, and body composition. Poult. Sci. 67:1407–1413.

Plavnik, I., and S. Hurwitz. 1989. Effect of dietary protein, energy and food pelleting on the response of chicks to early food restriction. Poult. Sci. 68:1118–1125.

Plavnik, I., and S. Hurwitz. 1991. Response of broiler chickens and turkey poults to food restriction of varied severity during early life. Br. Poult. Sci. 32:343–352.

Plavnik, I., J. P. McMurtry, and R. W. Rosebrough. 1986. Effect of early food restriction in broilers. I. Growth performance and carcass composition. Growth 50:68–76.

Roush, W. B., G. F. Barbato, and T. L. Cravener. 1994. A nonlinear dynamical (chaos) approach to the analysis of broiler growth. Poult. Sci. 73:1183–1195.

Roush, W. B., K. Tomiyama, K. H. Garnaoui, T. H. D'Alfonso, and T. L. Cravener. 1992. Kalman filter and an example of its use to detect changes in poultry production responses. Comp. Elect. Agric. 6:347–356.

Soeterboek, A. R. M. 1990. Predictive Control: A Unified Approach. T. U. Delft, Delft.

Stacey, K. F., D. J. Parson, A. R. Frost, C. Fisher, D. Filmer, and A. Fothergill. 2002. The development of an automatic growth and nutrition control system for broiler production. paper no. 02-AP-005 in Proceedings of AgEng2002. European Society of Agricultural Engineers, Silsoe, UK.

Summers, J. D., D. Spratt, and J. L. Atkinson. 1990. Restricted feeding and compensatory growth for broilers. Poult. Sci. 69:1855–1861.

Talpaz, H., J. R. de la Torre, P. J. H. Sharpe, and S. Hurwitz. 1986. Dynamic optimization model for feeding of broilers. Agric. Syst. 20:121–132.

Urdaneta-Rincon, M., and S. Leeson. 2002. Quantitative and qualitative feed restriction on growth characteristics of male broiler chickens. Poult. Sci. 81:679–688.

Xin, H., J. A. DeShazer, J. J. R. Feddes, and K. P. Rajurkar. 1992. Data dependent systems analysis of stochastic swine energetic responses. J. Therm. Biol. 17:225–234.

Young, P. C. 1984. Recursive Estimation and Time Series Analysis: An Introduction. Springer-Verlag, Berlin.

Zhang, X., W. D. Berry, and G. R. McDaniel. 1999. Body weight and semen production of broiler breeders males as influenced by crude protein levels and feeding regimes during rearing. Poult. Sci. 78:190–196.

Zubair, A. K., and S. Leeson. 1994. Effect of varying periods of nutrient restriction on growth performance and carcass characteristics of broiler chickens. Poult. Sci. 73:129–136.

Zubair, A. K., and S. Leeson. 1996. Compensatory growth in the broiler chickens: A review. World's Poult. Sci. J. 52:189–201.