Modelling the lysine requirements of weaned piglets

J.H.M. Rijpert, H. Nguyen Ba, S. Goethals, S. Millet, P. Bikker

Public
Report 1455

WAGENINGEN
UNIVERSITY & RESEARCH

Modelling the lysine requirements of weaned piglets

J.H.M. Rijpert[1], H. Nguyen Ba[1], S. Goethals[2], S. Millet[2], P. Bikker[1]

1 Wageningen Livestock Research, PO BOX 338, 6700 AH Wageningen, the Netherlands

2 Animal Sciences Unit, Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Scheldeweg 68, 9090 Melle, Belgium

This research was carried out by Wageningen Livestock Research and subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality, within the framework of Policy Support Research theme 'Name of Theme' (project number LWV20.189).

Wageningen Livestock Research
Wageningen, November 2023

Report 1455

Rijpert, J.H.M., Nguyen Ba, H., Goethals, S., Millet, S., Bikker, P., 2022. *Modelling the lysine requirements of weaned piglets.* Wageningen Livestock Research, Public Report 1455.

Summary
In the Benelux, amino acid requirements for weaned piglets are based on over twenty years old experiments; these were recalculated last year by the Centraal Veevoederbureau (CVB, Central Bureau for Livestock Feeding) to a standardized basis. To provide up-to-date recommendations, a factorial growth model has been constructed to estimate the SID lysine requirements of nursery piglets. This report elucidates the construction, calibration and validation of this model.

This report can be downloaded for free at https://doi.org/10.18174/641741 or at www.wur.nl/livestock-research (under Wageningen Livestock Research publications).

Public Wageningen Livestock Research Report 1455

Table of contents

Foreword

The research ‘Modelling the lysine requirements of weaned piglets’ was conducted by a collaboration of Wageningen Livestock Research, ILVO (Instituut voor Landbouw-, Visserij- en Voedingsonderzoek) and the Centraal Veevoeder Bureau as part of the Public Private Partnership “Voeding op Maat”. This project was funded by the members of the CVB and the Dutch Ministry of Agriculture, Nature and Food Quality. The authors thank members of the *ad hoc* committee and the technical committee of CVB for their support.

The authors:
Jordi Rijpert, Hieu Nguyen Ba, Sophie Goethals, Sam Millet and Paul Bikker

Summary

The essential amino acid lysine is of crucial importance to the growth and development of nursery piglets. Despite this, present recommendations on the lysine requirements for weaned piglets by the CVB are based on experiments conducted generally over 20 years ago and therefore required re-evaluation and, where necessary, actualisation. This was addressed using two methods. A literature review was conducted to derive lysine requirements from recent response studies in weaned pigs. The results are published in a separate report. Since static recommendations apply to standard animals and conditions, these cannot take into account potential variation in animal and farm characteristics. Therefore, it was considered valuable to additionally develop a model to calculate lysine requirements, allowing for variation in feed intake and growth capacity of the pigs and farm conditions that affect energy expenditure. In a combined effort, we have constructed a spreadsheet model that calculates the lysine requirements of weaned piglets based on physiological assumptions and related animal factors.

The aim of developing this model was to provide a decision support tool, able to calculate the standardized ileal digestibility (SID) lysine requirements of weaned piglets. It was decided to build this model since no publicly available model for weaned pigs has been described in literature. To this end, existing growth models for pigs (TMV, INRAPorc) were evaluated and assumptions and calculations were adapted to be representative for piglets in the 5-30 kg body weight range. These adaptations include (1) re-parameterisation of the model, (2) extending the description of the feed intake to represent low feed intake in the first days post-weaning and (3) developing assumptions and a description for protein- and lipid deposition at energy intakes below maintenance.

The model has been designed as a spreadsheet model in which input parameters are based on estimations obtained from literature. These parameters include the initial weight and body composition of the piglet, amount of feed intake and energy content of the diet, and a set describing physiological parameters and energetic efficiencies. Default values of input parameters are individually adaptable to suit specific situations. Based on the input and model parameters, protein and lipid deposition and body gain are calculated on a daily basis, assuming that amino acid supply is not limiting tissue deposition. Model output includes the change in body weight and body composition, daily SID lysine requirements, and derived parameters from the aforementioned outputs, such as the feed conversion- or gain to feed ratio. Validation of the model, using literature observations, indicate that it is capable of predicting the SID lysine requirement of piglets reasonably well when the model is parameterised to a specific case scenario.

1 Introduction

The amino acid lysine is a reference amino acid in modern, low crude protein feed formulations for weaned piglets. Lysine deficiency is correlated to impaired physiological performance in piglets, e.g. growth retardation or an increased chance of post-weaning diarrhoea (Yu et al., 2019). Inversely, excess intake of amino acids is linked to increased nitrogen excretion, negatively impacting the environment (Mallin and Cahoon, 2003). Despite its importance, CVB amino acid recommendations for weaned piglets have not been updated since 1996 (CVB Documentation report nr. 14, 1996). In addition, lysine requirements for weaned piglets may have increased with the continuous development of modern pig genotypes, which grow significantly faster and leaner than earlier generations of weaner pigs. An evaluation of the lysine requirements for weaned piglets provides options for further optimization of supplemental lysine in pig feed formulations. This also allows an update of the requirements to be based on the currently-used standardized ileal digestibility (SID), compared to the previously-used apparent ileal digestibility. To achieve the goal of consequent update of recommendations, two studies were conducted in parallel: (1) an empirical study evaluating dose response studies of amino acids in diets for weaned piglets, described in a companioning report (Goethals et al., 2023), and (2) the development of a factorial growth model to calculate lysine requirements of weaned piglets based on their feed intake and subsequent growth.

This report describes the model we constructed to estimate the lysine requirement of weaned piglets in relation to animal factors. A number of factorial growth models for growing-finishing pigs have previously been developed, e.g. TMV (Van der Peet – Schwering et al., 1994) and INRAPorc (Van Milgen et al., 2008). The strength of this type of model is that it can act as decision support tool for a wide range of pig genotypes and feed intake patterns. To the best of our knowledge, no growth models for weaned piglets have been published. As such, the model described here uses a similar approach as these previous models for growing-finishing pigs, while adapting them to be representative for nursery piglets in the body weight range of 5 to 30 kg (i.e. in the first period post-weaning).

Early post-weaning is a stressful period for nursery piglets as they adapt to their new housing conditions and the switch to solid feed (Blavi et al., 2021). Feed refusal is commonly observed in the first few days post-weaning and has major consequences on the growth and body composition of the piglets. As energy intake is very low in the first days, body fat mobilization is needed to overcome this energetic deficiency. In addition, observations from Whittemore et al. (1978) indicate that body protein does not suffer this same decrease and stays relatively preserved at the expense of lipid tissue. These factors play a significant role in the total daily lysine requirement; previous growth models of pigs did not take these into account, as they did not aim to model pig growth during low energy conditions. The model described in this report is specifically adapted to estimate animal factors during these early post-weaning days, and is subsequently capable of estimating SID lysine requirements of weaned piglets.

In this report, the theoretical framework, assumptions and calibrations needed to construct the model are described (chapter 2). The predictive capability of the model is validated in chapter 3. Finally, a number of standardized situations are used as model input and its respective outputs are given and discussed in chapter 4.

2 Model description and calibration

The model runs on a daily basis and requires an input of the starting weight and body composition of the piglet, the amount and extent of its feed intake, and a set of physiological parameters to further describe the piglet genotype. The estimation of daily SID lysine requirements is based on (1) protein tissue deposition, (2) basal endogenous losses, (3) losses via integument and basal turnover and (4) inevitable oxidative losses. In turn, these factors are based on an underlying factorial growth model where energy intake, maintenance, retention (in body lipid and protein) and efficiency of energy utilization are key parameters.

2.1 Structure and scope of the model

This model is developed to simulate the growth performance of weaned pigs based on feed consumption as specified by the user, assuming a non-limiting amino acid supply, and to subsequently calculate the dietary lysine contents required to realise the potential of growth associated with the feed and energy intake. Growth, body composition and lysine requirements of weaned piglets depend on a wide range of factors. This model was designed to simulate an individual healthy piglet (or a group of uniform piglets) housed in neutral climate conditions and is calibrated in a body weight range from 5 kg up to 30 kg. Feed intake is simplified to a daily amount of feed, reflecting an ideal mixture to simulate the daily energy intake, indicating that the model does not account for a lack of macro- and/or micronutrients, nor any amino acid imbalance. The maximum duration of a single complete simulation is seventy days.

Maintenance energy requirement of the piglet is derived from its body weight, and energy above maintenance is used for daily protein- and/or lipid accretion, which are partitioned using the ‘marginal ratio’ concept, as explained in paragraph 2.5. Protein-, fat-, water- and ash deposition are simulated daily based on their starting value and their rate of change.

These data allow to calculate the most important output parameters, which are (1) total weight change and body composition, (2) feed conversion ratio (FCR) / or gain to feed (G:F) ratio and (3) daily lysine requirements.

2.2 Initial body composition of piglets

The calculation of nutrient requirements and tissue deposition makes use of the initial body composition of piglets at weaning as a starting point. The initial body composition of the piglets can be provided as input by the user, or default parameters can be used. For the latter, we used carcass composition data from healthy pigs of a modern genotype (Piétrain boar × hybrid sow) weighing 7.6-7.9kg (Table 1; Warnants et al., 2006). Empty body weight (EB) of piglets (25 days of age) is assumed to be 95% of live weight, based on observations from Jones et al. (2012). We assumed these piglets to be representative of the breeds used in Dutch and Belgian farms. However, different genotypes may have slightly different body compositions at the same weight, where e.g. Danish pigs in the study of Hojgaard et al. (2020) had slightly more protein and fat (15.9±0.44% and 12.3±1.8% of EB, respectively).

Table 1 *Characteristics of piglets (Piétrain x hybrid), derived from Jones et al. (2012) and Warnants et al. (2006) and used as default initial body composition in the model.*

Characteristic	Mean (%)
Empty body weight	95.0
Fat (in EB)	10.5
Protein (in EB)	15.5
Ash (in EB)	2.9
Water (EB)	71.1

2.3 Feed intake

In the model, the daily feed consumption is an input factor to be provided by the user of the model. The minimum information is the total feed supply across the total period. The user can specify the feed allowance in shorter periods, e.g. on a weekly basis, with a maximum of five periods. This information is used to derive the feed intake on a daily basis for the calculation of protein and lipid deposition. Daily feed consumption of early post-weaning piglets is highly variable, due to the stress induced by the abrupt transition to solid feed, as well as the sudden change in housing situation and other factors related to the process of weaning (Blavi et al., 2021). In the following section, the assumptions made to attenuate some of this variance are presented, followed by the mathematical derivation of the daily feed intake function used during the simulation.

Feed acceptance on the first day post-weaning has a large impact on the described variance. Voluntary feed intake of weaner pigs has been found to range from absolute feed refusal to 150 g feed on the first day (Whittemore & Green, 2001). In their review, Blavi et al. (2021) reported that the most significant factor that influences this day-one feed intake is whether the piglets had received and ingested creep feed before weaning. Piglets that consumed creep feed during the suckling period have a significantly higher initial post-weaning feed intake than piglets that refused creep feed in earlier stages (deemed eaters and non-eaters, respectively). However, only between 40% and 60% of piglets voluntarily ingest creep-feed during lactation (Brooks et al., 2003; Sulabo et al., 2010). Hence, this aspect is not included in the model. Other factors influencing day-one feed intake were also assumed to be outside the scope of this model; these factors include gender (Bruininx et al., 2004), the amount of creep-feed consumed during lactation (Carstensen et al., 2005), feed composition (Whittemore & Green, 2001) and the use of milk replacer instead of creep feed to alleviate the abrupt dietary change (Blavi et al., 2021).

Combining results from Bruininx et al. (2002, 2004), Carstensen et al. (2005) and Sulabo et al. (2010), a linear increase in daily feed intake post-weaning was observed (Figure 1). Extrapolating to day 1 resulted in an initial feed intake of 66 g/day for eaters and 31 g/day for non-eaters. Since generally no information is available on the creep feed intake of piglets before weaning when using the model, we assumed that the average of these values is applicable to both types of piglet, resulting in the value used in the model for day-one feed intake being 48 g/day.

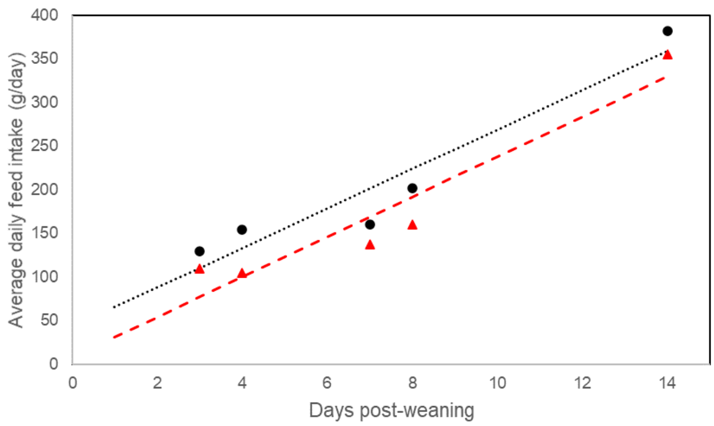

Figure 1 *Average daily feed intake of eater (··•··) and non-eater (--▲--) piglets (male/female combined) in the first two weeks post-weaning. Linear regression with R^2 = 0.916 and 0.913 for eaters and non-eaters, respectively.*

Alternatively, the user may decide to start the simulation a few days after weaning rather than immediately at weaning. The model is able to take an initial adaptation period of up to seven days into account, where the starting point of the simulation is taken as the first day after this user defined period. If applied, the initial feed intake increases linearly in respect to the length of the adaptation in days (Table 2), to account for the increased familiarity and acceptance of the piglets to their new feed. Using this option will only affect the initial feed intake used in the model calculations; other input parameters will still be used to describe a piglet at t=0 days (i.e. the first day after the adaptation period).

Table 2 *Initial feed intake as a function of the day after weaning that is chosen by the user as first day of the simulation period.*

Adaptation period length (d)	Initial feed intake (g/d)
1	71
2	94
3	117
4	140
5	162
6	185
7	208

Average feed consumption of postweaning piglets increases linearly during the first two weeks post-weaning, independent of the day-one feed intake itself (Bruininx et al., 2002). We assumed that this linear increase can be extrapolated for the entire nursery period until 30 kg of body weight. This is a slight deviation from previous suggestions for the development of feed intake, which proposed a curvilinear response (Cole et al., 1967; Whittemore, 1983). However, linear regression of the data of these studies showed that the curvilinear trends can be accurately described by a linear relation in the weight range of 5-30 kg (R^2 = 0.998, data not shown).

In the model, feed intake is provided as an input by the user, described by the total amount of feed supplied over a given period (in days) or in multiple shorter periods, e.g. weekly. These parameters, combined with the initial daily feed intake, are used to establish a discrete linear relationship over the time period(s) to give an estimate of the daily feed intake, which is subsequently used to obtain the total daily energy intake available for tissue deposition on each day of the simulated period.

Mathematically, the feed intake is described as

$$FI_{total} = (1 - FI_{spilled})\sum_{i=1}^{n}(ai + b) \tag{1}$$

where FI_{total} is the total feed intake [kg] over an input period, $FI_{spilled}$ is the fraction of the total feed intake that is spilled, n is the length of the input period in days, a is the daily increment to the feed intake [kg] and b is the feed intake [kg] on the first day of the period. Values for FI_{total}, $FI_{spilled}$ and n are presented as input, the value of b is obtained either as input or from Table 2 (when an adaptation period is included) or derived from the other input parameters and the value of a is derived from the other parameters. To derive these values, the model uses a set of mathematical translations that first modify the discrete feed intake function (eq. 1) into a continuous linear function with the slope and the y-intercept chosen such that the integral of the function over a feeding period of n days is equal to the total feed intake over the given period (i.e. the total sum of the feed intake on individual days after n days is equal to FI_{total}, while taking into account $FI_{spilled}$). For the first feeding period, the initial value of the y-intercept (b) is obtained as an input, making the slope (a) the only independent variable. Subsequent feeding periods obtain a new b by using the daily feed intake value (FI_{day}) of the function of the previous period. Consequently, we rewrite the discrete function to a continuous function using the standard function

$$\sum_{i=1}^{n}(i-1)a + b = \frac{n}{2}\big(2b + a(n-1)\big) \tag{2}$$

so that equation 1 can be rewritten with a slight adaptation of equation 2 to

$$FI = FI_{spilled}(\frac{n}{2}(2b + (n-1)a) - b) \tag{3}$$

where

$$a = \frac{2(b(-n+1) + FI)}{n(n-1)} \tag{4}$$

and

$$b = \begin{cases}(0.048 \cup 'table\ 2\ value'), & initial\ period \\ a \cdot n + b_{previous\ period}, & subsequent\ periods\end{cases} \tag{5}$$

In this way the model allocates the total (non-spilled) feed supplied per period (FI) specified by the user to a daily intake, based on the feed intake (b) on the first day of the period, defined above as (1) 0.048 kg/d in the first period, (2) the respective value of the first day post-adaptation period as presented in table 2 or (3) as the daily intake on the final day of the previous period (equation 5), and the daily increase (a) from equation 4. Ultimately, the daily feed intake in period i is described using a_i and b_i for each respective period via

$$FI_{day} = a_i n + b_i \tag{6}$$

2.4 Feed composition, energy intake and maintenance energy

The model does not require or use any specification of the composition of the nursery diet(s). The only input parameter defining the feed itself is its net energy (NE) content, provided as input per period in MJ NE/kg feed or EW/kg feed. Feed composition is assumed to be an ideal mixture of feed ingredients, with the actual amount of energy it provides as the only limiting nutrient (i.e. the feed is not limiting in the crude protein, amino acids, minerals or vitamins it provides). The model itself uses metabolizable energy (ME) to calculate tissue deposition, hence a NE/ME conversion factor of 0.74 is used (Noblet et al., 2022). The total daily metabolizable energy intake ME_{intake} (MJ ME/day) is calculated by multiplying the dietary net energy content with the feed intake and then this calculated net energy intake is divided by the conversion factor 0.74.

Energy available for tissue deposition is calculated from energy intake minus energy required for maintenance processes. In the model, metabolizable energy for maintenance ME_m is expressed as an amount of MJ ME/kg$^{0.6}$/d. The use of factor 0.60 instead of the previously established 0.75 is consistent with the suggestion by Everts (2015) that energy calculations using the factor 0.60 for smaller animals (i.e. <30 kg piglets) result in a smaller residual error than using the 0.75 factor.

A downside of this change in metabolic factor is that earlier studies which estimated the maintenance energy of young piglets (<30 kg body weight) using the factor 0.75 are unsuitable for development or validation of this model.

For further comparison, ME_m (in MJ ME) of piglets in the range of 5-30 kg has been calculated using both factors (Figure 2). For the 0.6 factor, a value of 745 kJ NE/kg$^{0.6}$/d was used, suggested by Everts (2015); for the 0.75 factor, a value of 475 kJ ME/kg$^{0.75}$/d was used, based on observations of Campbell & Dunkin (1982 & 1983) and McNutt & Ewan (1984). It is clear that using a factor 0.6 significantly increases the daily maintenance energy requirement of pigs <30 kg body weight. However, this increase is compensated by a parallel increase in the energetic efficiency values of both protein (k_p) and lipid (k_f) deposition, which are linked to the choice of metabolic body weight factor in the regression analyses of a specific dataset. As indicated by Everts (2015), MEm, k_p and k_f values are only realistically applicable in a model when they have been obtained from the same dataset (further explained in the next section). Thus, we assume that the value of 745 kJ NE/kg$^{0.6}$/d for pigs in the range of 20-110 kg, as presented by Everts (2015) after reviewing a number of studies, can be applied to lower body weights as well. Converted to ME, the adopted maintenance energy requirement of the piglets is 1.012 MJ ME/kg$^{0.6}$/d.

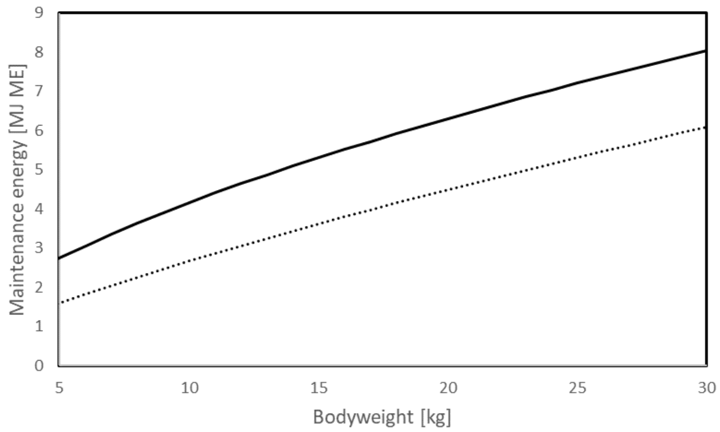

Figure 2 *Daily maintenance energy requirement of piglets (5-30kg) using different metabolic weight factors for energy requirement; based on 1012 kJ ME/kg$^{0.6}$/d (—) and 475 kJ ME/kg$^{0.75}$/d (···).*

2.5 Protein and lipid deposition

Protein and lipid deposition in the model are based on a reference point (intercept) at which lipid deposition is zero (further explained below) and the partitioning of metabolizable energy above maintenance to protein and lipid deposition. The concept of a marginal ratio is used to determine the partitioning of energy above maintenance requirements between protein and lipid deposition. The concept implies that, at a given body weight, both protein and lipid deposition increase linearly with increasing energy intake until an intrinsically determined maximum protein deposition (PDmax) is reached. The ratio between the slopes for lipid and protein deposition is referred to as marginal ratio. Thus the marginal ratio *MR* is defined as the ratio between the increase in lipid and protein deposition with increasing energy intake, when protein deposition is below its maximum capacity (De Greef, 1992). This description is consistent with earlier observations on pigs heavier than 25 kg by Black et al. (1986) and Bikker (1994). Comparing this concept to empirical data in the 5-30 kg weight range (Campbell & Dunkin, 1983; Campbell et al., 1988) implies that extrapolation to our weight range is feasible with some minor alterations.

It has been described that the marginal ratio increases with increasing body weight, reflecting that an increasing proportion of energy above maintenance is used for lipid deposition when pigs grow older. Therefore, for pigs heavier than 20-25 kg, the marginal ratio *MR* has originally been expressed as a function of the body weight *BW*, via

$$MR = MR_{int} + MR_{slope} \cdot BW \quad (7)$$

in which MR_{int} and MR_{slope} are parameters used to define the relationship of *MR* to *BW*. Although the value of MR_{slope} is dependent on the sex of the pig in larger animals above 25 kg body weight (Bikker, 1994), we assume that sex has an insignificant impact on tissue partitioning in young piglets.

Observations using an early version of the model indicated that *MR* tended to be underestimated for pigs in the weight range of our model when using values suggested for larger animals (MR_{int} = 0; MR_{slope} = 0.04 to 0.06), leading to unrealistically high and low deposition of protein and fat, respectively. To overcome this, we adapted the calculation of *MR* by changing MR_{int} to be a descending linear function itself, essentially summing two linear functions where the largest difference is found at lower body weights. This prevents the value *MR* becoming too low, which would give an unrealistic representation of the ratio of protein- and lipid deposition.

Mathematically, we expanded upon MR_{int} via the linear relationship

$$MR_{int} = \begin{cases} MR_0\left(1 - \frac{BW}{25}\right) + MR_{slope} \cdot BW, & BW \leq 25kg \\ 0, & BW > 25kg \end{cases} \quad (8)$$

in which MR_0 is the theoretical *MR* at a body weight of 0 (estimated MR_0 = 1). Equation 8 is obtained by adding equation 7 (MR_{int} = 0, right-hand term) with a linear function between the points (0, MR_0) and (25, 0) (left-hand term). The left-hand term is obtained via

$$MR_{to\ add} = \frac{\Delta y}{\Delta x} BW + MR_0 = \frac{0 - MR_0}{25 - 0} BW + MR_0 = MR_0\left(1 - \frac{BW}{25}\right) \quad (9)$$

In this way, *MR* is given a less steep decrease in value at a *BW* lower than 25 kg (Illustrated in figure 3; MR_0 = 1.0 and MR_{slope} = 0.05), both preventing unrealistic tissue deposition and still adhering to earlier established (linear) *MR* predictions at a body weight above 25 kg.

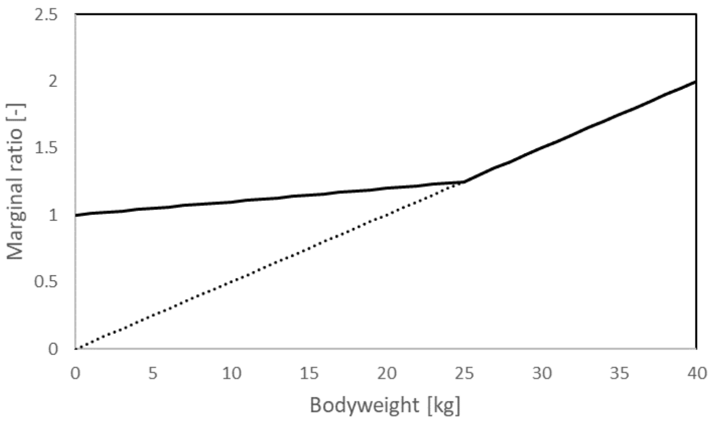

Figure 3 *Modelled marginal ratio as function of body weight in pigs (—), where the new y-intercept is based on MR_0 = 1.0 (eq. 7). The old marginal ratio formula with an y-intercept at MR_{int} = 0 is given as a comparison (···).*

The mathematical formula to partition metabolizable energy from the feed, ingested above maintenance requirements, between protein and lipid deposition is derived from the TMV-model (Van der Peet – Schwering et al., 1994). In this approach, the intercept for protein deposition, i.e. the energy intake at which protein deposition is zero is lower than for lipid deposition. Conceptually, these formulas are derived from the observation that, when fed at maintenance, pigs deposit protein and mobilise lipid tissue (Black et al., 1986; De Greef, 1992). Furthermore, data from Campbell et al. (1985) and Bikker (1994) suggest that lipid deposition equals zero when energy intake is 1.3 times maintenance requirements for growing pigs. We assume that this value is also applicable for pigs below 30 kg, based on data from Close and Stanier (1984). In addition, it is generally observed that the increase in protein deposition (the slope) with increasing energy intake exceeds the increase in lipid deposition (Figure 4A). However, these assumptions also directly cause fat mobilization to be much less than protein mobilization at low energy intake (Figure 4A). This is contradictory to observations by Whittemore et al. (1978), which indicate that low daily energy intake (e.g. during the first days post-weaning) coincides with relatively sustained protein content in the body at a significant loss of fat tissue.

Therefore, we have implemented an equation that linearly increases the *MR* when energy intake is lower than maintenance requirements. We arbitrarily set the *MR* to be doubled when energy intake is 10% of the maintenance requirement, such that the new *MR* becomes

$$MR_{new} = MR_{old}\left(\frac{19}{9} - \frac{10}{9}\frac{ME_{intake}}{ME_m}\right) \tag{10}$$

obtained by multiplying MR_{old} by a linear scaling factor (x2 at $ME_{intake}/ME_M = 0.1$, x1 at $ME_{intake}/ME_M = 1$), such that

$$x_{scaling,slope} = \frac{2\frac{ME_{intake}}{ME_m} - 1\frac{ME_{intake}}{ME_m}}{0.1 - 1} = -\frac{10}{9}\frac{ME_{intake}}{ME_m} \tag{11}$$

with accommodating y-intercept of of 19/9.
In effect, equation 10 increases the MR at lower energy intake levels, curving both the protein and lipid net deposition curves (figure 4B) to mimic the effect of protein retention at the cost of lipid tissue.

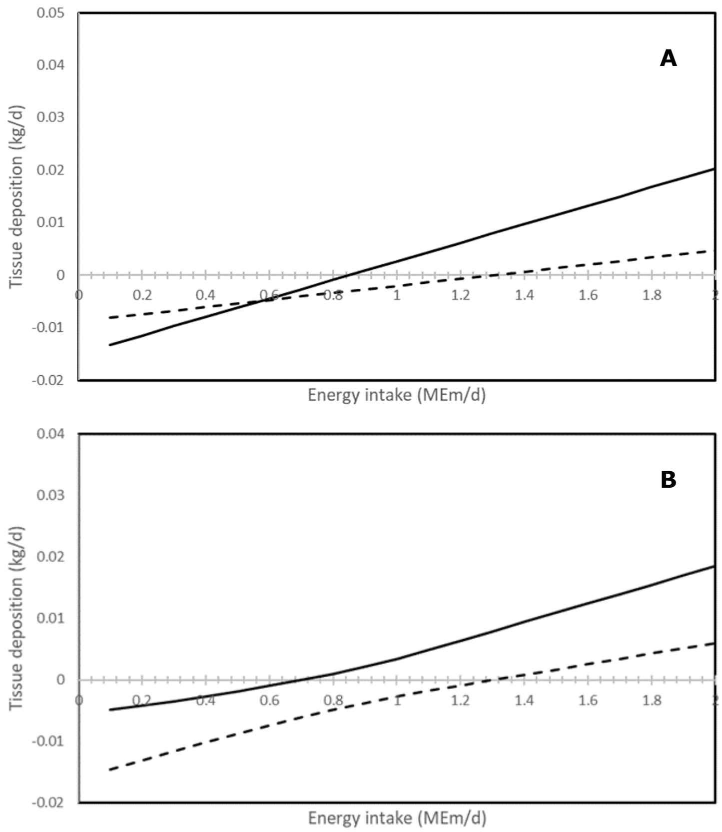

Figure 4 *Net protein (—) and lipid (---) deposition when not corrected (A) and corrected (B) for protein retention at low energy intake levels.*

The metabolizable energy efficiency for protein deposition k_p and lipid deposition k_f is assumed to be 0.63 and 0.80 respectively (Everts, 2015). This assumption is supported by Everts (2015) who suggested that ME_m, k_p and k_f values are only realistically applicable in a model when they have been obtained from the same dataset. Values of 23.8 MJ and 39.6 MJ were taken for the energy content of 1 kg of protein or lipid respectively (Everts, 2015). Finally, similarly to the TMV-model, a maximum rate of protein deposition, PD_{max}, was included. Whittemore (1981) suggested that weaned piglets are physiologically incapable of ingesting enough food to reach this theoretical plateau. Nonetheless, an option to implement a PD_{max} was included in the model, mainly to test hypothetical settings.

Ultimately, protein deposition *PD* [kg/day] is described as

$$PD[\frac{kg}{day}] = \frac{0.3 \cdot ME_m}{\frac{23.8}{k_p}} + \frac{ME_{intake} - 1.3 \cdot ME_m}{\frac{23.8}{k_p} + MR \cdot \frac{39.6}{k_f}} \quad (12)$$

with the additional constraint that *PD* cannot exceed a maximum of PD_{max}.

After which equation 12 is used to obtain the lipid deposition *LD* [kg/day] as

$$LD\left[\frac{kg}{day}\right] = \frac{ME_{intake} - ME_m - \frac{23.8}{k_p} \cdot PD}{\frac{39.6}{k_f}} \quad (13)$$

2.6 Water and ash deposition

Daily water deposition in weaned piglets appears to be correlated to protein deposition over the modelled weight range from weaning to 30 kg, except for the very first days post-weaning. Rapid loss of lipid tissue during this early post-weaning period is expected as a result of inadequate food intake. Whittemore et al. (1978) found that this loss of fat coincided with a two-fold gain in water content, resulting in net weight gain at very low energy intake levels. This is possibly a direct result of insulin-induced tissue oedema formation in response to a sudden change to a high-glycaemic diet (Walmsley, 2013; Theo A. van Kempen, personal communication). Hence we assume that water 'replaces' fat tissue for modelling purposes, although this is not directly reflected in a physiological mechanism. Whittemore et al. (1978) noted that this 'replacement effect' ceased when weight gain became more than 200g/day. We assumed that this rate of weight gain is achieved after 7 days post-weaning, based on earlier data from Whittemore and Green (2001). To simulate this replacement, the water deposition as a result of initial loss of fat WD_{fat} is assumed to be equal to fat mobilisation during the first 7 days and modelled as

$$WD_{fat}\left[\frac{kg}{day}\right] = \begin{cases} 2 \cdot |LD|, & t \leq (7 - adaptation\ period), LD < 0 \\ 0, & t > (7 - adaptation\ period), LD \geq 0 \end{cases} \quad (14)$$

Additionally, in line with TMV and INRAPorc, we assumed that protein deposition can be used as the parameter to determine water deposition. This is substantiated by the following observations that no significant difference in water content per kg of protein per kg of bodyweight was found: in piglets (6.4-25 kg body weight) when provided different levels of crude protein (Hou et al., 2021); between light and heavy piglets (4.5-18.5 kg and 6.7-22.8 kg body weight respectively; Vieira et al., 2015); and in piglets (9.4-25 kg body weight) fed at different NE levels (Oresanya et al., 2008). It is important to note that these data were obtained from healthy piglets fed enough energy to ensure proper growth. Thus, we assume this is also applicable in our model.

We use the formula derived by De Lange (2003) to link water deposition WD_{PD} [kg/day] to the *PD*, via

$$WD_{PD}[\frac{kg}{day}] = 5.20 \cdot PD^{0.855} \quad (15)$$

which is used with equation 14 to calculate the total water deposition *WD* via

$$WD\left[\frac{kg}{day}\right] = WD_{fat} + WD_{PD} \quad (16)$$

Ash content in the empty body of piglets was found to be constant, independent of whether the energy intake or crude protein content in their diet was limiting or not (Campbell & Dunkin, 1983; Oresanya et al., 2008). Therefore, building on the assumption of a non-limiting feed mixture and to stay within the scope of the model, the model assumes that a constant ash content equal to the ash content in the empty body at weaning, as default value (2.9%) or specified by the user, is maintained throughout the simulation.

To achieve a constant ash content, ash deposition *AD* has been defined as

$$AD\left[\frac{kg}{day}\right] = \frac{C_{A,0}(M_P + PD + M_F + LD + M_W + WD)}{100 - C_{A,0}} - M_A \quad (17)$$

in which M_P, M_F, M_W, and M_A are the absolute mass in kg of protein, fat, water and ash respectively, and $C_{A,0}$ is the starting ash content percentage of the piglet.

The first term of equation 17 calculates how much the new absolute ash mass should be, after deposition of protein, lipid and water have been, to assure a constant ash content. By subtracting M_A from this term, the required *AD* is found.

2.7 Total mass gain, feed conversion- and gain to feed ratio

The total daily mass gain *DG* of the piglet is obtained by dividing the sum of the protein-, lipid-, water- and ash deposition by the ratio between empty body *EB* and live weight *LW* of the piglet, via

$$DG[\frac{kg}{day}] = \frac{PD + LD + WD + AD}{EB/LW} \tag{18}$$

in which EB/LW has a default value of 0.95. Equation 18 is used to calculate the feed conversation ratio *FCR* and the gain to feed ratio *G:F* using the feed intake *FI*, where

$$FCR = \frac{FI}{DG} \tag{19}$$

and

$$G{:}F = \frac{DG}{FI} \tag{20}$$

2.8 Lysine requirement

Lysine and all other essential amino acids are assumed to be not limiting protein deposition in the model calculations, regardless of the feed supply given as input. Hence, calculated protein deposition is determined by energy intake. Subsequently, SID lysine requirements are calculated and provided as an output, obtained as a function of model parameters based on the bodyweight, feed intake and protein deposition of the pig. These requirements account for the lysine needed to compensate for losses via integument and basal turnover (Moughan, 1998), basal endogenous losses (Noblet et al., 2002) and to deposit protein tissue (Le Bellego & Noblet, 2002). Inevitable oxidative losses also need to be taken into account and are usually expressed as the maximum efficiency of lysine utilization (Sève, 1994).

To the best of our knowledge, none of the values for any of the aforementioned lysine requirements are specifically determined for weaned piglets. Therefore, we assume that the values reported for lysine by Van Milgen et al. (2008) for a pig weighing 55 kg and expressed per kg of metabolic body weight ($BW^{0.75}$) are also applicable in our model: integument loss (4.5 mg/kg $BW^{0.75}$/d) and losses due to basal turnover (23.9 mg/kg $BW^{0.75}$/d) combined are 28.4 mg/kg $BW^{0.75}$/d, basal endogenous losses are 0.313 g/kg dry matter intake, the lysine content of body protein is 0.0696 and a maximum efficiency for using standardized ileal digestible lysine for body protein deposition of 0.72. We assume the modelled feed contains 11% water to calculate the dry matter intake from the given feed intake.

Combined, this allows the daily lysine requirement [g/day] to be expressed as

$$Lysine\ required\left[\frac{g\ SID\ Lys}{day}\right] = \frac{(turnover + integument) + endogenous + prot.deposition}{efficiency} \tag{21}$$

or with aforementioned parameter values as

$$Lysine\ required\left[\frac{g\ SID\ Lys}{day}\right] = \frac{0.0284 \cdot BW^{0.75} + 0.313 \cdot 0.89 \cdot FI + 0.0696 \cdot 1000 \cdot PD}{0.72} \tag{22}$$

Additionally, values for lysine required per kg of feed or per unit of energy supplied to the pigs are provided as model output, by dividing the result of equation 22 by the daily feed or energy intake.

2.9 Overview of model parameters and output

Table 3 provides an overview of the standard input parameters described throughout this chapter. These values may not be representative for all different breeds of piglets, housing conditions or various other factors which might influence these parameters. Hence, all inputs can be modified by the user to accommodate a wide range of different piglets and situations.

Model output is based on the functions described in this chapter. Additionally, change in piglet body composition is derived from the daily deposition of various tissues. All outputs can be represented visually in an output graph in the Excel model. The model also includes a query function to obtain the numerical values of piglet composition, average daily gain, FCR, G:F and SID lysine required (g/kg feed) per feeding period or across the entire simulation.

Table 3 *Standard input parameters of the model, based on a healthy piglet housed in neutral climate conditions.*

Parameter	Value	Unit	Description
Piglet starting composition			
Bodyweight	7.14	kg	Starting total (live) bodyweight
Empty body	95	%	Empty body content in live body weight
Fat (EB)	10.5	%	Starting fat content on empty body basis
Protein (EB)	15.5	%	Starting protein content on empty body basis
Ash (EB)	2.9	%	Starting ash content on empty body basis
Water (EB)	71.1	%	Starting water content on empty body basis
Lysine requirements			
Integument loss	0.0045	mg/kg $BW^{0.75}$	Daily integument losses of lysine
Basal turnover	0.0239	mg/kg $BW^{0.75}$	Lysine lost due to basal daily protein turnover
Endogenous losses	0.313	g/kg DMI	Basal endogenous losses of lysine
Body protein lysine content	6.96	%	Lysine content in body protein
k_{AA}	0.72	-	Maximum efficiency of lysine utilization
Other			
k_p	0.63	-	ME efficiency of protein deposition
k_f	0.80	-	Energetic efficiency of lipid deposition
ME_m	1.012	MJ/$kg^{0.6}$/d	Daily energy requirement for maintenance
Feed spillage	0	%	Amount of feed spilled from total feed allowance
MR_0	1	-	Y-intercept of marginal ratio when bodyweight <25kg
MR_{slope}	0.05	-	Slope of the marginal ratio
$X_{intercept}$	1.3	ME_m	Level of energy intake at which there is no net lipid deposition
NE/ME	0.73	-	Conversion factor between NE and ME
PDmax	180	g/day	Maximum daily protein deposition
Day 0 feed intake	0.048	kg/day	Feed intake on the first day post-weaning (no adaptation period)
Starting lag period	0	days	Number of days post-weaning before simulation period is started

3 Validation of the model with data

Predictive capability of the model was tested using data from eight studies, which are described in more detail in chapter 3.1. Where possible, Dutch or Belgian studies were used to ensure piglet genotype is relatively equivalent to model calibration parameters and relevant for the CVB partners. For each study, we used the standard model parameters, as expressed in Table 3, with the exception of the starting weight, piglet composition (if known), starting day (after weaning) of the simulation period and the amount of feed intake, energy content and duration of the study. These were based on actual values and adapted per study to the input format of the model. For each study, the diet that was assumed to be the least limiting was chosen as the best option to represent unlimiting nutrient supply. Complete adherence to all nutrient requirements for piglets per diet was not checked. The 'smoothen intake' function of the model was turned off for all validations. An overview of all variable input parameters used for the validation is provided in appendix I.

Output parameters used for validation were the average daily weight gain, piglet body composition and the SID lysine required in g/kg feed. Values of the output were obtained from the 'output query' of the model. Correlation between observed and simulated data is shown graphically in chapter 3.2. The relative error between observation and simulation is calculated as the absolute difference between the two, divided by the observed value; these values are presented in tables in appendix I.

3.1 Description of data used for validation

Bikker et al. (2018) aimed to determine the effect of dietary phosphorus supply in gestation and lactation on the physiological performance of suckling and weaned pigs. To this end, a 2x2 factorial arrangement was used; differentiating between low- and high phosphorus in diets of sows and weaned pigs. This study was chosen as we assumed it is representative of our model piglets in the early post-weaning period, and provided data on body composition at different stages of the piglets' life. Piglets were subjected to a dietary treatment for 35 days, starting immediately after weaning without adaptation period; the diet used for validation was the high-phosphorus (110% of requirements, CVB) diet to ensure sufficient nutrients were available. Calculated AID lysine content is reported as 10.9 g/kg feed, indicating it might be a limiting factor. Energy content of the diet was 1.12 EW/kg (13.3 MJ NE/kg) throughout the entire experiment. Piglet body composition at weaning was assumed to be equal to the data determined for piglets sacrificed five days prior to weaning. Average daily gain was given over the periods of 0-14 and 15-35 days and piglet body composition at day 35 post-weaning. Values used for validation of this study are presented in Table 4.

Table 4 *Dietary input and different standard parameters for validation with data from Bikker et al. (2018).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (EW/kg)***
0-13	14	3.81	1.12
14-34	21	14.57	1.12
Piglet			
Bodyweight (kg)	7.56		
Piglet starting composition			
Protein (%)	***Fat (%)***	***Ash (%)***	***Water (%)***
14.7	14.3	2.9	67.1

Bikker et al. (2020, confidential WLR report) studied the impact of different levels of a supplement on the growth performance of weaned piglets over 42 days.

The diet chosen for validation is the control diet, with all dietary components adhering to nutrient recommendations (CVB and NRC), containing 1.17 EW/kg (13.9 MJ NE/kg) in the first two weeks and 1.15 EW/kg (13.7 MJ NE/kg) in the remainder of the experimental period. Lysine content (SID) of the feed was estimated at 11.3 g/kg. This study gives a good indication of the average daily gain of our modelled piglets, assigned to a non-limiting diet and housed under thermoneutral climate conditions for a prolonged period. Piglets weighed an average of 8.08 kg at the start; the experiment started immediately after weaning. Table 5 gives an overview of the used input parameters.

Table 5 *Dietary input and different standard parameters for validation with data from Bikker et al. (2020, confidential WLR report).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (EW/kg)***
0-13	14	3.79	1.17
14-27	14	9.32	1.15
28-41	14	15.62	1.15
Piglet			
Bodyweight (kg)	8.08		

In another study, Bikker et al. (2021) determined the influence of dietary calcium and phosphorus concentration on performance parameters of weaned piglets over a period of five weeks. Similar to the previously mentioned studies, the non-limiting control diet was used to correlate feed and energy intake to overall weight gain in weaned piglets in our model. For this study, energy of the diet was 1.19 EW/kg (14.1 MJ NE/kg) across the entire period. Lysine content (SID) was determined to be 12.2 g/kg. Data is given for the first two and last three weeks separately. Piglets started with a bodyweight of 8.77 kg and were given no adaptation period post-weaning. Table 6 show the input parameters of this study.

Table 6 *Dietary input and different standard parameters for validation with data from Bikker et al. (2021).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (EW/kg)***
0-13	14	3.96	1.19
14-34	21	13.78	1.19
Piglet			
Bodyweight (kg)	8.77		

Millet et al. (2021) examined the effect of high- and low protein, and high- and low salt levels of diets for piglets between 4 and 9 weeks of age on the growth performance of piglets to test the correlation between increased protein levels and higher dietary salt requirements in weaned piglets. Two protein levels and four salt levels in the diets lead to a 2x4 factorial arrangement, for validation we used the high protein (220 g/kg), medium salt (2.3 g Na/kg) diet with an estimated energy content of 10.82 MJ NE/kg and SID lysine content of 12.5 g/kg. By assuming that the medium-salt, high-protein diet was non-limiting, this study provides representative data to correlate feed intake with average daily weight gain over a period of five weeks. Piglets were weaned at 28 days, and the experiment started immediately thereafter. Weekly weight gain and feed intake were determined, which provides insight on how well the model is able to simulate five different input periods. Input values for this study are provided in Table 7.

Table 7 *Dietary input and different standard parameters for validation with data from Millet et al. (2021).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (MJ NE/kg)***
0-6	7	1.26	10.82
7-13	7	2.65	10.82
14-20	7	4.24	10.82
21-27	7	5.13	10.82
28-34	7	5.83	10.82
Piglet			
Bodyweight (kg)	7.93		

Millet et al. (2020) explored the SID lysine requirements and the valine-to-lysine ratio in four to nine weeks old piglets using two dose response experiments: Experiment 1 was tested at high CP levels, while Experiment 2 was tested at lower levels and supplemented with more essential amino acids in pure form. For our validation, we used the most non-limiting diet of Experiment 1, containing 13.5 g SID lys/kg and 210 g CP/kg, estimated to contain 10.19 MJ NE/kg. Performance data are available for average daily weight gain across the five week experimental period. In contrast to data from Millet et al. (2021), this study provides validation of our model to data over a single prolonged period, with the additional difference being the slightly lower energy content of the diet in Experiment 1. Values for this study are given in Table 8.

Table 8 *Dietary input and different standard parameters for validation with data from Millet et al. (2020).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (MJ NE/kg)***
0-34	35	15.75	10.19
Piglet			
Bodyweight (kg)	7.7		

Validation of the lysine requirements of piglets was done using data from three studies (Kahindi et al., 2016; Zhou et al., 2019; Lee et al., 2021). These studies did not use a similar genotype as used for calibration of the model , hence results might not be entirely representative. To the best of our knowledge however, no recent lysine requirement (i.e. dose-response) studies for weaned piglets of our genotype have been published. As such, we assumed that these three studies are the best option to challenge our model with experimental data. The average daily weight gain of the piglets is also represented in these studies, although they are not used for validation given that we assume the aforementioned studies are more representative in this aspect.

In the first study, Kahindi et al. (2017) performed two relatively similar experiments with piglets between 7.1 and 13.3 kg bodyweight fed a non-limiting, wheat-corn-soybean based diet *ad libitum* for 21 days to determine SID lysine requirements. Different levels of SID lysine content were used (0.99-1.81%). For our validation we used the 1.81% diet as input; the authors reported a required lysine content of 1.32%. Energy content of the diet was estimated at 10.4 MJ NE/kg. Piglets were given a 4-day adaptation period prior to the experiment. Values for validation of this study are presented in Table 9.

Table 9 *Dietary input and different standard parameters (from table 3) for validation with data from Kahindi et al. (2016).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (MJ NE/kg)***
0-6	7	1.75	10.40
7-13	7	3.99	10.40
14-20	7	5.99	10.40
Piglet			
Bodyweight (kg)	7.13		
Adaptation period (days)	4		

The second study (Zhou et al., 2019) aimed to evaluate SID lysine requirements of weaned piglets (8-20 kg) given low CP, corn-soybean based diets. Similar to Kahindi et al. (2019), this was done by assigning piglets to one of five diets differing in lysine content (9.8 to 14.8 g SID lys/kg) and correlating this to both the average daily gain and the G:F ratio. For validation purposes, we used the most non-limiting diet, containing 18.5% CP, 14.8 g SID lys/kg and an estimated 10.5 MJ NE/kg, which exceeds the lysine requirement presented by the author of 13.1 g SID lys/kg. An adaptation period of five days was used to accommodate the piglets to the experimental conditions. Table 10 contains the input values for validation of this study.

Table 10 *Dietary input and different standard parameters (from table 3) for validation with data from Zhou et al. (2019).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (MJ NE/kg)***
0-14	15	6.048	10.50
15-28	14	11.760	10.50
Piglet			
Bodyweight (kg)	8.1		
Adaptation period (days)	5		

Finally, Lee et al. (2021) evaluated SID lysine requirements of weaned piglets fed a corn-soybean based diet for 21 days, containing one of six SID lysine levels (1.00-1.80%). Lysine requirements were obtained by correlating the G:F ratio with lysine levels of the diet. For validation, we used the diet containing 1.80% SID lysine, exceeding the reported requirement of 1.32%. Estimated energy content of the diet is 10.85 MJ NE/kg. Data is presented weekly for each of the three experimental weeks. A 5-day adaptation period was implemented prior to the experiment. Input parameters for this study are presented in Table 11.

Table 11 *Dietary input and different standard parameters (from table 3) for validation with data from Lee et al. (2019).*

Diet			
Day	***Duration (days)***	***Total feed intake (kg)***	***Energy content (MJ NE/kg)***
0-6	7	2.023	10.85
7-13	7	3.871	10.85
14-20	7	5.705	10.85
Piglet			
Bodyweight (kg)	6.51		
Adaptation period (days)	5		

3.2 Results of the validation

The model predicts reasonably well the average daily weight gain of piglets as a result of the variety of diets and starting conditions used for validation (Figure 5). Model predictions were both above (data from Bikker et al. (2018 and 2020) and below (data from Millet et al. (2021) observed ADG (more than 10% rel. error). This implies that the chosen model parameters on average represent the animals and experimental conditions. Differences between studies may be linked to conditions outside the scope of the model or an indication that the standard model parameters do not adequately / precisely reflect conditions of individual studies being only an average across various datasets. Comparing the FCR prediction (Figure 6) to the ADG shows that there is an expected correlation between overpredicted ADG and underpredicted FCR (within a single experiment), though that the extent of this correlation itself is irregular (when comparing the relative error of the ADG/FCR per data point, (Figure I.1, appendix I)). This directly reinforces the hypothesis that certain model parameters used in our standard situation do not reflect the actual *in vivo* situation between different studies. However, the linear correlation between the data points within a single experiment between the observed- and predicted ADG implies that model mechanisms itself are working correctly.

A more in-depth examination between the different experiments indicates that the ADG of piglets used in two WLR studies (Bikker et al. 2018, 2020) was overpredicted while the ADG in the studies of ILVO (Millet et al. 2020, 2021) were both underpredicted. This expectedly correlates with an under- and overpredicted FCR for the WLR and ILVO piglets respectively. In the model, a high total daily body gain combined with a generally low FCR indicates that the simulated piglets are too efficient at depositing protein when energy is provided via the diet in high quantity. Additionally, piglet body composition of the experiment of Bikker et al. (2018) is predicted reasonably well by the model, with a relative error of 7.2%, 9.9% and 0.1% for protein, lipid and water content (EB) respectively (table I.2, appendix I). As the pool size of data for validation is small, no general conclusions can be drawn. It is plausible to assume that the three main energy metabolism parameters (k_p, k_f, ME_m) are not exactly representative of every different piglet used as a model animal for the different experiments. However, no dataset containing all three the ME_M, k_p and k_f currently exists for piglets of a modern genotype, thus changing a single parameter of the three is arbitrary at best. More data to validate the model's ability to predict changes in body composition would further strengthen trust in the model, either by giving a different set of parameters for the energy utilization or by providing more datapoints to compare the model's predictive capability to. For now, model parameters are able to be adapted to adhere to non-standard situations (e.g. an increased maintenance energy to simulate suboptimal housing conditions), however these changes are to be made at the user's discretion.

With the knowledge that the post-weaning period is highly stressful for piglets, we assume that multiple model parameters cannot realistically be represented as a constant parameter (e.g. ME_m). However, no current empirical data exists to allow for further calibration of the model for this stressful time. Hence, the model is assumed to be valid with the current parameters for estimation of the ADG in weaned piglets as long as the model is parameterised to match the experimental ADFI, ADG and FCR (or more parameters where possible).

Model predictions for the lysine requirement (SID g/kg feed) of all three studies used for validation are low compared to the observed data (Figure 7). Comparison between observed and predicted ADG and FCR indicated that the standard parameters reflected the piglets used in the experiment reasonably well (Table I.1, appendix I). As the SID lysine requirement is relatively low for the first days post-weaning (Figure I.2, appendix I), this reduces the average requirement over the entire period. Piglets *in vivo* will be affected by a lysine restriction during or shortly after days where lysine requirements are highest (i.e. after the first week), hence the discrepancy between model and data can be explained by the use of the average instead of maximum SID lysine requirement. Furthermore, the actual amount of digested and absorbed lysine from feedstuff may be less than modelled, as the model calculates the physiological SID lysine requirement while the validation studies are mostly based on table values of growing-finishing pigs for their digestibility coefficients. Should weaned piglets have less capacity of digesting and absorbing lysine, this would imply that the reported values of lysine (in the literature used for calibration) are overestimated, further decreasing the discrepancy between the model output and the observed values.

Even with aforementioned implications on the model validation (composition, ADG and FCR), this indicates that the model is quite capable of predicting the overall SID lysine requirement over a certain feeding period. However, it is imperative that for an accurate prediction the model itself is parameterised adequately for each specific scenario. Finally, the model is technically able to predict daily SID lysine requirements (see Chapter 4); no data exists to validate this on a daily basis and thus this should be cautiously interpreted.

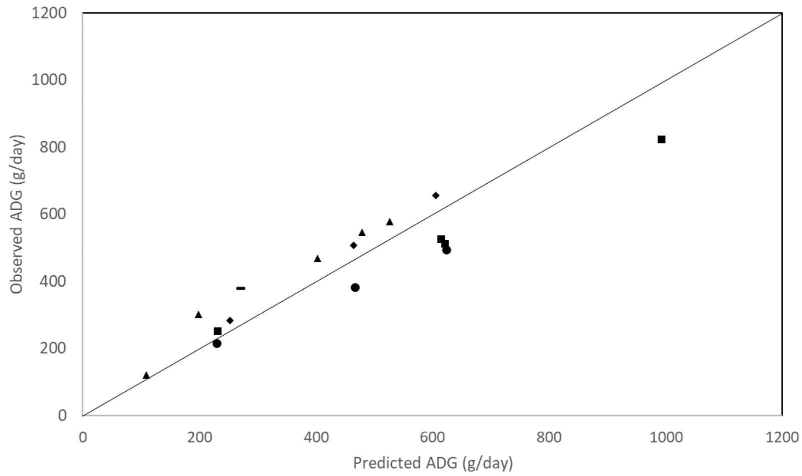

Figure 5 *Observed and predicted ADG for (●) Bikker et al. (2018); (■) Bikker et al. (2020); (♦) Bikker et al. (2021); (▲) Millet et al. (2021); (-) Millet et al. (2020).*

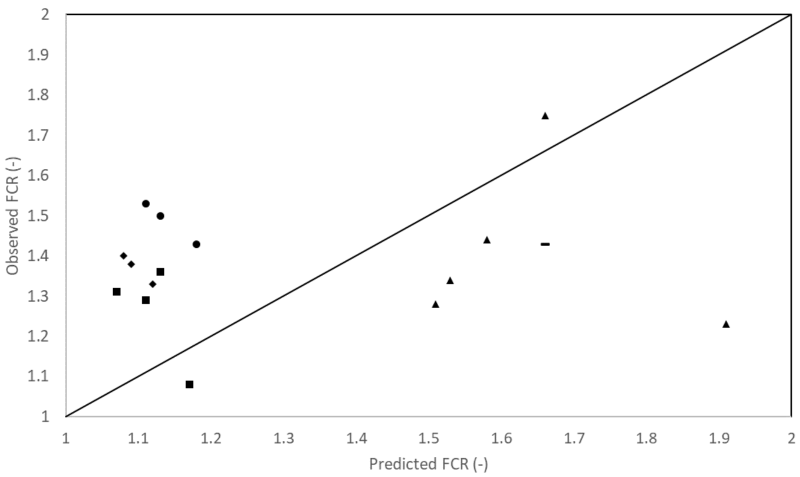

Figure 6 *Observed and predicted FCR for (●) Bikker et al. (2018); (■) Bikker et al. (2020); (♦) Bikker et al. (2021); (▲) Millet et al. (2021); (-) Millet et al. (2020).*

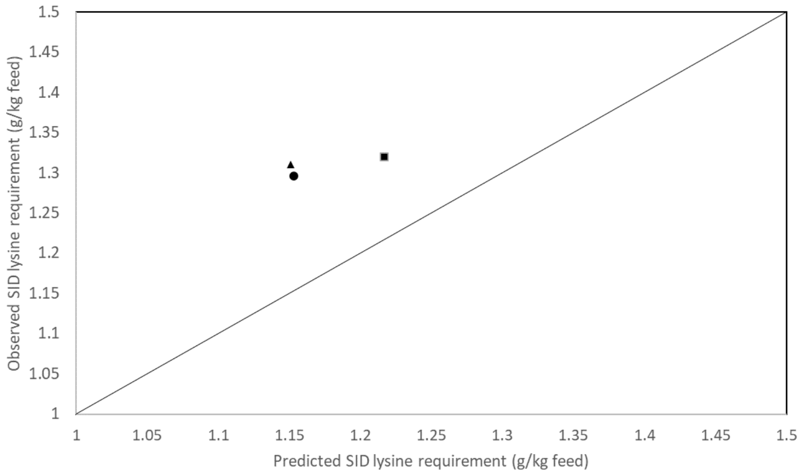

Figure 7 *Observed and predicted SID lysine requirement for (●) Kahindi et al. (2017); (■) Zhou et al (2019); (♦) Lee et al. (2021).*

4 Predicting standard situations

In this chapter we present a number of standard situations and discuss the model predictions of the SID lysine requirements to make the results of this report valuable independent of access to the Excel model itself. The aim of these standard situations is to provide realistic inputs to the model, and provide calculated SID lysine requitements and recommendations for practically relevant situations.

All standard situations are based on a diet containing 1.15 EW/kg feed (13.7 MJ NE/kg), as the amount of (dry) feed intake directly influences the lysine requirement (as basal endogenous losses are a function of the feed intake, equation 21); a period of five weeks in a single feeding period is used for all experiments. All model parameters not mentioned here were similar to those shown in Table 3. To address a range of practical situations, we used low and high ADFI (500 and 700 g/d, respectively) with piglets that have a low and high FCR (1.5/1.7 and 1.3/1.5 for low and high FCR respectively). Model parameters describing the tissue deposition partitioning (MR_{slope} and MR_0) were changed after feed intake levels were set to achieve the desired FCR in the model; this was done arbitrarily by gradually modifying each individual value. An overview of the modified parameters is provided in Table 12.

Table 12 *Input values for k_p, k_f and ME_m used in the model to create four standard situations.*

	Low ADFI (500 g/d)		High ADFI (700 g/d)	
Parameter	***FCR = 1.5***	***FCR = 1.7***	***FCR = 1.3***	***FCR = 1.5***
MR_0 (-)	1.04	1.36	1.08	1.14
MR_{slope} (-)	0.16	0.35	0.16	0.32

Predicted growth of the model piglets was within realistic boundaries for each model situation, although the water content of the piglets was relatively high at the end of the 35-day period (Table 13) compared to pigs of a similar genotype (Bikker et al., 2013). Protein and fat content were similarly underestimated in the model. However, for the SID lysine requirement this does not have a direct significant effect, as the absolute amount of protein deposition is used to estimate the lysine requirements. Based on this and previous implications discussed in Chapter 3.2, we assumed these values were representative of possible *in vivo* circumstances to predict the SID lysine requirement during this period.

Table 13 *Output results of the model using the parameters for the four standard situations.*

	Low ADFI (500 g/d)		High ADFI (700 g/d)	
Parameter	***FCR = 1.5***	***FCR = 1.7***	***FCR = 1.3***	***FCR = 1.5***
ADG (g/day)	384	346	536	476
Protein (%)	15.4	14.7	14.9	14
Fat (%)	13.6	16	18.4	22
Water (%)	68.1	66.4	63.8	61.13
Max. SID lysine req. (g/kg feed)	25.6	40.6	24.6	35.9
Cum. Average[1] SID lysine req. (g/kg feed)	12.7	10.9	12.1	10.0

1 Cumulative average taken for weeks 2-5

Daily SID lysine requirement (in g/kg feed) followed a similar trend for all four situations (figure 8A), where a steep decrease can be observed during the first week of the simulation followed by a relatively stable period in the final weeks. This is consistent with the low feed intake during the initial days where absolute lysine requirements (figure 8B) are also low, but still require a very high concentration in the feed to meet the demands of the piglet. The use of g/kg feed as a unit during the first days post-weaning is therefore questionable. Providing sufficient lysine to piglets immediately post-weaning is also implied to be unfeasible, as the low feed intake requires a dramatic increase in lysine concentration in the feed to overcome the calculated SID lysine requirement.

After the initial week, the daily SID lysine requirement stabilized. Piglets that had a lower FCR had a higher SID lysine requirement (cumulative average over period) than those with a higher FCR (Table 13). This is consistent with the increased protein deposition correlated to lower FCR values, and also with the choice of input parameters in Table 12 (lower MR_0/MR_{slope} correspond with increased protein deposition in favour of lipid deposition). Every model situation saw a slight decrease in lysine requirement (g/kg feed) during the later weeks of the simulation period, as the ever increasing lysine requirement in g/day is compensated for by the increase in feed intake.

The average SID lysine requirements are plausible and conform to the range of empirical evidence, though being all on the lower side (rapport Sophie). Protein deposition is the major factor influencing lysine requirements, which is properly reflected in the lower feed intake levels during the first two weeks of all simulations being correlated with a lower, but gradually increasing, SID lysine requirement (in g/day) in the model. This might imply that a diet containing less lysine may be sufficient for piglets who manage to eat sufficiently in the first week post-weaning, although the chaotic nature of this period makes any prediction tenuous at best. The decrease in requirement is consistent with the model behaviour that, over time, relatively less protein is being deposited in favour of more fat deposition.

Concluding, the SID lysine requirement (g/kg feed) predicted by the model is consistent within the range of empirical data during later periods of the simulation. The initial period post-weaning may overestimate the SID lysine requirement (g/kg feed) as a result of the low initial feed intake of the piglets. Simulated piglets appear to deposit too much water compared to observed piglets, which implies that this mechanism may need either revision or additional data for calibration; this does not significantly affect the estimation of the lysine requirement. Other mechanisms of the model follow expected patterns, but extra data is required for creating a set (or sets) of parameters that is able to simulate a wider range of pig genotypes.

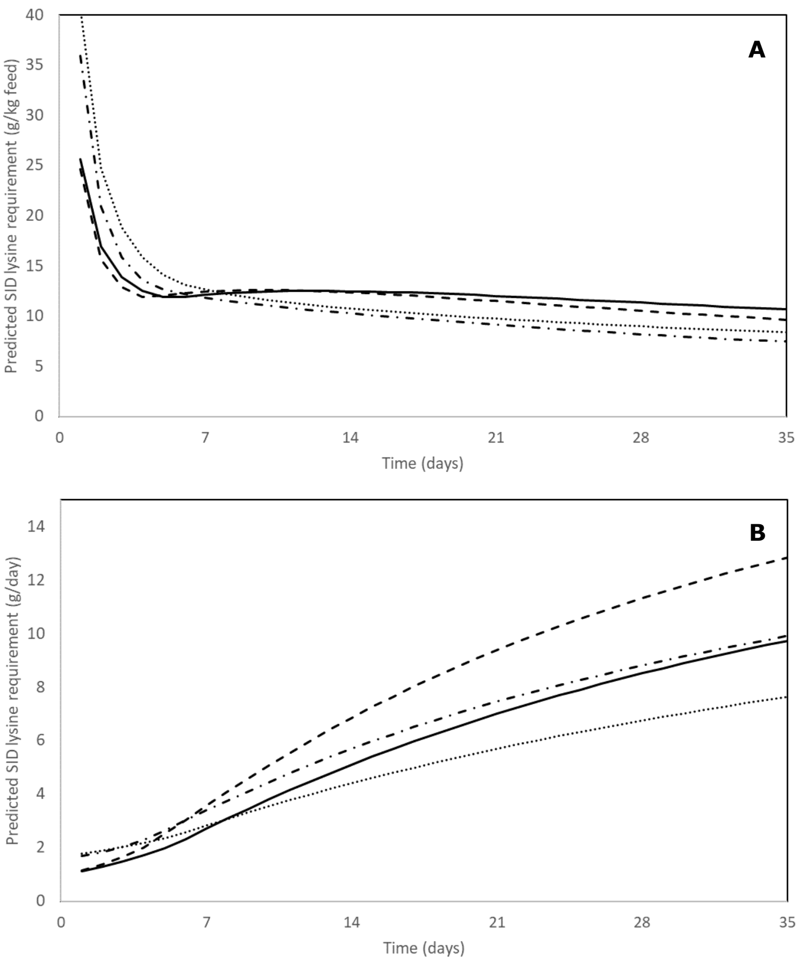

Figure 8 *SID lysine requirements in g/kg feed (A) and g/day (B) for model piglets subjected to four different standard situations: (—) 500, 1.5; (···) 500, 1.7; (---) 700, 1.3; (-·-) 700, 1.5; for ADFI/FCR respectively.*

References

Bikker P. 1994. Protein and lipid accretion in body components of growing pigs: effects of body weight and nutrient intake. *PhD dissertation*, Wageningen University.

Bikker P., Dekker R.A., van Diepen J.T.H.M., van Krimpen M.M., Jongbloed A.W. and Millet S. 2013. Behoefte en vastlegging van fosfor bij vleesvarkens. *Wageningen UR Livestock Research rapport 723*.

Bikker P., Van Baal J. and Liesegang A. 2018. Early nutritional programming of phosphorus metabolism in pigs. *Wageningen UR Livestock Research rapport 1091*.

Bikker P., Fledderus J. and Van Helvoort M. Impact of calcium content and calcium to phosphorus ratio in diets for weaned pigs. *Wageningen UR Livestock Research rapport 1309*.

Black J.L., Campbell R.G., Williams I.H., James K.J. and Davies G.T. 1986. Simulation of energy and amino acid utilisation in the pig. *Research and Development in Agriculture*, 3:121-145.

Blavi L., Solà-Oriol D., Llonch P., López-Vergé S., Martín-Orúe S.M. and Pérez J.F. 2021. Management and Feeding Strategies in Early Life to Increase Piglet Performance and Welfare around Weaning: A Review. *Animals*, 11:302.

Brooks P.H. and Tsourgiannis C.A. 2003. Factors Affecting the Voluntary Feed Intake of the Weaned Pig. In: *Weaning the Pig, Concepts and Consequences*; Pluske, J.R., Le Dividich, J., Verstegen, M.W.A., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2003; pp. 81–116.

Bruininx E.M.A.M., Binnendijk G.P., Van der Peet-Schwering C.M.C., Schrama J.W., Den Hartog L.A., Everts H. and Beynen A.C. 2002. Effect of creep feed consumption on individual feed intake characteristics and performance of group-housed weanling pigs. *Journal of Animal Science*, 80(6):1413-1418.

Bruininx E.M.A.M., Schellingerhout A.B., Binnendijk G.P., Van der Peet-Schewering C.M.C., Schrama J.W., Den Hartog L.A., Everts H. and Beynen A.C. 2004. Individually assessed creep food consumption by suckled piglets: influence on post-weaning food intake characteristics and indicators of gut structure and hind-gut fermentation. *Animal Science*, 78:67-75.

Campbell R. and Dunkin A. 1982. The effects of birth weight and level of feeding in early life on growth and development of muscle and adipose tissue in the young pig. *Animal Science*, 35(2):185-192.

Campbell R. and Dunkin A. 1983. The influence of dietary protein and energy intake on the performance, body composition and energy utilization of pigs growing from 7 to 19 kg. *Animal Science*, 36(2):185-192.

Campbell R., Taverner M.R. and Curic D.M. 1985. Effects of sex and energy intake between 48 and 90 kg live weight on protein deposition in growing pigs. *Animal Production*, 40:497-503.

Campbell R., Taverner M. and Rayner C. 1988. The tissue and dietary protein and amino acid requirements of pigs from 8 to 20 kg live weight. *Animal Science*, 46(2):283-290.

Carstensen L., Ersbøll A.K., Jensen K.H. and Nielsen J.P. 2005. *Escherichia coli* post-weaning diarrhoea occurrence in piglets with monitored exposure to creep feed. *Veterinary Microbiology*, 110:113-123.

Close W. and Stanier M. 1984. Effects of plane of nutrition and environmental temperature on the growth and development of the early-weaned piglet 2. Energy metabolism. *Animal Science*, 38(2):221-231.

Cole D.J.A., Duckworth J.E. and Holmes W. 1967. Factors affecting voluntary feed intake in pigs. *Animal Production* 9:141-148.

De Greef K.H. 1992. Prediction of production. Nutrition induced tissue partitioning in growing pigs. *PhD dissertation*, Wageningen University.

De Lange C.F.M., Morel P.C.H and Birkett S.H. 2003. Modeling chemical and physical body composition of the growing pig. *Journal of Animal Science*, 81(14), E159:E165.

Everts H. 2015. Energy requirement for maintenance in growing pigs. *CVB-Documentation Report nr. 57*.

Goethals, S., Rijpert J.H.M., Spek J.W., Millet S., Bikker P. 2023. Amino acids requirement of weaned piglets. *Wageningen UR Livestock Research rapport 1436.*

Hou L., Wang L., Qiu Y., Xiong Y., Xiao H., Yi H., Wen X., Lin Z., Wang Z., Yang X. and Jiang Z. 2021. Effects of Protein Restriction and Subsequent Realimentation on Body Composition, Gut Microbiota and Metabolite Profiles in Weaned Piglets. *Animals*, 11:686.

Jones C.K., Gabler N.K., Main R.G. and Patience J.F. 2012. Characterizing growth and carcass composition differences in pigs with varying weaning weights and postweaning performance. *Journal of Animal Science*, 90(11):4072-4080.

Kahindi R.K., Htoo J.K. and Nyachoti C.M. 2016. Dietary lysine requirement for 7–16 kg pigs fed wheat–corn–soybean meal-based diets. *Journal of Animal Physiology and Animal Nutrition*, 101(1):22-29.

Le Bellego L. and Noblet J. 2002. Performance and utilization of dietary energy and amino acids in piglets fed low protein diets. *Livestock Production Science*, 76:45-58.

Lee J., González-Vega J.C., Htoo J.K. and Nyachoti C.M. 2021. Evaluating the standardized ileal digestible lysine requirement of 7- to 15-kg weanling pigs fed corn-soybean meal-based diets. *Animal*, 15(2).

Mallin M.A. and Cahoon L.B. 2003. Industrialized animal production — A major source of nutrient and microbial pollution to aquatic ecosystems. *Population and Environment*, 24:369-385.

McNutt S. and Ewan R.C. 1984. Energy utilization of weanling pigs raised under pen conditions. *Journal of Animal Science*, 59(3):738-745.

Millet S., Minussi I., Lambert W., Aluwé M., Ampe B., De Sutter J. and De Campeneere S. 2020. Standardized ileal digestible lysine and valine-to-lysine requirements for optimal performance of 4 to 9-week-old Piétrain cross piglets. *Livestock Science*, 241:104263.

Millet S., Ampe B. and Tokach M.D. 2021. The effects of salt and protein level on the performance and fecal consistency of piglets between 4 and 9 weeks of age. *Livestock Science*, 247:104478.

Moughan P.J. 1998. Protein metabolism in the growing pig. In: Kyriazakis, I., *A Quantitative Biology of the Pig*. CABI Publishing, Oxon, UK, pp. 299–331.

Noblet J., Sève B. and Jondreville C. 2002. Valeurs nutritives pour les porcs. In: Sauvant D., Perez J.-M., Tran G. *Tables De Composition Et De Valeur Nutritive Des Matières Premières Destinées Aux Animaux D'Elevage*. INRA Editions, Paris, pp. 25–35.

Noblet J., Wu S-B. and Choct M. 2022. Methodologies for energy evaluation of pig and poultry feeds: A review. *Animal Nutrition*, 8:185-203.

Oresanya T.F., Beaulieu A.D. and Patience J.F. 2008. Investigations of energy metabolism in weanling barrows: The interaction of dietary energy concentration and daily feed (energy) intake. *Journal of Animal Science*, 86:348-363.

Sève B. 1994. Alimentation du porc en croissance: intégration des concepts de protéine idéale, de digestibilité digestive des acides aminés et d'énergie nette. *INRAE Productions Animales*, 7:275-291.

Sulabo R.C, Tokach M.D., Dritz S.S., Goodband R.D., DeRouchey J.M. and Nelssen J.L. 2010. Effects of varying creep feeding duration on the propotion of pigs consuming creep feed and neonatal pig performance. *Journal of Animal Science*, 88(9):3154-3162.

van der Peet - Schwering C. M. C., Vos H. J. P. M. and van der Peet G. F. V. 1994. Technisch model varkensvoeding : informatiemodel. *Werkgroep TMV*.

Van Milgen J., Valancogne A., Dubois S., Dourmad J-Y., Sève B. and Noblet J. 2008. InraPorc: A model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology*, 143(1-4):372-386.

Vieira M.S., Ribeiro A.M.L., Kessler A.M., Chiba L.I. and Bockor L. 2015. Performance and body composition of light and heavy early-weaning piglets subject to different dietary energy levels. *Livestock Science*, 178:272-278.

Walmsley R.S. 2013. Refeeding syndrome: screening, incidence, and treatment during parenteral nutrition. *Journal of Gastroenterology and Hepatology*, 28(4):113-117.

Warnants, N., Van Oeckel, M., De Paepe, M., Millet, S., & De Brabander, D. 2006. Evolutie van de lichaamssamenstelling van big tot slachtvarken. *Infonamiddag ILVO-DIER "Actuele onderzoeksresultaten bij éénmagigen"*, Melle (BE):35-50.

Whittemore C.T., Aumaître A. and Williams I.H. 1978. Growth of body components in young weaned pigs. *Journal of Agricultural Science, Cambridge*, 91:681-692.

Whittemore C.T. 1983. Development of recommended energy and protein allowances for growing pigs. *Agricultural Systems*, 11:156-186.

Whittemore C.T. and Green D. 2001. Growth of the young weaned pig. In: *The weaner pig: nutrition and management.* Proceedings of a British Society of Animal Science Occasional Meeting, University of Nottingham, UK.

Yu D., Zhu W. and Hang S. 2019. Effects of Long-Term Dietary Protein Restriction on Intestinal Morphology, Digestive Enzymes, Gut Hormones, and Colonic Microbiota in Pigs. *Animal*, 9:180.

Zhou H., Chen D., Mao X., He J., Yu J., Zheng P., Luo J., Gao J., Htoo J.K. and Yu B. 2019. Evaluation of standardized ileal digestible lysine requirement for 8–20 kg pigs fed low crude protein diets. *Animal Science Journal*, 90(2):237-246.

Appendix I – Model validation data

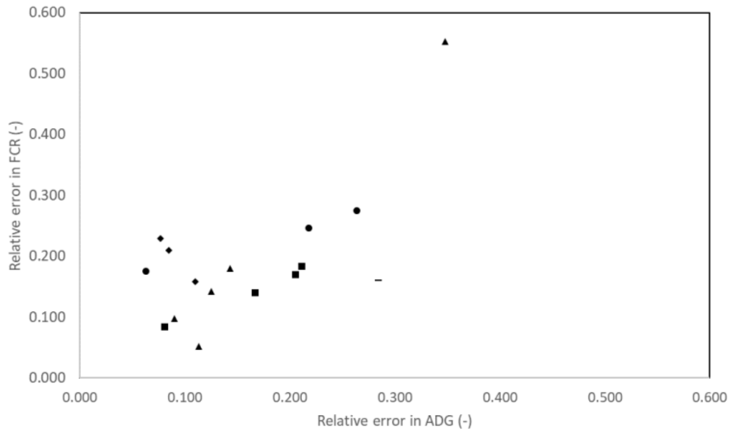

Figure I.1 *Comparison of the relative errors of matching data points for prediction of the ADG/FCR, for (●) Bikker et al. (2018); (■) Bikker et al. (2020); (♦) Bikker et al. (2021); (▲) Millet et al. (2021); (-) Millet et al. (2020).*

Table I.1 *Raw data of the observed and predicted values and their respective relative error for each of the studies used for validation of the ADG, FCR and SID lysine requirement.*

		ADG (g/day)			FCR (-)		
Reference	***Period (days)***	***Observed***	***Predicted***	***Rel. error***	***Observed***	***Predicted***	***Rel. error***
Bikker et al. (2018)	0-14	216	229	0.063	1.43	1.18	0.175
	14-35	494	624	0.264	1.53	1.11	0.275
	0-35	383	466	0.218	1.5	1.13	0.247
Bikker et al. (2020)	0-13	252	231	0.081	1.08	1.17	0.083
	14-27	513	621	0.212	1.31	1.07	0.183
	28-41	823	992	0.205	1.36	1.13	0.169
	0-42	527	615	0.167	1.29	1.11	0.140
Bikker et al. (2021)	0-14	283	251	0.110	1.33	1.12	0.158
	14-35	656	605	0.077	1.4	1.08	0.229
	0-35	507	464	0.085	1.38	1.09	0.210
Millet et al. (2021)	0-6	122	108	0.113	1.75	1.66	0.051
	7-13	303	197	0.348	1.23	1.91	0.553
	14-20	469	401	0.143	1.28	1.51	0.180
	21-27	547	478	0.125	1.34	1.53	0.142
	28-34	578	526	0.090	1.44	1.58	0.097
Millet et al. (2020)	0-34	378.6	270	0.284	1.43	1.66	0.161
Kahindi et al. (2017)	0-20	386	395	0.024	1.42	1.41	0.007
Zhou et al. (2020)	0-28	458	433	0.053	1.39	1.47	0.057
Lee et al. (2021)	0-20	417	414	0.005	1.23	1.33	0.080

Table I.2 *Piglet body composition at the end of the simulation for every study used for validation of the ADG, FCR and SID lysine requirement.*

	Piglet body characteristic at the end of simulation(%)		
Study	***Protein***	***Fat***	***Water***
Bikker et al. (2018)	16.3	11.1	69.4
Bikker et al. (2020)	16.8	11.9	68.4
Bikker et al. (2021)	16.6	9.7	70.8
Millet et al. (2021)	16.5	8.2	72.5
Millet et al. (2020)	16.3	6.6	74.2
Kahindi et al. (2017)	16.0	9.5	71.6
Zhou et al. (2020)	16.4	9.8	70.9
Lee et al. (2021)	16.0	9.8	71.6

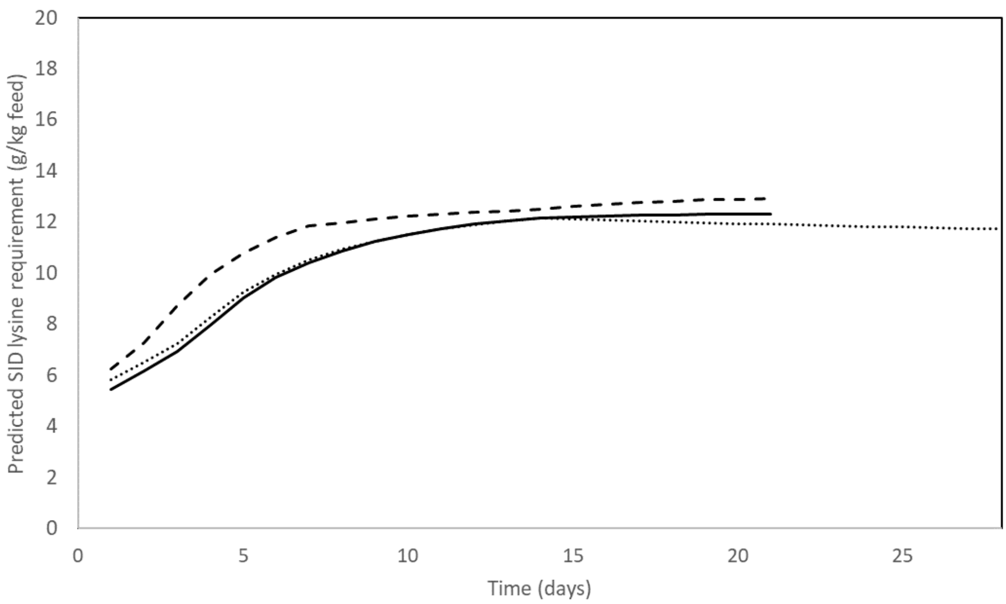

Figure I.2 *Predicted SID lysine requirements on a daily basis for the data from (—) Kahindi et al. (2017); (···) Zhou et al. (2020); (---) Lee et al. (2021).*

Appendix II - Smoothen feed intake graph derivation

An option exists in the Excel model to replace the defined input function (explained in Chapter 2.3) with a logarithmic function that may improve the initial input by smoothening out the (sometimes occurring) jaggedness of the multiple linear composites of the overall input function. The smoothened input curve is corrected on each individual day for the difference in total feed intake across the input period and will therefore give a similar total feed intake over the given simulation period. Daily feed intake will differ slightly however, therefore the use of the smoothen intake function is optional and up to the user's discretion to determine whether it better reflects the provided diet.

Daily feed intake values (FI_i) per day (t_i) obtained using equation 6 are used as an input to the smoothen function. To construct a logarithmic function of the general form

$$y = m \cdot t^b \qquad (II.1)$$

or

$$\ln(y) = \ln(m) + bt \qquad (II.2)$$

we use the built-in Excel function LINEST to estimate ln(m) and b from the transformed values ln(FI_i) and ln(t_i). In turn, these are used to construct the initial logarithmic feed intake function FI_{log} via

$$FI_{log} = e^{\ln(m)} + t^b \qquad (II.3)$$

To correct for the difference in cumulative feed intake over the entire period, daily corrected feed intake $FI_{corr,i}$ is calculated, where

$$FI_{corr,i} = FI_{log,i} \frac{\sum FI_{log} - \sum FI}{t_{max}} \qquad (II.4)$$

in which t_{max} is the index of the final day of the simulation. Outputs from equation II.4 are plotted as a function of time (in days, example in figure II.1) and used for further calculations in the model.

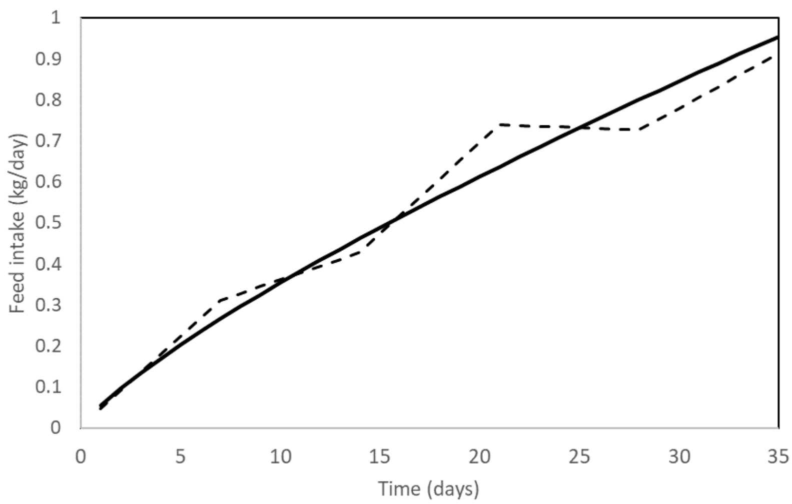

Figure II.1 *Difference between the composite linear feed intake function (dashed line) and the smoothened logarithmic function (solid line) for an example diet consisting of five 7-day periods with total feed intake values of 1.260, 2.649, 4.243, 5.127 and 5.830 for periods 1 to 5 respectively. Total feed intake across the entire simulation period is equal between both functions. Daily feed intake differs from day to day and will therefore present a different simulation output. Use of the 'smoothen input graph' function is up to the user's discretion.*

To explore the potential of nature to improve the quality of life

Wageningen Livestock Research
P.O. Box 338
6700 AH Wageningen
The Netherlands
T +31 (0)317 48 39 53
E info.livestockresearch@wur.nl
www.wur.nl/livestock-research

Wageningen Livestock Research creates science based solutions for a sustainable and profitable livestock sector. Together with our clients, we integrate scientific knowledge and practical experience to develop livestock concepts for future generations.

Wageningen Livestock Research is part of Wageningen University & Research. Together we work on the mission: ‘To explore the potential of nature to improve the quality of life’. A staff of 6,500 and 10,000 students from over 100 countries are working worldwide in the domain of healthy food and living environment for governments and the business community-at-large. The strength of Wageningen University & Research lies in its ability to join the forces of specialised research institutes and the university. It also lies in the combined efforts of the various fields of natural and social sciences. This union of expertise leads to scientific breakthroughs that can quickly be put into practice and be incorporated into education. This is the Wageningen Approach.