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ORIGINAL ARTICLE

A simulation model for predicting the voluntary feed intake of a growing pig

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Abstract

The main goal of this simulator is to predict voluntary feed intake based on the effects of temperature and stocking density. The model indicates the limiting factors relative to diet (protein, energy or ash), housing environmental conditions and stocking density. The concepts of compensatory protein growth, correction of lipid growth, the desired feed intake to meet energy, protein and ash requirements, and influences of stocking density, genotype and sex are also introduced in this model. This study draws a flow chart and steps to predict feed intake of a growing pig to make it clear how the model works. The model simulates the outcomes of feed intake, energy and protein requirements for maintenance, the energy cost for cold thermogenesis, and protein and lipid retention on a daily basis until slaughter weight. This model was also validated by comparison with published experiments.

Keywords: Growing pig, simulation model, voluntary feed intake.

1. Introduction

Animal growth modelling has become mainstream over the last two decades, and important causal theories of growth have been developed and demonstrated to be useful in practice (Moughan, 2003). The simulation of swine growth for the purpose of predicting pigs' responses to nutrient inputs has progressed significantly since the first conceptual frameworks were published by Whittemore and Fawcett (1976) and Emmans (1981). These simulations were based primarily on empirical equations, but protein and energy utilisation were represented in a conceptual manner. A number of models differing in complexity and application have been reported in the scientific literature; each of these models uses its own description of growth and predictive objectives (Black et al., 1986; Pomar et al., 1991; Ferguson et al., 1994; Birkett & de Lange, 2001; Green & Whittemore, 2003; Wellock et al., 2003a). One proposed model predicted voluntary feed intake (VFI) based on the pig's energy and protein requirements and the composition of the offered diet. The objective of the present study was to integrate the current state of knowledge in a pig growth model to predict VFI, and the aim was to explain the model and the method used to calculate the VFI of a growing pig and make it available as a decision support tool to end-users by online access.

2. Modelling approach

2.1. Body composition and verification of carcass composition at start weight

The chemical composition of the pig's body at the start of the simulation period is calculated from the initial body weight (W₀, kg), assuming that the pig has the desired chemical composition (Wellock et al., 2003a). Body protein mass (PT) and body lipid mass (LT) are key state variables in pig growth models. Empty body weight is defined in the model as the algebraic sum of the main chemical components of the empty animal. These components are the total
body mass of protein (PT), lipid (LT), water (YT) and ash (AT) (de Lange et al., 2003; Schinckel et al., 2008). To predict growth responses and carcass characteristics, PT and LT must be quantitatively related to the chemical and physical body composition (de Lange et al., 2003). In younger pigs at about 20 kg live weight, the ratio of new protein retained to total protein turned over is about 1:5, but for older pigs at 100 kg live weight, this ratio is about 1:8. The total body lipid mass (LT) of a weaning pig is more than 15%, and a thin, weaning pig will usually contain 0.16W of lipid and 0.16W of protein (LT = PT); a LT value of < 0.20W is indicative of a fat pig (Whittemore et al., 1988). A body mass of ash of 0.03W is usually used (Whittemore, 1983). However, AT can be predicted from PT with reasonable accuracy using Ash (kg) = c × PT (kg), in which c varies between 0.186 and 0.210 (≈ 0.20PT) (ARC, 1981; Moughan et al., 1990). Similarly, Kyriazakis and Emmans (1992a) and Kyriazakis and Whittemore (2006) suggested that Ash (kg) = 0.19 × PT (kg), reflecting the close association between bone tissue, which contains most of the body ash, and lean tissue. However, AT can be derived from the chemical analysis of the Barrhill data set (Fisher et al., 2003; Green & Whittemore, 2003; Whittemore et al., 2003) described in Equation 3. The remaining chemical component of the body is water. Kyriazakis and Whittemore (2006) suggested that YT could be determined from the mature total protein mass (PTM) and the total protein mass (PT). The water-to-protein ratio at maturity is near an assumed value of 3.04 kg/kg for all genotypes.

\[
PT = 0.16 \text{W} \\
LT = 0.16 \text{W} \\
AT = 0.216 \text{PT}^{0.94} \\
YT = 3.04 (\text{PTM}^{0.145}) (\text{PT}^{0.855}).
\]

The body composition can be used to verify the present model. The Edinburgh Model Pig version 2 (Roan, 1991) includes scores of fleshiness and fatness. The score of fleshiness (FLS) is used to describe the degree of lean tissue at the start and ranges from 0 (very poorly fleshed) to 10 (very well fleshed). Similarly, the score of fatness (FSC) is used to adjust the lipid mass at the start and ranges from 1 (very thin for weight) to 10 (very fat for weight) (Roan, 1991). The carcass data reported by Tullis (1982) and Henderson (1982) demonstrated that the normal ratio of protein to ash is about 5:1 under non-limiting nutritional conditions, and the ratio of lipid to protein is 1:1 in a well-rounded weaner pig. Consequently, the model assumes that the protein:ash and lipid:protein ratio ranges are 4:1–5:1 and 0.1:1–2:1, respectively, based on the condition of the pig (Whittemore, 1983; Roan, 1991). A FSC of 5.5 represents a well-rounded weaner with a lipid:protein ratio of 1. The FLS is a linear relationship with body protein in the model. The ratio of protein:ash at the start weight (PAR) and the ratio of lipid:protein at the start weight (LPR) can thus be derived. Figure 1 shows the relationships between FLS and the protein:ash ratio and between FSC and the lipid:protein ratio.

\[
PAR = 4 + 0.1 (\text{FLS}). \quad (5)
\]

If FSC is less than 5.5, then

\[
LPR = 0.1 + (1 - 0.1)/(5.5 - 1) \times (\text{FSC} - 1). \quad (6)
\]

If FSC is greater than 5.5, then

\[
LPR = 1 + (2 - 1)/(10 - 5.5) \times (\text{FSC} - 5.5). \quad (7)
\]

To verify whether the present model is working well, Roan (1991) proposed that the carcass inputs should be divided into the initial total protein mass.

![Figure 1. The relationships between the score of fleshiness and the protein:ash ratio and between the score of fatness and the lipid:protein ratio.](image-url)
was in the range of 0.65 proposed by Kyriazakis and Emmans (1992b) and meet the protein requirements of the pig. PEEF was important for predicting the desired feed intake to meet the energy requirements as 0.458W0.75, 0.444W0.75 and 0.470 W0.75 MJ/kg, respectively. The estimated energy efficiency of protein and lipid deposition is affected by the energy requirement for maintenance. Whittemore and Fawcett (1976) proposed that EM be corrected by the energy cost of protein synthesis associated with (minimal) maintenance turnover (0.05PT), which would be accommodated in the growing pig by the estimate of the efficiency of energy conversion into deposited protein (kPr). Thus, EM = 0.475W0.75 – 7.3 (0.05PT). Whittemore (1983) and Whittemore et al. (2001a) proposed that EM may be related to turnover of the protein mass, where PT is the protein mass of the pig, and these reports suggest that there is also some logic in the linear relationship EM = 1.68 + 0.952PT or the fitted curve EM = 1.85PT0.78. Tess et al. (1984) proposed that EM = 1.68PT0.79 for fasting heat production in 17-week-old pigs, and the authors determined compatible values of EM = 2.19PT0.79 by regression. Subsequently, Emmans and Fisher (1986), Roan (1991), Emmans and Kyriazakis (1999), Wellock et al. (2003b) and Kyriazakis and

(PT), the PAR, LPR, PTM and PT to verify carcass composition at the start weight.

\[ \text{AT} = \frac{\text{PT}}{\text{PAR}} \]  
\[ \text{LT} = (\text{LPR}) \times (\text{PT}) \]  
\[ \text{YT} = 3.2(\text{PTM}0.1) \times (\text{PT}0.9). \]

2.2. Carcass composition and live weight after the first day

There is ample evidence showing that as the protein mass increases, the amount of water associated with protein in the lean mass is reduced (Whittemore, 1987). Work of Kotarbinska (1969) cited by Whittemore (1983), body weight and fat are statistically independent, and PT can be used to predict YT and AT with little loss of accuracy. Whittemore (1983, 1987), Henderson (1982) and Roan (1991) suggested that carcass composition and live weight after the first day can be analysed as follows:

\[ \text{PT} = \text{PT} + \text{PR} \]  
\[ \text{LT} = \text{LT} + \text{PT} \]  
\[ \text{AT} = \text{AT} + 0.21\text{PT} \]  
\[ \text{YT} = 4.9\text{PT}0.855 \]  
\[ \text{WE} = \text{PT} + \text{LT} + \text{AT} + \text{YT} \]  
\[ \text{GUT} = 0.05\text{WE} + (0.05\text{WE}) \times (0.008(\text{CF} - 40)) \]  
\[ \text{W} = \text{WE} + \text{GUT}. \]

Gut weight (GUT) represents the difference between empty body weight (WE) and live body weight (BW) and is often assumed to represent a constant 5% of BW (ARC, 1981; Stranks et al., 1988; de Lange et al., 2003). However, findings such as those reported by Lorschy et al. (1997) and Whittemore (1998) indicate that GUT represents close to 9 and 4.5% of the BW in pigs at 20 kg and 100 kg BW, respectively.

2.3. Feed composition

The efficiency of the protein (PEEF) used in feed is important for predicting the desired feed intake to meet the protein requirements of the pig. PEEF was proposed by Kyriazakis and Emmans (1992b) and Gordon (2008); these reports suggested that PEEF was in the range of 0.65–0.90 and PEEF = 0.0112 × (FEEC/DCP), where FEEC is the feed effective energy content (MJ ME/kg feed) and DCP (kg/kg) is the digestible crude protein content of the feed (CP). The feed effective energy content (FEEC) of the diet is the difference between the digestible energy content (DE) of the diet and losses resulting from the ingested diet. Emmans (1994) suggested that FEEC can be calculated as FEEC (kJ/g) = 1.17MEC – 4.2 CP – 2.44, where MEC (kJ/g) is measured at, or corrected to, zero N-retention and CP is the crude protein (N × 6.25) content of the feed. The metabolisable energy content of feed (MEC) was calculated according to Noblet and Perez (1993). The MEC ((MJ/kg of DM) = 0.999 × DE – (0.00343 × DCP)) differs from Emmans (1994); Pomar et al. (2003) and Ferguson (2006) suggested that MEC can be estimated as MEC = DE – (5.63 – DPC). The ideal protein content of feed (FIPC) is derived from DCP and protein value (PV) (Roan, 1991): FIPC = PV × DCP, where PV is calculated from the lowest value in the comparison of the proportion of each individual amino acid in the feed protein with that in the ideal protein (Whittemore, 1987).

Roan (1991) recommended that the DCP be estimated as DCP = DIG × CP, where DIG is the apparent protein digestibility coefficient.

2.4. Desired feed intake to meet energy requirements

The energy requirement for maintenance (EM, MJ ME per day) is usually expressed as a function of live weight to the three-quarter power (W0.75). Because larger animals have a smaller maintenance requirement in relation to body weight, Noblet et al. (1999) suggested that expressing the maintenance requirement as BW0.75 underestimates the requirement for a growing pig. The ARC (1981), the NRC (1998) and Dividich and Se’ve (2001) expressed maintenance requirements as 0.458W0.75, 0.444W0.75 and 0.470 W0.75 MJ/kg, respectively. The estimated energy efficiency of protein and lipid deposition is affected by the energy requirement for maintenance. Whittemore and Fawcett (1976) proposed that EM be corrected by the energy cost of protein synthesis associated with (minimal) maintenance turnover (0.05PT), which would be accommodated in the growing pig by the estimate of the efficiency of energy conversion into deposited protein (kPr). Thus, EM = 0.475W0.75 – 7.3 (0.05PT). Whittemore (1983) and Whittemore et al. (2001a) proposed that EM may be related to turnover of the protein mass, where PT is the protein mass of the pig, and these reports suggest that there is also some logic in the linear relationship EM = 1.68 + 0.952PT or the fitted curve EM = 1.85PT0.78. Tess et al. (1984) proposed that EM = 1.68PT0.79 for fasting heat production in 17-week-old pigs, and the authors determined compatible values of EM = 2.19PT0.79 by regression. Subsequently, Emmans and Fisher (1986), Roan (1991), Emmans and Kyriazakis (1999), Wellock et al. (2003b) and Kyriazakis and
Whittemore (2006) suggested that EM could be calculated from PT and the mature total protein mass (PTM) from \( EM = 1.63^{PTM} - 0.27 \) (PT), where the value of 1.63 is assumed to be constant across animals and diets if the level of physical activity is constant. EM is defined as that needed to maintain zero rates of retention of both protein and lipid. Although physical activity may represent a major source of variation in EM between genotypes (van Milgen et al., 1998), the energy needed for activity is currently included in the estimate for EM as a fixed cost (Wellock et al., 2003b).

During normal growth, the desired protein mass (PTC) of a pig should be about five times that of AT (Tullis, 1982; Kyriazakis et al., 1990; Roan, 1991).

\[
PTC = 5AT.
\]  

(18)

The intrinsic potential for protein deposition (PRM) is assumed to follow the derivative of a Gompertz growth function (Emmans, 1997; Emmans & Kyriazakis, 2001; Pomar et al., 2003; Whittemore et al., 2003; Green & Whittemore, 2005; Kyriazakis & Whittemore, 2006), as described below:

\[
PRM = (B) (PT) \log (PTM/PT). 
\]  

(19)

The PRM is estimated from the parameters B, a growth rate parameter, and PTM, the mature total protein mass; these parameters are assumed to be specific to each pig and based on its current protein weight, as shown in Table I (Kyriazakis & Whittemore, 2006). Values for each parameter range from 0.0095 to 0.0125 for B and from 32.5 to 47.5 for PTM depending on the genotype and sex of the pigs. The PTM is difficult to quantify because few experiments have maintained pigs to their mature size and then determined their protein mass. The available evidence suggests that values for protein mass are between 32.5 and 47.5 kg (Kyriazakis & Whittemore, 2006); the lower value applies to castrates, and the higher value applies to entire males. Different pig genotype and sex can be described in terms of their values for B and for PTM. These two values for B and PTM are pivotal to the protein deposition of pigs. Daily maximum protein retention after compensation (PR1, kg/day) can thus be adjusted by the maximum protein retention (PRM, kg/day), desired protein mass (PTC) and PT. Daily protein retention (PR) must not exceed PR1 (Roan, 1991).

\[
PR1 = PRM + (PTC - PT). \text{ Among (PTC - PT)} \geq 0.
\]  

(20)

The desired lipid mass (LTC) can be calculated from the PTC, PTM, the desired ratio of lipid mass to protein mass at maturity (LPRM) and the scaling of lipid mass to protein mass during potential growth (b); values for LPRM and b are shown in Table II (Roan, 1991; Kyriazakis & Whittemore, 2006). The parameters LPRM and b, which are used to characterise the animal’s genetic potential for lipid growth and the ability to predict VFI, respectively, are important when the relationship between growth potential and feed intake is of interest (Pomar et al., 2003). The pig will take in feed in such a way as to meet the minimum desired lipid mass (LRM) and to increase lipid retention by LTC – LT (Roan, 1991; Kyriazakis & Whittemore, 2006).

\[
LTC = (LPRM) (PTM - b) (PTC(b + 1)) \\
LRC = (LPRM) (b + 1) (PTM/PT)b (PR) \\
LR = LRM + (LTC - LT).
\]  

(21)  

(22)  

(23)

The energy needed above maintenance to allow potential growth to be attained depends on energy cost for protein retention (EPR) and energy cost for lipid retention (ELR). EPR is the value of heat production after catabolism and urinary energy are taken away from the heat of protein combustion. Thus,

\[
EPR = 23.6PR + 31PR = 54.6PR
\]  

(24)

where 23.6 is the protein energy content in the body of the pig (MJ/kg) and 31 is the heat production of

- **Table I.** The values of the growth rate parameter (B) and mature total protein mass (PTM).

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Entire males</th>
<th>Females</th>
<th>Castrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved</td>
<td>47.5</td>
<td>45.0</td>
<td>42.5</td>
</tr>
<tr>
<td>Commercial</td>
<td>42.5</td>
<td>40.0</td>
<td>37.5</td>
</tr>
<tr>
<td>Utility</td>
<td>37.5</td>
<td>35.0</td>
<td>32.5</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved</td>
<td>0.0125</td>
<td>0.0120</td>
<td>0.0115</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.0115</td>
<td>0.0110</td>
<td>0.0105</td>
</tr>
<tr>
<td>Utility</td>
<td>0.0105</td>
<td>0.0100</td>
<td>0.0095</td>
</tr>
</tbody>
</table>

protein synthesis (MJ/kg) (Kyriazakis & Whittemore (2006).

The efficiency of energy conversion into deposited protein (kPr) varies between 0.36 and 0.57 (Tess et al., 1984). Notably, Whittemore (1998) and Kyriazakis and Whittemore (2006) proposed a value of 0.44 for kPr. Using a slightly different approach, Emmans and Kyriazakis (1999) calculated a value of 0.40 for kPr.

The energy cost for lipid retention (ELR, MJ/kg) can be calculated by using a value of 39.3 MJ/kg for the retained lipid energy and a value of 14 MJ/kg for the energy cost of lipid deposition, based on a kLr value of 0.74 (ARC, 1981; Whittemore, 1983) or 0.75 (Kyriazakis & Whittemore, 2006). Fowler (1979) suggested that the efficiency of energy conversion into deposited lipid (kLr) ranged from 0.7 to 0.77. If a significant proportion of the substrate for lipid synthesis is dietary lipid, kLr may be greater than 0.75. One kilogram of LR will contain 39.3 MJ. Most of the work energy associated with lipid retention is caused by the creation and linking together of the appropriate fatty acids, and there is little energy cost for lipid turnover.

\[
ELR = 14LR + 39.3LR = 53.3LR
\] (25)

where 14 is the energy cost for each kilogram of lipid deposited (MJ/kg).

The effective energy requirement (EERQ, MJ/kg) is used to calculate the energy requirement; EERQ can therefore be quantified (Emmans, 1994; Emmans and Kyriazakis 1999; Pomar et al., 2003; Whittemore et al., 2003):

\[
EERQ = EM + EPR + ELR.
\] (26)

The feed intake that allows the requirements for both energy and protein for potential growth to be satisfied is termed the desired feed intake to meet energy requirement (DFIE). DFIE, as proposed by Roan (1991), Pomar et al. (2003), Whittemore et al. (2003) and Sandberg et al. (2006, 2007), is derived from EERQ and FEEC. If energy is the first limiting nutrient, then DFIE will be

\[
DFIE = \frac{EERQ}{FEEC}.
\] (27)

2.5. Desired feed intake to meet protein requirements

When energy is the first limiting nutrient, the desired feed intake to meet protein requirement (DFIP) is estimated from the equation DFIP = IPRQ/FIPC, where IPRQ is the ideal protein requirement and FIPC is the ideal protein content of the feed that is derived from DCP and PV in the equation FIPC = (PV) (DCP) (Roan, 1991; Pomar et al., 2003; Sandberg et al., 2006). IPRQ is quantified by the equation IPRQ = IPM + (PR1/PEFF) (Roan, 1991; Mordenti et al., 2003; Pomar et al., 2003). The ideal protein requirement for maintenance (IPM) is the amount of protein needed to support the obligatory protein losses from the body via urine and the intestine (Whittemore, 1987; Roan, 1991); IPM is calculated from IPM = 0.005 EM. Roan (1991) suggested that IPM was proportional to the energy cost for maintenance (EM) because total ideal protein absorbed (IPT) is partitioned into protein required for IPM and for the ideal requirement for protein retention (IPPR); thus, IPM = 0.005 EM.

2.6. Desired feed intake to meet ash requirements

The body ash is held in fairly strict ratio to protein:ash = 0.20PT, which is not surprising in view of the support role that the skeleton has for the lean tissue mass (Roan, 1991; Kyriazakis & Whittemore, 2006). According to some experiment at the Edinburgh School of Agriculture (Henderson, 1982; Roan, 1991), ash growth is quite stable compared to protein growth in the growing stage. It is expected that ash retention (ARM, kg/day) will reach potential ash retention (ARM, kg/day) with non-limiting ash contents of feed. If bone maintains the normal growth

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Entire males</th>
<th>Females</th>
<th>Castrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPRMa</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Improved</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Commercial</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Utility</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Improved</td>
<td>0.7</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.9</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Utility</td>
<td>0.9</td>
<td>1.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*aRoan (1991); bKyriazakis and Whittemore (2006).*
energy will cause extra lipid retention (LREX, kg/day):\
\[
LRM = LPRM (b + 1) (PT/PTM)b (PR) \\
LR = (FI \times FEEC - 54.6PR - EM)/(39.3 + 14) \\
LREX = LR - LRM. 
\]

2.8. Heat production and heat loss

The physical environment is described by the ambient temperature (Ta), air velocity, floor type and relative humidity. To calculate the effect of the thermal environment on pig performance, heat production (HP, MJ/day) must first be calculated. Additionally, the current climate must be assessed to determine the maximum (HLmax, MJ/day) and minimum (HLmin, MJ/day) heat that the pig may lose to the given environment (Wellock et al., 2004; Kyriazakis & Whittemore, 2006). Intake will be constrained in a hot environment due to an inability to lose the heat that is produced by maintenance and growth to the surrounding environment. In cold environments, an extra thermal demand is placed on the pig. If conditions are thermoneutral, no further action is taken (Wellock et al., 2004). The prevailing temperature as perceived by the pig (Te, effective temperature of the house) may be equal to or different from the Ta. Some housing conditions allow Te to exceed Ta, whereas Ta will fall short of Te in other housing conditions (Whittemore et al., 2001b). The determination of the Te is controversial. Bruce and Clark (1979) are often considered to have written the seminal text on this issue. This text was considered by the ARC (1981) but put aside in favour of using less deductive coefficients accounting for insulation, draughts and bedding. Whittemore (1983, 1998) and Whittemore et al. (2001b) followed the lead of the ARC (1981) by developing the empirical findings of Mount’s Cambridge School as follows:

\[
Te = (Ta) (Ve) (VI), 
\]

where Ta is the ambient temperature, Ve is the score for the rate of air movement and degree of insulation and VI is the floor type in the lying area. Details are given in Table III. Kyriazakis and Whittemore (2006) described the dependence of the comfort temperature (Tc, °C) upon the heat output (H, MJ/day) from the pig’s body, which can be broadly expressed for live weights of 10 kg or more as follows:

\[
Tc = 27 - 0.6H, 
\]

where H expresses the total heat output generated within the pig; H is the sum of the work energy used
for maintenance, the growth of protein and fatty tissues and the production of milk (Whittemore, 1983; Roan, 1991; Kyriazakis & Whittemore, 2006). The comfort temperatures for pigs of different body weights are shown in Table IV.

NRC (1998) first calculated Tc as a function of body weight using the following equation:

\[ Tc = 26 - 0.0614W \]  

(41)

The amount of heat lost (H) by the reference pig, which is also the maximal amount of heat that any simulated pig can produce (Whittemore, 1983; Pomar et al., 2003), is estimated as follows:

\[ H = (\text{MEC}) (FI) - 31PR - 39.3LR. \]  

(42)

Similarly, heat production (HP) is calculated from the maintenance requirements of the pig, the HP associated with protein and lipid retention and the direct heat increment of feeding (Roan, 1991; Wellock et al., 2003a).

\[ HP = (\text{MEC}) (FI) - 23.6PR + 14LR + EM. \]  

(43)

Within this equation, HP is also calculated as the difference between daily energy intake and the amount of energy retained to check the energy balance (Wellock et al., 2003a). At temperatures equal to or above Tc, HP is the same as H. At temperatures below Tc, energy is required for cold thermogenesis and is first diverted from fat growth; energy is then diverted from both fat and lean growth to satisfy this need (Roan, 1991).

Roan (1991) estimated that H is scaled to weight raised to the 0.67 power. Scaled, sensible heat loss

Table IV. Comfort temperature for pigs at different body weights.

<table>
<thead>
<tr>
<th>Live weight of pig</th>
<th>Comfort temperature (Tc) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suckling pigs</td>
<td></td>
</tr>
<tr>
<td>&lt; 2 kg</td>
<td>32</td>
</tr>
<tr>
<td>&lt; 5 kg</td>
<td>28</td>
</tr>
<tr>
<td>Weaner pigs</td>
<td></td>
</tr>
<tr>
<td>&lt; 8 kg</td>
<td>28</td>
</tr>
<tr>
<td>&lt; 10 kg</td>
<td>26</td>
</tr>
<tr>
<td>10–15 kg</td>
<td>22</td>
</tr>
<tr>
<td>Growers</td>
<td></td>
</tr>
<tr>
<td>15–30 kg</td>
<td>20</td>
</tr>
<tr>
<td>30–60 kg</td>
<td>18</td>
</tr>
<tr>
<td>60–120 kg</td>
<td>16</td>
</tr>
<tr>
<td>Finishers</td>
<td></td>
</tr>
<tr>
<td>Feed restricted</td>
<td>18</td>
</tr>
<tr>
<td>In groups on straw</td>
<td>15</td>
</tr>
<tr>
<td>Pregnant sows</td>
<td></td>
</tr>
<tr>
<td>Feed restricted</td>
<td>16</td>
</tr>
<tr>
<td>In groups on straw</td>
<td>18</td>
</tr>
<tr>
<td>Lactating sows</td>
<td></td>
</tr>
</tbody>
</table>
depends only on the effective environmental temperature (T) and increases by 32 kJ/C/day as the temperature falls below 38°C. The minimum and maximum scaled, evaporative heat losses are 350 and 500 kJ/day, respectively. Chen (2004) adjusted maximum scaled evaporative heat loss to 450 kJ/day. The lower (LCT) and upper critical temperatures (UCT) can then be calculated for a pig producing heat at a given rate:

\[
LCT = 38 - \left( \frac{H}{W^{0.67}} - 0.35 \right)/0.032 \quad (44)
\]

\[
UCT = 38 - \left( \frac{H}{W^{0.67}} - 0.50 \right)/0.032. \quad (45)
\]

2.9. Predicted feed intake in the thermoneutral zone

The flow chart of predicted feed intake (Roan, 1991) is shown graphically in Figure 2 to illustrate the relationships among heat loss, PR, LR and VFI. In the thermoneutral zone, HP occurs at a rate that depends primarily on the level of feeding and the live weight of the pig (Holmes & Close, 1977). Therefore, FI is not changed when T is between LCT and UCT.

2.9.1. Predicted feed intake below the lower critical temperature (\(T < LCT\)). When a pig experiences cold temperatures (\(T < LCT\)), the heat flow lost from the body (\(HL_{\text{min}}\)) necessitates an increase in the heat product (HP) to maintain core body temperature (Kyriazakis & Whittemore, 2006).

![Figure 2. The flow chart of predicted voluntary feed intake.](image-url)
Thus, a pig requires more energy for cold thermogenesis, and FI will increase to supply the extra heat (HEXTRA); heat loss at the lower critical temperature (H1) can thus be derived from the equation mentioned above and will reach (Roan, 1991)

\[ H1 = (W0.67) \times (0.35 + 0.32 (38 - Te)) \]  

(46)

HEXTRA = H1 - H.  

(47)

If DFEI exceeds the FI previously calculated, then extra feed intake (FIEX) is needed; this intake can be calculated from MEC.

\[ \text{FIEX} = \frac{\text{HEXTRA}}{\text{MEC}} \]  

(48)

\[ \text{FI} = \text{FI} + \text{FIEX}. \]  

(49)

If FI is greater than DFEI, and the heat from excess lipid (39.3LREX) is greater than HEXTRA, FI and PR are not changed. LR can then be derived from the lipid after supply the extra heat needed.

\[ \text{LR} = \text{LR} - \frac{\text{HEXTRA}}{39.3}. \]  

(50)

If FI > DFIE and 39.3LREX < HEXTRA, the new LR can be derived using the previously determined LREX. The FIEX and new FI are estimated as follows:

\[ \text{LR} = \text{LR} - \text{LREX} \]  

(51)

\[ \text{FIEX} = \frac{\text{HEXTRA} - 39.3\text{LREX}}{\text{MEC}} \]  

(52)

\[ \text{FI} = \text{FI} + \text{FIEX}. \]  

(53)

The FI does not exceed FIM, so FI, PR and LR are not changed, and a new PR is recalculated. Thus,

\[ \text{PR} = (\text{FI} \times \text{FIPC} - \text{IPM}) (\text{PEEF}), \]  

(54)

where PR cannot exceed PR1, and LR can also be calculated as follows:

\[ \text{LR} = (\text{FI} \times \text{MEC} - 31\text{PR} - H1)/39.3. \]  

(55)

2.9.2. Predicted feed intake above the upper critical temperature (T > UCT). At temperatures above the UCT, the pig needs to reduce HP to balance the heat stress and must reduce FI. Thus, heat loss at the upper critical temperature (H2) can be calculated as follows (Roan, 1991):

\[ H2 = (W0.67) \times (0.5 + 0.32 (38 - Te)). \]  

(56)

Heat loss is the same as HP at temperatures equal to or above the LCT. Therefore, FI, PR and LR must be recalculated as follows (Roan, 1991):

\[ \text{FI} = (53.3(H2 - 23.6\text{PR} \]  

- EM) + 14 (EM + 54.6\text{PR})/(53.3 (\text{MEC} - \text{FEEC}) + 14 \text{FEEC}). \]  

(57)

The FI does not exceed FIM, and the new PR can be recalculated in the same manner as for T < LCT, where PR ≤ PR1. When PR > PR1, then PR = PR1, and the new LR can be derived again using the following equation:

\[ \text{LR} = (\text{FI} \times \text{MEC} - 31\text{PR} - H2)/39.3. \]  

(58)

2.10. Stocking density

Pigs are known to grow more slowly as the stocking density increases. Decreasing space allowance (SM) decreases feed intake and growth (Edwards et al., 1988; Gonyou & Stricklin, 1998). The extent may depend on the type of pig. A substantial element of this response is a negative effect on feed intake (Whittemore et al., 2001a). Edwards et al. (1988) and Wellock et al. (2004) suggested that space allowance (SM, m²) equals kW0.67. It is assumed that there is a critical value for SM (SMcrit, m²/BW0.67), below which performance becomes depressed (Wellock et al., 2003a). On the other hand, above SMcrit, SM has no effect on performance. The value assigned to SM is the area required for a pig within range proposed by Wellock et al. (2003a) of 0.035–0.039 m²/BW0.67. Kyriazakis and Whittemore (2006) suggested SMcrit value of 0.032 for the industrial, standard pig house. The k value in this equation is about 0.05 (Edwards et al., 1988; Roan, 1991; Whittemore et al., 2001; Kyriazakis & Whittemore, 2006). This k value results in about 1 m²/100 kg of pig weight in the pen. However, if the pen floor is fully slatted or consists of suspended wire mesh and the house is closely environmentally controlled, this calculated weight may be considered adequate. The model suggests here is to use the SM for optimal feed intake recommended by NRC (1998) to derive a stocking density coefficient (STOC), k value, which is about 0.05.

\[ \text{STOC} = \frac{\text{SM}}{W0.67}. \]  

(59)

At a value of STOC ≥0.05, feed intake is not influenced by the stocking density. If STOC is less than 0.05, the following equation is suggested to adjust for the effect of stocking density:

\[ \text{FI} = \text{FI} (1 + 0.33 \times \log (\text{STOC}/0.05)). \]  

(60)

3. Using the model to predict VFI

The model was set up to run at daily intervals using the list of inputs (Table V) from the starting BW until the target BW was reached. The flow chart of steps used to run the model to predict VFI is shown in Figure 3. This model was designed by adopting the
Microsoft Windows 2003 Server as the operation system and was written with ASP.NET 2.0 (Active Server Pages.NET 2.0) in coordination with a Microsoft Access 2007 Database. The key assumptions in the model are (1) the animal will always aim to achieve its potential growth, (2) VFI will always be sufficient to achieve potential growth within the constraints of gut capacity and heat balance, (3) the animal has free access to a feed that is free of toxins and (4) the animal is in good health and remains free from disease and infection (Wellock et al., 2003a). In order to perform a simulation, an animal profile, a feeding strategy and environment is required. Subsequently, after inputting some

![Image]

**Table V. Model inputs and outputs.**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detail of growing pig</strong></td>
<td><strong>Efficiency report</strong></td>
</tr>
<tr>
<td>Sex</td>
<td>Pig live weight (kg)</td>
</tr>
<tr>
<td>Breed</td>
<td>Feed intake (kg/day)</td>
</tr>
<tr>
<td>Blockiness coefficient (0–1)</td>
<td>Total feed intake (kg)</td>
</tr>
<tr>
<td>Initial weight (kg)</td>
<td>Feed intake plus wastage (kg)</td>
</tr>
<tr>
<td>Final weight (kg)</td>
<td>Daily live weight gain (kg/day)</td>
</tr>
<tr>
<td>Fatness (1–10)</td>
<td>Feed conversion ratio from feed consumed</td>
</tr>
<tr>
<td>Fleshiness (0–10)</td>
<td>Feed conversion ratio from feed used</td>
</tr>
<tr>
<td><strong>Feed details</strong></td>
<td><strong>Biological report</strong></td>
</tr>
<tr>
<td>Crude protein (%)</td>
<td>Energy cost of maintenance (MJ/day)</td>
</tr>
<tr>
<td>Protein digestibility coefficient (0–1)</td>
<td>Energy cost of protein deposition (MJ/day)</td>
</tr>
<tr>
<td>Crude lipid (%)</td>
<td>Energy cost of fat deposition (MJ/day)</td>
</tr>
<tr>
<td>Lipid digestibility coefficient (0–1)</td>
<td>Protein deposition (g/day)</td>
</tr>
<tr>
<td>Crude fibre (%)</td>
<td>Fat deposition (g/day)</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>Ash deposition (g/day)</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>Water deposition (g/day)</td>
</tr>
<tr>
<td>Digestibility energy (kcal)</td>
<td>The energy for cold thermogenesis (MJ)</td>
</tr>
<tr>
<td>Protein value (0–1)</td>
<td></td>
</tr>
<tr>
<td><strong>Housing environment</strong></td>
<td></td>
</tr>
<tr>
<td>Rate of air movement</td>
<td></td>
</tr>
<tr>
<td>Floor type</td>
<td></td>
</tr>
<tr>
<td>Housing temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>Outside temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>Space allowance (m²/head)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.** The flow chart of steps used to run the model to predict voluntary feed intake.
information about growing pigs, feeding regimes, feed details, housing environment, the system was then executed to predict VFI of growing pig and growth performance at each day until feeding age or slaughter weight.

4. Results and discussion

The proposed model predicts VFI based on the animal’s energy and protein requirements and the composition of the offered diet. The model was designed to be flexible, and the effects of genotype, diet and management strategy can be simulated for a wide range of circumstances. A deterministic model based on theoretical concepts and relationships regulating VFI and nutrient partitioning in pigs has been described. This mechanistic approach advances the mathematical representation of VFI, growth and pig body composition, regardless of the animal’s age or physiological status. Because of their universal nature, incorporating these mechanisms should result in accurate simulation of the effects of nutritional, genetic and other factors on VFI. The discussion here will focus on the theory and concepts used in the model.

4.1. Body composition and carcass composition

The four main chemical constituents of the pigs’ empty body weight (WE) at the start weight are PT, LT, AT and YT. These components are calculated from the equations described above. de Lange et al. (2003) described the chemical composition of a WE at 7 kg of BW as having PT 16% and LT 16%, but at 25 kg of BW as having PT 16% and LT 12%, respectively. Correspondingly, Mitchell et al. (2001) analysed pig body composition using magnetic resonance imaging (MRI), and the results revealed that the LT value was lower than the PT value for the pig’s body weight after weaning. Kyriazakis and Whittemore (2006) proposed that LT can be calculated from $LT = LTM \times (PT^d/PTM^b)$, where LTM is the mature total lipid mass (kg), and the value of $d$ is estimated from $1.46 x (LTM/PTM)^{0.23}$ to reflect its strong relationship with mature fatness. Table VI summarises LT values for various genotypes and sexes of pigs.

Ash weight has commonly been described as only depending on protein weight. The value of the constants is agreed to be close to 0.2 in potential growth across pig genotypes. However, even considerable errors in estimating AT have relatively trivial effects on the estimation of body weight (Emmans & Kyriazakis, 1997). Gut weight (Equation 18) is estimated by crude fibre (CF); factors that influence Gut weight include not only diet characteristics (de Lange et al., 2003) but also feeding level and time off feed (Stranks et al., 1988). Fibre intake is likely to mediate the effects of feed intake and diet composition on gut weight (Whittemore, 1998).

Whittemore (1983) proposed that YT depends only on PT (Equation 16) but subsequently described its dependence on both PT and PTM (Roan, 1991; Kyriazakis & Whittemore, 2006) in Equation 7 and Equation 12, respectively. The different equations estimated YT using PT = $0.16W$, PTM = 40 kg and a pig live weight = 8–20 kg. The results presented in Figure 4 shows that the estimated percentage differs from 6 to 21%, and the estimated YT weight differs from 1.04 to 2.16 kg. However, the equations used by Roan (1991) were more accurate than other calculation methods (Figure 4). Moreover, the equation derived from Kyriazakis and Emmans (1992a) proposed that $YT = 5.04PT^{0.855}$ for estimations in female pigs.

4.2. Feed composition

There is a VFI response in pigs to the feed composition. The model considers PV, PEEF and FEFC to calculate chemical growth in the first day. Kyriazakis and Whittemore (2006) suggested that PV usually varies between 0.65–0.85 in a growing pig’s diet. In this model, PV came from the user’s input or was calculated from essential amino acids in the feed and in the ideal protein. According to Roan (1991),

<table>
<thead>
<tr>
<th>Breed Sex</th>
<th>CAstrates</th>
<th>Females</th>
<th>Entire males</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTM$^a$</td>
<td>32.5</td>
<td>35.0</td>
<td>37.5</td>
</tr>
<tr>
<td>LPRM$^b$</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
</tr>
<tr>
<td>LTM</td>
<td>130.0</td>
<td>122.5</td>
<td>112.5</td>
</tr>
<tr>
<td>D</td>
<td>2.008</td>
<td>1.948</td>
<td>1.880</td>
</tr>
<tr>
<td>LT</td>
<td>0.120</td>
<td>0.121</td>
<td>0.124</td>
</tr>
</tbody>
</table>

$^a$Derived from Kyriazakis and Emmans (1992a).

PEEF is a function of the energy:protein ratio of the feed, and \( PEEF = 0.0125 \times (\text{FEEC}/\text{DCP}) \); this calculation contrasts with the equation \( PEEF = 0.0112 \times (\text{FEEC}/\text{DCP}) \) proposed by Kyriazakis and Emmans (1992b), Kyriazakis et al. (1994) and Gordon (2008). Figure 5 shows the simulations that calculated PEEF based on the different PEEF equations, using CP values of 12–24\% and a DE value of 13.5 MJ/kg. The simulations show that higher CP levels always resulted in a lower PEEF value than low CP levels. Furthermore, the differences between the results from the different equations were lower at high CP levels.

Using DE values from 11.5 to 15.0 MJ/kg and a CP value of 18\%, simulation with the different PEEF equations showed that higher levels of DE always resulted in a higher PEEF value, and the different equations from Roan (1991) with Kyriazakis and Emmans (1992a) and Gordon (2008) from 4.0–5.4\% (Figure 6). These PEEF values show that PEEF was not constant at a constant protein intake, and it varied with energy supply (Kyriazakis & Emmans, 1992b).

Not surprisingly, the PEEF value was also increased by high DE levels and low CP levels, which is contrary to the decrease in PEEF value caused by
low DE levels and high CP levels (Figure 7). These PEEF values challenge the assumption that PEEF is constant and independent of the energy supply (Stanks et al., 1988) and that PEEF is only a function of CP intake (ARC, 1981). However, if a calculated PEEF of more than 1 is unreasonable, Roan (1991) suggested that PEEF/C30 0.85 if PEEF/C21 0.85. Kyriazakis and Emmans (1992b) proposed that the value of PEEF is the same for different pig genotypes and for pigs with a given genotype at different stages of maturity, and Kyriazakis et al. (1994) and Kyriazakis and Emmans (1995) agree with this proposal for Large White x Landrace and Chinese Meishan pigs. The value of PEEF was not found to differ between these two very different pig genotypes (Emmans & Kyriazakis, 1997).

4.3. Desired feed intake to meet energy requirements

The energy requirements for maintenance (EM, MJ ME per day) are estimated in the present method based on a live weight of between 8 and 20 kg, PT = 0.16W and PTM = 40 (Table I). As illustrated in Figure 8, the EM values for the different equation methods and parameters vary, and different equations vary widely in their energy maintenance requirements; thus, assuming a constant requirement is not reasonable in reality. Furthermore, EM values calculated by Emmans and Fisher (1986) are lower than those calculated by other equations due to the fact that calculations are based on PT and PTM instead of only PT.

4.4. Desired feed intake to meet protein requirements

Kyriazakis and Whittemore (2006) proposed that IPM could be calculated on the basis of metabolic body weight (IPM = 0.0013W0.75) rather than on the basis of PT (Whittemore, 1987; Wellock et al., 2003b) or EM (Roan, 1991) values. Figure 9 shows...
IPM simulations estimated from metabolic body weight and PT; there is a value in the vicinity of IPM more than EM. Moreover, the value of IPM using the EM value derived by Emmans and Fisher (1986) was lower than the value of IPM estimated using the EM value derived by Tess et al. (1984).

4.5. Maximum feed intake

Roan (1991) suggested that FIM could be evaluated based on FOMC and PT (Equation 43). Consequently, Whittemore (1998) explored the influence of the digestibility coefficient and pig weight: FIM = 0.013W/(1 – DIG). The value 0.013W is derived from an estimate of the FOMC by pigs (Whittemore et al., 2001b). Ferguson et al. (1994) concluded that FIM is constrained by PT and BULKDN: FIM = 0.09 (PT/BULKDN), where BULKDN is the feed bulk; BULKDN is the estimated content of indigestible organic matter in the feed and is therefore rather similar to (1 – DIG), and 0.09PT is similar to the 0.013W value. Moreover, in this model, the scale of the feed bulk is the water-holding capacity (WHC) devised by Kyriazakis and Emmans (1995), so the FIM = (0.23W + 0.000476W²)/WHC. Further evidence in Tsaras et al. (1998) suggested that WHC can adequately describe the bulkiness of fibrous feeds: FIM = 207(1/WHC). The latter FIM cloud is estimated based on the metabolic body weight:
FIM $= 0.1W^{0.75}$ (Kyriazakis & Whittemore, 2006). However, the BULKDN used by Ferguson et al. (1994) may have more general value than that used by Tsaras et al. (1998). If a wider range of pig sizes is needed to test the different scaling rules that have been proposed, the use of PT may be preferable to that of live weight. Pigs at the same PT but with different live weights will differ mainly in their lipid weight (Tsaras et al., 1998). The model simulations for estimated FIM are shown in Figure 10 for different equations. FIM was estimated to have large differences for live weights of female pigs between 8 and 20 kg, a CP value of 18%, a DE value of 3,150 kcal/kg and a DIG value of 0.8.

4.6. Predicted feed intake relative to temperature and stocking density

At the lower critical temperature, Roan (1991) suggests that the energy cost could be derived from the pig surface area ($W^{0.67}$), as shown in Equation 54; however, this calculation is inconsistent with those of the ARC (1981), Noblet et al. (1985), the NRC (1998) and Kyriazakis and Whittemore (2006) in demonstrating the increase in heat production (Table VII). Earlier work by the ARC (1981) showed that the choice of $W$ to the first power and the separation between individuals and groups reflect greater possibilities for the latter to make behavioural adaptations. Whittemore et al. (2001b) suggested that the values for individual pigs may be more appropriate for the factorial determination of energy requirements, even for pigs kept in groups. Roan (1991) used temperatures below 38°C to estimate the increase in heat production, and another model suggested the use of $Tc$ to make this prediction. Substantial stocking density values have a negative effect on FI. A change in the $k$ value of 0.05 below optimum is associated with a 4% change in FI (Whittemore & Green, 2001) or 8% for every 0.01 unit of change in $k$. Conversely, increasing the $k$ value of stocking density from 0.31$W^{0.66}$ to 0.48$W^{0.66}$ was associated with a 10% increase in FI (Kyriazakis & Whittemore, 2006).

Table VII. The heat loss at the lower critical temperature from different sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC (1981)</td>
<td>$H_1 = (0.00131W + 0.0953) (Tc – Te)$</td>
</tr>
<tr>
<td>Noblet et al. (1985)</td>
<td>$H_1 = (0.0155) - (0.0189 W^{0.75}) (Tc – Te)$</td>
</tr>
<tr>
<td>Roan (1991)</td>
<td>$H_1 = (W^{0.67}) (0.35 + 0.32 (38 – Te))$</td>
</tr>
<tr>
<td>NRC (1998)</td>
<td>$H_1 = (0.313 W + 22.71) (Tc – Te)$</td>
</tr>
<tr>
<td>Kyriazakis and Whittemore (2006)</td>
<td>$H_1 = (0.012 W^{0.73}) (Tc – Te)$</td>
</tr>
</tbody>
</table>

References

Agricultural Research Council (1981). The Nutrient Requirements of Pigs (Farnham Royal, Common wealth Agricultural Bureaux).


Appendix 1. List of symbols used in the text.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Meanings</th>
<th>Symbols</th>
<th>Meanings</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.63</td>
<td>The urinary energy of catabolised protein (MJ/kg)</td>
<td>FLS</td>
<td>The score of fleshiness</td>
</tr>
<tr>
<td>14</td>
<td>The energy cost of lipid retention (MJ/kg)</td>
<td>FSC</td>
<td>The score of fatness</td>
</tr>
<tr>
<td>23.8</td>
<td>The heat of combustion of protein (MJ/kg)</td>
<td>FOMC</td>
<td>Faecal organic matter contents (kg/kg)</td>
</tr>
<tr>
<td>39.3</td>
<td>The energy retained in lipid (MJ/kg)</td>
<td>GUT</td>
<td>Gut weight (kg)</td>
</tr>
<tr>
<td>53.3</td>
<td>Total energy of lipid deposition (MJ/kg)</td>
<td>H</td>
<td>Heat loss (MJ/day)</td>
</tr>
<tr>
<td>AR</td>
<td>The daily rate of ash retention (kg/day)</td>
<td>H1</td>
<td>The heat loss at the lower critical temperature (MJ/day)</td>
</tr>
<tr>
<td>ARM</td>
<td>Maximum ash retention (kg/day)</td>
<td>H2</td>
<td>The heat loss at the upper critical temperature (MJ/day)</td>
</tr>
<tr>
<td>ASH</td>
<td>Feed ash content (kg/kg)</td>
<td>HEXTRA</td>
<td>Extra heat needed (MJ/day)</td>
</tr>
<tr>
<td>AT</td>
<td>The total ash mass (kg)</td>
<td>HP</td>
<td>Heat production (MJ/day)</td>
</tr>
<tr>
<td>B</td>
<td>Scaling of lipid mass to protein mass during potential growth</td>
<td>IAM</td>
<td>Ideal ash requirement for maintenance (kg/day)</td>
</tr>
<tr>
<td>B</td>
<td>Growth rate parameter</td>
<td>IARQ</td>
<td>Ideal ash requirement (kg/day)</td>
</tr>
<tr>
<td>BW</td>
<td>Initial body weight (kg)</td>
<td>IPM</td>
<td>Ideal protein requirement for maintenance (kg/day)</td>
</tr>
<tr>
<td>CF</td>
<td>Crude fibre contents of the feed (kg/kg)</td>
<td>IPRQ</td>
<td>Ideal protein requirement (kg/day)</td>
</tr>
<tr>
<td>CL</td>
<td>Crude lipid content of the feed (kg/kg)</td>
<td>LCT</td>
<td>Lower critical temperature (°C)</td>
</tr>
<tr>
<td>CP</td>
<td>Crude protein content of the feed (kg/kg)</td>
<td>LDIG</td>
<td>Digestibility of the crude lipid of the feed (%)</td>
</tr>
<tr>
<td>DAC</td>
<td>Digested ash contents of the feed (kg/kg)</td>
<td>LPR</td>
<td>The ratio of lipid to protein</td>
</tr>
<tr>
<td>DCHO</td>
<td>Digested carbohydrate contents of the feed (kg/kg)</td>
<td>LPRM</td>
<td>Values for the desired lipid mass to protein mass</td>
</tr>
<tr>
<td>DCL</td>
<td>Digested crude lipid contents of the feed (kg/kg)</td>
<td>LR</td>
<td>The daily rate of lipid retention (kg/day)</td>
</tr>
<tr>
<td>DCP</td>
<td>Digested crude protein contents of the feed (kg/kg)</td>
<td>LRM</td>
<td>Minimum desired lipid retention (kg/day)</td>
</tr>
<tr>
<td>DE</td>
<td>Digestible energy contents of the feed (MJ/kg)</td>
<td>LREX</td>
<td>Extra lipid retention (kg/day)</td>
</tr>
<tr>
<td>DFIA</td>
<td>Desired feed intake to meet ash requirement (kg/day)</td>
<td>LTM</td>
<td>The total lipid mass (kg)</td>
</tr>
<tr>
<td>DFIE</td>
<td>Desired feed intake to meet energy requirement (kg/day)</td>
<td>LTC</td>
<td>The desired lipid mass (kg)</td>
</tr>
<tr>
<td>DFIP</td>
<td>Desired feed intake to meet protein requirement (kg/day)</td>
<td>ME</td>
<td>The energy requirement for maintenance (MJ/kg)</td>
</tr>
<tr>
<td>DIG</td>
<td>Digestibility of the crude protein of the feed</td>
<td>MEC</td>
<td>Metabolisable energy contents of the feed (MJ/kg)</td>
</tr>
<tr>
<td>EERQ</td>
<td>Effective energy requirement (MJ/day)</td>
<td>OMC</td>
<td>Organic matter contents of the feed (kg/kg)</td>
</tr>
<tr>
<td>EH1</td>
<td>The energy cost for cold thermogenesis (MJ/day)</td>
<td>PAR</td>
<td>The ratio of protein to ash at start weight</td>
</tr>
<tr>
<td>EM</td>
<td>Energy requirement for maintenance (MJ/day)</td>
<td>PEEF</td>
<td>The efficiency of use of protein</td>
</tr>
<tr>
<td>EPR</td>
<td>The energy requirement for protein retention (MJ/day)</td>
<td>PR</td>
<td>The daily protein retention of the pig (kg/day)</td>
</tr>
<tr>
<td>FEEC</td>
<td>Feed effective energy contents (MJ/kg)</td>
<td>PRM</td>
<td>Maximum protein retention (kg/day)</td>
</tr>
<tr>
<td>FI</td>
<td>Feed intake (kg/day)</td>
<td>PT</td>
<td>The total protein mass (kg)</td>
</tr>
<tr>
<td>FIEX</td>
<td>Extra feed intake (kg/kg)</td>
<td>PTC</td>
<td>The desired protein mass (kg)</td>
</tr>
<tr>
<td>FIPC</td>
<td>Ideal protein contents of the feed (kg/kg)</td>
<td>PTM</td>
<td>The mature total protein mass (kg)</td>
</tr>
<tr>
<td>FIM</td>
<td>Maximum feed intake (kg/day)</td>
<td>PV</td>
<td>Protein value</td>
</tr>
</tbody>
</table>

Symbols

SM Space allowance (m²/pig)

STOC Stocking density coefficient

Th Ambient temperature (°C)

Tc Comfort temperature (°C)

Tr Effective temperature of the house

UCT Upper critical temperature (°C)

Ve Score for rate of air movement and degree of insulation

VFI Voluntary feed intake (kg/day)

VI Score for floor type in lying area

W Live weight (kg)

W₀ Initial body weight

YT The total water mass (kg)
Appendix 2. Steps of using the model to predict voluntary feed intake

Step 1: Definition of the internal environment
1. Sex: entire male, female, castrate, both entire male and female or mixed castrate and female
2. Pig type: improved, commercial, utility
3. Initial weight
4. Blockiness coefficient: (0–1)
5. Condition of pig at start: score of fatness and fleshiness
6. Composition at start

   \[
   \begin{align*}
   PT &= 0.16W \\
   AT &= PT/PAR \\
   LT &= (LPR) \times (PT) \\
   YT &= 3.04 (PTM^{0.145}) (PT^{0.855}) \\
   WE &= PT + LT + AT + YT \\
   GUT &= 0.05WE + (0.05WE) \times (0.008(CF - 40)) \\
   W &= WE + GUT
   \end{align*}
   \]

   If the calculated start weight was less than the expected start weight, the model increased the weight by 0.02 kg of protein mass and recalculated AT, LT, YT and GUT. Otherwise, if the calculated start weight was 0.3 kg greater than the expected start weight, the model decreased the weight by 0.02 kg of protein mass to readjust the start weight.

Step 2: Definition of the nutritional environment
1. Feed: setup feed detail
2. DE = MEC + 5.63DCP or as input
3. Feed composition:

   \[
   \begin{align*}
   DCP &= (DIG) (CP) \\
   FIPC &= (PV) (DCP) \\
   DCL &= (LDIG) (CL) \\
   MEC &= (DE) - 5.63DCP \\
   DCHO &= (MEC - 18.17DCP - 39.3DCL)/17.2 \\
   OMC &= 1 - (ASH + WATER) \\
   FOMC &= OMC - (DCP + DCL + DCHO) \\
   FEEC &= 1.17MEC - 4.2CP - 2.44 \\
   PEEF &= 0.0112 \times (FEEC/DCP)
   \end{align*}
   \]

4. Maximum feed intake (FIM)

   \[
   \text{FIM} = 0.075PT/FOMC
   \]

Step 3: Definition of the non-nutritional environment
1. Temperature

   \[
   T = (Ta) (Ve) (Vi)
   \]

   (Table III)

Step 4: Calculation of chemical growth in the first day
1. Estimation of the possibility for PR

   \[
   \begin{align*}
   \text{PRM} &= (B) (PT) \log (PTM/PT) \\
   \text{PCT} &= 3AT \\
   \text{PR1} &= \text{PRM} + (PTC - PT) \\
   \text{IPM} &= 0.005EM
   \end{align*}
   \]

   \[
   \text{PR} = (FI \times FIPC - IPM) (PEEF) \text{where PR} \leq \text{PR1}
   \]

2. Estimation of the possibility for AR

   \[
   \begin{align*}
   \text{ARM} &= (B) (AT) \log (0.2PTM/AT) \\
   \text{DAC} &= 0.7\text{ASH} \\
   \text{FIAC} &= 0.8\text{DAC} \\
   \text{IAM} &= 0.001EM \\
   \text{AR} &= 0.8 (FI \times \text{FIAC} - \text{IAM}) \text{where AR} \leq \text{ARM}
   \end{align*}
   \]

3. Definition of energy requirements for maintenance (EM)

   \[
   \text{EM} = (1.63PTM^{0.27}) (PT)
   \]

4. Definition of energy requirements for protein retention (EPR)

   \[
   \text{EPR} = 54.6PR
   \]

5. Definition of energy requirements for lipid retention (ELR)

   \[
   \text{ELR} = (FI) (FEEC) = (EPR + EM + EH1)
   \]

6. Estimation of the possibility for lipid retention (LR)

   \[
   \text{If} \ ELR < 0, \ \text{then} \ LR = ELR/39.3 \ \text{else} \ LR = ELR/(14 + 39.3).
   \]

7. Definition of energy requirements for cold thermogenesis (EH1)

   \[
   \begin{align*}
   H &= (MEC) (FI) - (31PR + 39.3LR) \\
   \text{HW1} &= H^{0.67} \\
   \text{HEXTRA} &= H1 - H \\
   \text{LCT} &= 38 - ((H/W^{0.67}) - 0.35)/0.032 \\
   \text{UCT} &= 38 - ((H/W^{0.67}) - 0.50)/0.032 \\
   \text{H1} &= (W^{0.67}) (0.35 + 0.032 (38 - T)) \\
   \text{EH1} &= H1 - H
   \end{align*}
   \]

   If EH1 > 0, then LR is diminished to provide the required energy.

Step 5: Estimation of new values for body composition at the end of the first day

   \[
   \begin{align*}
   PT &= PT + PR \\
   LT &= LT + LR \\
   AT &= AT + AR \\
   YT &= 3.2(PTM^{0.1}) (PT^{0.6}) \\
   WE &= PT + LT + AT + YT \\
   GUT &= 0.05WE + (0.05WE) (0.008(CF - 40)) \\
   W &= WE + GUT
   \end{align*}
   \]

Step 6: Assignment of new values
1. Values originally assigned in Step 1 updated according to the current values found at Step 5.
2. Return to Step 3.
3. Continue until \( W \geq \text{intended slaughter weight.} \)