Improvement of feed and nutrient efficiency in pig production through precision feeding

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Review: Improvement of feed and nutrient efficiency in pig production through precision feeding

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Highlights

- Environment, animal and feed characteristics influence nutrient utilization in pigs.
- Mathematical models can be used to estimate real-time daily nutrient requirements.
- Thanks to technological advances, each pig can receive its daily nutrient requirements.
- Precision feeding may also reduce feed cost and environment load.

Abstract

Nutrient requirement change over time and individual variability in pigs influences the efficiency of nutrient utilization. These variabilities should be considered to predict nutrient requirements more accurately. The goal of precision feeding is to develop systems able to estimate and deliver, at the right time, a ration with a quantity and composition adapted to the daily requirements of each animal. It would improve feed and nutrient efficiency, which is a major issue for the sustainability of all pig production systems. The objectives of this review

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Abbreviations: Feed conversion ratio (FCR), residual feed intake (RFI), metabolizable energy (ME), crude protein (CP), amino acid (AA), body weight (BW), phosphorus (P), nitrogen (N)

were: 1) to define feed efficiency and present the factors that affect it, as well as challenges to and strategies for improving it; 2) to define precision feeding and the sources of variability in nutrient requirements and show the need for new technology to obtain real-time data; and 3) to present current models and applications of precision feeding for fattening pigs and sows. Feed efficiency is expressed as the ratio of mean daily weight gain to mean daily feed consumption over a given period. In practice, the inverse of this ratio is generally used for breeding animals and represents the efficiency of converting feed into weight gain (feed conversion ratio, FCR). Several factors influence FCR, such as spillage, feed digestibility, composition of weight gain, feed intake and nutrient utilization. Selecting the appropriate form of feed and the appropriate nutrient density and supply, as well as reducing negative effects of environmental factors should improve FCR. New feeding technologies (e.g. sensors, feeders) allow group-housed animals to be fed based on their individual requirements, which improves group efficiency. Predictive models of nutrient requirements and excretion, such as InraPorc, have been developed and used to select the best feeding strategies. For growing pigs, precision feeding strategies are a promising solution to reduce nutrient excretion by adjusting the nutrient supply to each individual at different points in time. Recent simulations indicate that precision feeding might also be a relevant strategy for sows.

Keywords: farming conditions, feed conversion ratio, nutritional models, pig production, precision feeding

Introduction

Animal feed, human food, and bio-industries compete for crop resources, which places societal pressure on farming. Moreover, feed cost represents around two thirds of the production costs for fattening pigs (Pomar et al., 2009), and 15-17% of the production costs for sows and their litters until weaning (Solà-Oriol and Gasa, 2017). Consequently, nutrition is a major mechanism for improving the sustainability of pig production. Reducing the use of feed would reduce feed cost, and consequently nutrient excretion. It can also influence product quality: lean-to-fat ratio, fat quality, and the homogeneity of products. Currently, most of fattening pigs are group-housed and fed based on the average pig requirements of the room or the pen (Whittemore, 2006). Consequently, some pigs are overfed and others are underfed. Sows are usually fed two diets, one restrictively during gestation and the other nearly ad libitum during lactation (Solà-Oriol and Gasa, 2017); both based on an average sow's requirements. The goal of precision feeding is to develop systems that estimate and deliver, at the right time, a ration with a quantity and composition adapted to the requirements of each animal. The challenges in these systems reside in estimating individual requirements and distributing different diets to animals in the same group. These systems would improve feed and nutrient efficiency, major issues for the sustainability of all pig production systems (conventional and alternative). The objectives of this review were 1) to define feed efficiency and present the factors that influence it, as well as challenges to and strategies for improving it; 2) to define precision feeding and the sources of variability in nutrient requirements and show the need for new technology to obtain real-time data; and 3) to present the current models and applications of precision feeding for fattening pigs and sows.

1. Feed and nutrient efficiency

1.1. Definition and measure of feed efficiency

Feed efficiency (FE) is the ratio of mean daily weight gain to mean daily feed consumption over a given period (Gilbert, 2015). It can also be expressed as the ratio of growth to energy intake, which depends less on energy density in the diet. However, in practice, the inverse of FE is generally used for pigs, representing the efficiency of converting feed into weight gain (Gilbert, 2015). This feed conversion ratio (FCR) is similar to an economic measure of feed cost, whereas FE is similar to biological efficiency. The animals with the lowest FCR tend to be the most efficient (Bouquet, 2013).

Genetic improvement has reduced the FCR for most of the conventional pig breeds (Bouquet, 2013). Nevertheless, producers still seek to minimize FCR. Selecting animals for increased growth may lead to increased ingestion, whereas selecting for decreased ingestion may lead to decreased growth. More recently, to avoid this selection difficulty, residual feed intake (RFI) was used as another measure of efficiency. The RFI is calculated as an animal's daily feed consumption minus the quantity of feed required to meet its theoretical energy requirements (Bouquet, 2013). Pigs with high RFI are less energy efficient because they produce more heat, mainly due to increased physical activity and basal metabolic rate (Barea, 2010). RFI has high variability, but genetic selection can decrease it. Since RFI is not correlated with growth but is positively correlated with feed intake and FCR, selecting animals for lower RFI should have no influence on growth but would reduce ingestion. However, recent studies at IFIP (French Pork and Pig Institute) showed that selecting for FCR results is still more economic than selecting for RFI (Bouquet, 2013).

For fattening pigs, FCR is usually calculated from 10 weeks of age (around 30 kg of body weight, BW) to slaughter (around 115 kg of BW). FCR can also be calculated from weaning to around 10 weeks of age, or from weaning to slaughter (Gilbert, 2015). FCR for reproductive sows is more difficult to assess. It can be expressed, as for fattening pigs, as the amount of feed consumed over a given period divided by the BW gain of sows and piglets (total BW of piglets at weaning plus net increase in sow BW) over the same period. Another way to express FCR for sows would be as the amount of feed consumed per weaned piglet produced.

FCR can be expressed in different units; kg feed/kg gain is the most common unit, but MJ energy/kg gain is often used to consider variations in feed energy content. Cost of feed/kg gain is another way to express FCR that is more similar to the economic efficiency (Gilbert, 2015). Ultimately, FCR is not determined by growth rate and feed intake, but by factors that influence them, such as genetics, feeding practices, environmental conditions and health status. For example, data obtained from a French pig farm survey (Table 1) indicate that FCR depends on the breeding system and production period: herd FCR is greatest for the breeder-sale-at-weaning system (5.45 kg) and lowest for the weaner-fattener system (2.64 kg/kg). FCR is greater for the fattening period than for the post-weaning period, and these values vary among farms.

1.2. Factors that influence feed efficiency

Three equations can be used to express the FCR of growing pigs in different ways to identify the factors that influence FCR and how they do so. FCR depends on feed intake, feed spillage and animal growth (Eq. 1). It also depends on feed digestibility, digestive efficiency of pigs, the relative importance of maintenance and growth (Eq. 2 and 3), and the tissue (i.e. lean-to-fat ratio, Eq. 2) or chemical (Eq. 3) composition of weight gain.

$$\text{[Eq. 1] FCR} = (\text{feed intake} + \text{spillage}) / \text{pig growth}$$

$$\text{[Eq. 2] FCR} = (\text{indigestible} + \text{maintenance} + \text{growth}) / (\text{lean} + \text{fat} + \text{bone} + \text{skins} + \text{organs})$$

$$\text{[Eq. 3] FCR} = (\text{indigestible} + \text{maintenance} + \text{growth}) / (\text{protein} + \text{water} + \text{lipids} + \text{minerals})$$

Spillage. In Eq. 1, increased spillage increases the FCR. Spillage can be reduced by selecting feeder type. In the study of Pierozan et al. (2016), a linear dump feeder had less feed waste and lower FCR than other types of feeders, such as conical semiautomatic feeders (2.41 and 2.44, respectively, P = 0.04). Comparisons between feeder types are limited due to their diversity and the difficulty in developing trials to test the effect of feeder type on FCR, as it requires modifying the feeders (Pierozan et al., 2016). Feeder characteristics (individual shoulder protection, number of places per pig, and water supply) and localization in the pen are essential when selecting a feeder to reduce feed waste (Averós et al., 2012). Averós et al. (2012) reported that feeders with shoulder protection resulted in lower FCR than unprotected feeders due to a reduction of pig aggressions at the feeder. Feed restriction may also help reduce feed waste and improve FE (Patience et al., 2015). Another way to reduce spillage is to fed pellets instead of mash diets. Indeed, the review of Vukmirović et al. (2017) reported a general agreement on the fact that feeding pellets to pigs improved FCR, by improving DM digestibility and reducing feed wastage, compared to feeding mash diets. However, size particle is reduced during pelleting process, which can have negative effects on the gastrointestinal tract health.

Feed intake, growth and maintenance. Genotype determines growth rate because feed intake and growth rate differ among breeds. For example, Piétrain males have lower feed intake, growth rate, and fat deposition than Large White, Landrace and Duroc males (Edwards et al., 2006)(Fig. 1). FCR is a function of BW, and as pigs grow toward market weight, they become less efficient at converting feed into BW gain (Patience et al., 2015). This increase in FCR results from the increase in maintenance requirements, which depend on BW, and the decrease in the muscle lean-to-fat ratio. There is an increase in ingestion far above the protein deposition capacity; therefore, nutrients are deposited as fat, which decreases feed efficiency. However, this increase in FCR with BW varies with sex. For entire males, FCR increases slightly as BW increases, whereas for female and castrated pigs, FCR increases more rapidly with BW due to differences in feed intake and growth rate between sexes (Noblet et al., 1994) (Fig. 1).

During lactation, parity affects sow's feed intake. Sows of parity 1 or 2 consume about 15% less feed than older sows (Koketsu et al., 1996). This gradual increase in feed intake with advancing parity is consistent with the increase in maintenance energy requirements associated with the age-related increase in BW (O'Grady et al., 1985). Sows' mean daily feed intake also increases as litter size increases from small litters of 3-6 piglets up to 11 piglets, whereas it remains relatively constant for more than 11 piglets. Sows with small litters (< 7 piglets) have a mean daily feed intake of 4 kg lower than that of sows with larger litters (Koketsu et al., 1996). This increase in feed intake can be related to the increase in milk production as litter size increases (Auldist et al., 1998; Ngo et al., 2012).

Environmental factors such as space allowance, group size, number of feeders, flooring conditions, enrichment, temperature, ventilation rate, relative humidity, pathogens and stressors influence FCR (Averós et al., 2012; Averós et al. 2010) due to variation in feed intake.

Digestibility of feed and digestive efficiency of pigs. In Eq. 2 and 3, FCR increases as the indigestible portion of the feed increases. The digestibility of feed depends greatly on its composition (Ponter et al., 2004) and on animal digestive capacity, which has been shown to vary among pigs in interaction with feed composition (Noblet et al., 2013). For example, a greater proportion of fiber in the diet is a challenge for digestion and results in high variability in pig performance. Noblet et al. (2013) found that the digestibility of energy is influenced by sire, which suggests that digestibility depends on heritable genetic variability. Kyriazakis (2011) also reports that selecting pigs for digestive efficiency would improve nutrient efficiency. Further research is needed to understand underlying mechanisms.

Composition of weight gain (lean-to-fat ratio). Eq. 2 and 3 indicate that the chemical and tissue compositions of BW gain influence FCR. The chemical composition of empty BW gain in minerals and protein (around 3% and 16-17% of empty BW, respectively) (Table 2) is similar among breeds and sexes, except for certain traditional breeds whose protein content is lower (Noblet et al., 1994). Conversely, the percentages of water and lipids are largely related to genotype and sex, which influence the energy content of gain. Adipose tissue yields around four times as much energy as muscle tissue (protein and lipid deposition cost 9.1 and 29.2 MJ of ME per kg, respectively) because it contains less water. This results in large differences in the energy content of BW gain among genotypes (e.g. 11.2 MJ/kg in Piétrain males vs. 21.1 MJ/kg in Meishan castrates) and between sexes (12.3, 13.8, and 15.6 MJ/kg for Large-White males, females, and castrated males, respectively) (Noblet et al., 1994). Over the past 40 years, most genetic improvement in FCR has been obtained by reducing the proportion of lipids in BW gain. Selection for fast growing and lean animals has increased the potential for protein deposition and reduced the amount of energy required to achieve this potential, usually with little influence on feed intake (Gilbert, 2015).

In the meta-analysis of Averós et al. (2012), pigs fed ad libitum had higher FCR than pigs fed restrictively. The effect of feed restriction on FCR varied with the type of animal. For a lean animal, a restriction in energy supply reduced similarly the deposition of proteins and lipids while for a fat animal, fat deposition is reduced in priority without increasing protein deposition (Gilbert, 2015). Therefore, in fat animals, FCR decreases, whereas in lean animals FCR changes little or even increases due to increased maintenance requirements (Bikker et al., 1996).

Nutrient utilization. As previously mentioned, FCR is affected by the efficiency of energy utilization, which depends on the energy content of BW gain and the effect of maintenance requirements. Similarly, to the energy, the efficiency of utilizing nutrients, such as amino acids (AA) and minerals, is also affected by nutrient digestibility and maintenance requirements Above maintenance, the apparent efficiency of use of digestible minerals and AA for tissue deposition depends on their metabolic efficiency of retention, and on their possible oversupply. In case of nutrient undersupply, the marginal efficiency of retention is at highest, but due to insufficient supplies, growth rate decreases resulting in an increased FCR. Conversely, when nutrients are supplied in excess to the requirement they contribute to increasing excretion, which results in reduced efficiency of retention. For instance, in growing pigs, metabolic efficiency of digestible lysine retention is about 72%, whereas on average in practice, over the fattening period, its apparent efficiency with conventional two-phase feeding programs is only about 45% (van Milgen et al., 2008). Thus, improving efficiency of use of nutrients requires (i) to improve their digestibility and (ii) to provide them, over time, as close as possible to individual animals' requirements in order to limit their oversupply.

Up to 80% of P in feedstuff (cereals and seeds) is tightly bound in phytate, but pigs do not produce enough phytase enzyme to degrade phytate, which encapsulates P, protein, and AA in feedstuffs. Adding exogenous phytase is thus an effective way to improve the digestibility and efficiency of utilizing P and, to some extent, other nutrients (Jondreville and Dourmad, 2005). Adequate supplies of minerals and AA are needed to respectively maximize growth and bone mineralization (Letourneau et al, 2016) and protein retention, and therefore minimize FCR. The supply of an AA such as lysine influences FCR in different ways (Fig. 2). The lack of one or more AA limits protein deposition as protein synthesis decreases. This results in an increase in lipid deposition and consequently a decrease in growth rate and an increase in FCR (van Milgen, 2008). When one AA is limiting, the other AA in excess are catabolized and excreted as urea, reducing energy efficiency and increasing cost and waste. Similarly, an excessive supply of nutrients increases nutrient excretion, fat deposition and FCR. Nutrient requirements also depend on pig characteristics such as sex, age and genotype. For example, entire males require more lysine than females (Fig. 2) and castrated males. In growing pigs, the AA requirement relative to energy decreases as BW increases (Van Milgen et al., 2008, Noblet et al., 2016). In sows, the AA requirement increases with the stage of pregnancy and is greatest during lactation (Dourmad et al., 2008). Similar trends are observed for mineral requirements of growing pigs and sows. This indicates the need to optimize each individual’s nutrient ingestion to maximize individual efficiency and reduce excretion. Taking into account individual characteristics (age, breed, sex, BW) can be used to better feed to animals up to their individual requirement. Nutrient ingestion can be optimized by using predictive models of nutrient requirements (Brossard et al., 2017) (see section 3).

1.3.Strategies to improve feed efficiency

Genetics and microbiota. Feed efficiency is one of the most important selection criteria in breeding programs, as it affects total cost of pig production and environmental footprint (Kanis et al., 2005; Reckmann et al., 2016). Thus, FE and related traits are a major target for genomic selection, a growing and promising method. Until recently, FCR and RFI were the two main traits used to evaluate FE, as described in the first part of this review. With the development of new technology and automatic data recording, recent studies have been looking for new traits related to FE like, for example, feed intake and feeding behavior (daily occupation time, daily feeder visit, and daily feeding rate) recorded daily and individually. Major quantitative trait loci for feed intake and for feeding behavior traits have been identified on different chromosomes as well as the positional and functional candidate genes (Reyer et al., 2017). This is a first step toward the understanding of the genetic connection between distinct feeding behavior traits and FE that can be used to select the most efficient animals.

Genetic factors are also influencing the abundance of distinct bacterial species (Benson et al., 2010). Several studies found a link between the porcine intestinal microbiome and FE (McCormack et al., 2019a; Tan et al., 2017). While the effect of intestinal microbiota in expressing FE has been confirmed, methods to phenotype the microbiota should be developed to use this information on farms. McCormack et al. (2019b) reported the effect of fecal microbiota transplantation (FMT), using fecal extracts from highly feed-efficient pigs, in pregnant sows on the offsprings performance. The FE of the offsprings from a mother under FMT was improved compared to the one of offsprings from a mother not under FMT (similar feed intake but growth differences). However, the negative effect of FMT on the offsprings growth limits the application of this procedure in commercial farms. Manipulations of bacterial populations can also be used to improve digestibility and FE (Le Sciellour et al., 2018) that would allow more flexibility regarding ration composition especially on the amount of fibers. Niu et al. (2015) reported that several bacteria were correlated with apparent crude fiber digestibility; of these, Clostridium is associated with dietary fiber metabolism. They also found that the abundance and diversity of the gut microbiota in pigs increased and changed with increasing age. Intestinal microbiota facilitates digestion of fiber, but its effects on the variability in FE needs to be assessed and broken down into the fraction that depends on animal genetics, the fraction that depends on breeding conditions and the fraction that sows transmit to piglets at birth and during lactation.

Finally, robust indicators need to be developed to quantify the sensitivity of animals to variations in the environment. For example, it seems that feed intake and growth rate of pigs selected for lower RFI are less affected by the quality of the environment than those of pigs selected for higher RFI (Gilbert et al., 2017).

Removing external stressors. Black et al. (2001) reported that removing one or more stressors, or reducing their influence, improves pig performance because the stressors may have additive effects. Structural changes in buildings like the addition of cooling systems, floor type reduce climate stress (Black et al., 2001). During a short-term exposure to hot conditions (32°C as opposed to 21°C), pigs ate about 60 to 100 g less feed each day per °C of heat stress (Heitman and Hughes, 1949; Heitman et al., 1958). In their meta-analysis, Renaudeau et al. (2011) reported that feed intake and average daily weight gain of growing-finishing pigs are decreasing with increasing temperature starting from 20°C. Moreover, these effects were more pronounced with increasing pig body weight. Ambient temperature clearly impact feed intake and consequently FCR. Structural changes in the building also help improving cleanliness. Reducing the microbial load by ensuring building hygiene has increased production and decreased disease incidence (Le Floc'h et al., 2006). In a dirty environment measured through air quality (amount of ammonia, CO2 and dust), pigs' feed intake has been found to decrease of 100 g/kg compared to a cleaner environment, especially for individually housed pigs (Currie et al., 1997; Lee et al., 1997). The type of feeder (design, access, location) also has an effect on FCR (Rantanen et al., 1994).

Adequate nutrient supply. As previously indicated, feed and nutrient efficiency depend partly on nutrient utilization, which is based on adjusting nutrient supply to requirements. Therefore, one way to improve FE is to refine this adjustment by estimating animal requirements more accurately. Two methods are generally used to estimate nutrient requirements for pigs: empirical and factorial. Briefly, requirements in the empirical method correspond to those of a population for a given performance target and time interval. However, the estimated requirements cannot be extrapolated to other situations because they vary as a function of animal characteristics and environments (Pomar et al., 2003). In contrast, nutrient requirements in the factorial method are estimated for an average animal at a given stage. However, pig performance depends on pig characteristics (genetic, age, weight, sex, social status and health), feed characteristics (feed allowance, nutrient composition and digestibility), and housing conditions (ambient temperature and space allowance) (Noblet and Quiniou, 1999). Models based on the factorial approach have been developed to simulate performance of a single animal and can predict nutrient requirements and appropriate feeding strategies (e.g., van Milgen et al., 2008). However, because they are based on an average animal, feeding strategies based on this approach means that many animals are inevitably underfed or overfed (Pomar et al., 2003). Individual variability influences the efficiency of nutrient utilization (Pomar et al., 2003, Brossard et al., 2009). In addition, the fact that nutrient requirements change over time needs to be considered to predict them more accurately. Precision feeding requires developing new feeding strategies to refine the adjustment of nutrient supply to requirements.

2. Individual variability, the key point of precision feeding

2.1.Precision feeding: definition, objectives, advantages

Precision feeding is one way to better consider individual variability in nutrient requirements within a group. It involves using technology to provide the right amount of feed, with the right composition and at the right time, to a group of animals or to individuals (Pomar et al., 2009). Precision feeding aims to improve characterization of individuals (feed intake, growth potential, body condition, physical activity, health, etc.) or small groups to better adapt the quantity, quality and timing of feed supplied to them. It also aims to improve efficiency by reducing farm costs, reducing excretion, and monitoring quality (Fig. 3). Applying precision feeding and doing so accurately requires assessing the nutritional potential of feed ingredients and nutrient requirements of each animal to formulate balanced diets accurately to minimize nutrient deficiency or excess (Pomar et al., 2009).

The results of previous precision feeding assessments are promising (Andretta et al., 2014, Pomar et al., 2014, Andretta et al., 2016). For growing-finishing pigs, compared to a classic three-phase group-feeding strategy, adjusting feed composition daily based on the performance of an average animal in the group decreased N excretion by 12% without influencing growth (Pomar et al., 2007). This continual adjustment also has an economic advantage because it can be based on a mixture of two feeds, one with a high nutrient content and one with a lower nutrient content. At the individual scale, precision feeding of growing-finishing pigs further reduces N and P excretions compared to a multiphase group-feeding strategy (respectively, 38 vs. 42 g/d for N, and 5 vs. 6 g/d for P) (Andretta et al., 2014). Simulations indicate that precision feeding could also be beneficial for sows: using a multiphase feeding strategy (a mixture of two feeds) during gestation reduced the quantity of lysine ingested (-17%), N excretion (-19%), and feed cost (-8%) (Dourmad et al., 2015). These results for sows need to be confirmed with trials in experimental farms. “On-farm” application of precision feeding requires designing and developing measuring devices (for intake, BW), calculation methods and a feeding system that provides the required amount of feed with a composition that optimizes animal performance while minimizing the use of farm resources (Pomar et al., 2009).

2.2.Variation in nutrient requirements

Two main sources of variation in nutrient requirements must be considered: variations over time and differences between animals. Nutrient requirements vary over time (Andretta et al., 2014) and among growing pigs in a group receiving the same feed (Pomar et al., 2007, Brossard et al., 2009), due to sex (castrated or entire males, females), age (different nutritional requirements), weight and individual potential. Nutritional requirements of sows also vary with individual characteristics such as physiological status, age, weight and prolificacy

(Dourmad et al., 2017). Sows of parity 1, 2, or 3 continue to grow while gestating, whereas sows of parity 4 or more have already reached their mature weight, which means that their requirements are limited to maintenance, gestation and rebuilding body reserves used up during gestation. These between-animal variations influence the population response, the efficiency of nutrient utilization, and consequently the optimal nutrient supply for the population (Pomar et al., 2003, Brossard et al., 2009). Therefore, stochasticity has been introduced into models to address variability, simulate responses of groups of pigs (Pomar et al., 2003) and define strategies to improve on-farm nutrient efficiency (Brossard et al., 2017). These variations among animals and over time show the relevance of developing more individualized feeding strategies (see section 3).

In growing pigs, Cloutier et al. (2015) reported that the factorial method used to estimate individual daily lysine requirements was able to accommodate the small genetic differences in feed intake without a specific correction for genetic differences. This method can be used in precision feeding systems without adjustments for small genetic differences but should be studied further for larger genetic differences in feed intake and protein deposition patterns.

2.3.Feeding technologies and real-time data

Improving FE requires considering individual feeding requirements. Precision feeding uses feeding technologies to adjust animals' diets. Development of precision feeding systems requires automatic data collection, data processing, and system monitoring.

Technology and individual data collection. Farm animals can be identified by radiofrequency (RFID), which makes data collection reliable and simplifies management of individuals (Cornou and Kristensen, 2013). Using RFID and sensors automates farm equipment, which can transfer real-time data to a farmer or an automated decision support system that can make rapid management decisions (Fig. 3). Cornou and Kristensen (2013) listed several sensors used in pig production and how their data can be used to support decisions. Automatic identification of an animal is the first step in monitoring production efficiency and is performed on pig farms usually by placing an ear-tag containing an RFID chip on each animal to recognize the animal, for example at the feeder. Electronic feeding stations can record the number, time and duration of the visits, and the quantity of feed ingested by each pig. In commercial herds, only sows are individually identified at electronic feeding stations. Individual identification is uncommon for fattening pigs due to its cost, although the technology is available for selection herds. Several technologies exist that automatically record BW: foreleg weighing systems (Ramaekers et al., 1995), image analysis (Parsons et al., 2007), the walk-through using machine vision (Banhazi et al., 2011) and photogrammetry to determine pigs' three-dimensional shapes (Wu et al., 2004). Knowing the body composition might also be required to individualize the diet, especially in gestating sows. Body composition can be determined by analyzing images or videos or measuring backfat thickness with ultrasound; however, this last technique is performed manually and would need to be automated. Pig activity, which may also be of interest, can be automatically recorded using photocells, force sensors for sows housed in crates (Oliviero et al., 2008), and accelerometers for sows in loose housing or crates (Cornou and Lundbye-Christensen, 2012). Finally, pig temperature influences FE and can be automatically recorded using an ear-based temperature sensor or estimated using an image-analysis procedure based on the pig's thermoregulatory behavior (Wouters et al., 1990).

Data processing. The sensors described above provide large amounts of data on a daily basis. The biological characteristic of interest needs to be extracted from each measurement. First, the data are cleaned by removing abnormal values, which requires defining thresholds. Then, the characteristic of interest is generally extracted by smoothing the data; the amount of smoothing is based on the objective (Friggens and Robert, 2016). These data will then serve as inputs to models to predict animals' nutrient requirements.

3. Models and applications of precision feeding

Applying precision feeding requires developing models that predict nutrient requirements and using the models to test and select new feeding strategies. These models are of interest to compare alternative production systems to existing ones, from a time and economical point of view, and also to gain confidence in the success of a new strategy before testing it in real-life. Until now, most of the production models were based on an average animal, but individual variability need to be considered to gain in precision (Knap et al., 1995; Kyriazakis, 1999).

3.1. Fattening pigs

Hauschild et al. (2012) developed a model that predicts real-time individual AA requirements of growing-finishing pigs. The model consists of two components (Fig. 4). The empirical component uses individual pig information (intake and BW) in real time to estimate daily feed intake and daily gain for the current day. Based on these estimates, the mechanistic model uses factorial equations to predict net energy intake and AA requirements (expressed through standardized ileal digestible lysine, SID Lys). The optimal AA concentration needed to meet each pig's requirements is predicted daily. To do so, the model requires at least seven consecutive feed intake measurements and two BW measurements to begin predicting feed intake, BW and the nutrient requirements.

The Hauschild et al. (2012) model was evaluated using data from a previous trial (Pomar et al., 2007) that tested the influence of a daily 3-phase or multiphase feeding strategy on pig efficiency. Daily feed intake and BW trajectories of an animal could be predicted 1 day or 7 days in advance, respectively, with an average mean absolute error of 12% and 1.8%, respectively. The mechanistic component of the Hauschild model has been used in two animal trials (Zhang et al., 2012, Cloutier et al., 2015). In the Zhang et al. (2012) trial, the model accurately predicted SID Lys requirements of pigs of 25-55 kg BW, but underpredicted the requirements of heavier animals. In the Cloutier et al. (2015) trial, the model was used to predict individual daily SID Lys requirements and to consider the influence of small genetic differences on them. Three trials evaluated the overall approach of estimating real-time AA requirements and the effect of switching from conventional to precision feeding systems in growing-finishing pig operations on productive performance, nutrient utilization, body composition and environmental costs (Andretta et al., 2014, Pomar et al., 2014, Andretta et al., 2016). Pomar et al. (2014) found that a daily phase-feeding strategy (mixing two feeds) reduced N intake by 7.3%, P intake by 3.3%, N excretion by 11.7%, P excretion by 1.9% and feed cost by 1.3% compared to those of a 3-phase feeding strategy. Andretta et al. (2014) found that a multiphase individual feeding strategy reduced SID AA intake by 27%, P excretion by 27% and N excretion by 20% compared to those of a 3-phase feeding strategy. Andretta et al. (2016) found that an individual feeding strategy (in which the mixing proportions of two feeds were updated daily to meet 100% of the lysine requirement) reduced SID Lys intake by 26%, N excretion by 30% and feeding cost by 10% compared to those of a group-feeding strategy. These three trials show that using precision feeding techniques to feed growing-finishing pigs with diets that are tailored daily is an effective approach to reduce nutrient excretion without compromising performance. It confirms that combining precision feeding with real-time modeling of requirements can improve the efficiency of use of feed and nutrient, and to some extend the economic result. However, this requires more sophisticated equipment (e.g. equipment for feed storage and distribution, smart feeders, weighing scale), with more supervision, inducing additional costs that were generally not considered in the economic evaluation. Predictive models require further improvements, such as including health factors (environmental stressors, pathogen levels), and prediction of technical, economic and environmental effects of precision feeding on commercial farms. For example, Monteiro et al. (2016) used the InraPorc decision support tool (https://inraporc.inra.fr/inraporc/index_en.html) to predict production data that they then used as input data for life cycle assessment to compare environmental effects of four pig feeding strategies. They predicted that an individual feeding strategy yielded the lowest life cycle effects for pig fattening in all situations (in France and Brazil). Finally, this technology needs to be implemented and validated on commercial farms. Current technology can feed pig groups based on their weight, but automatic feeders with a decision support tool are not yet commercially available.

3.2. Sows in gestation and lactation

Mechanistic models such as InraPorc (Dourmad et al., 2008) and the model of Hansen et al. (2014) were developed to simulate energy and nutrient partitioning of reproductive sows on a daily time step. These models represent sows as the sum of multiple compartments: body protein, body lipids, body minerals and the uterus (Dourmad et al., 2008) (Fig. 5). Equations describing nutrient utilization by sows were used to build InraPorc, which predicts daily nutrient and energy flows from feed to storage in the body and then excretion. InraPorc simulates daily utilization of key nutrient pools by a sow. InraPorc also predicts energy and AA requirements of sows based on production objectives, as well as changes in body composition due to a given feeding strategy or housing condition (Gaillard et al., 2019a).

Dourmad et al. (2015) used InraPorc to simulate and evaluate two-phase and multiphase feeding strategies during gestation. Simulations results indicate that compared to one-phase feeding, the two-phase and multiphase strategies could respectively reduce crude protein (CP) intake by 10% and 14%, SID Lys intake by 11% and 17%, P intake by 5% and 7 %, N excretion by 15% and 20%, and P excretion by 9% and 12%. Dourmad et al. (2017) and Gaillard et al. (2019a) developed a decision support tool for gestating sows based on InraPorc. Optimal supply for a given sow was determined each day by a factorial approach that considered all the information available about the sows (genotype, parity, gestation stage, etc.). Energy supply was calculated for each sow to reach a target BW at farrowing. Precision feeding with the mixing of two feeds was then simulated and compared to conventional feeding (single feed). Simulations indicated that compared to conventional feeding, precision feeding could reduce total SID Lys supply by 27%, total CP supply by 28%, and the number of under- or over-fed sows (Gaillard et al., 2019b). Adapting the feeding strategy during gestation to capture changes in nutrient requirements more adequately appears a promising approach to reduce N and P excretion without increasing feed cost, but this remains to be validated on experimental farms. During gestation, sows are housed in groups, offering the potential to use automatic feeders and apply these new feeding plans that consider sow characteristics, such as parity, weight, and backfat thickness at the start of gestation. However, although this approach is possible, the use of models and the potential to improve FE remains limited in practice, mainly due to insufficient data collection and the lack of decision support systems.

On most farms, sows are fed different diets for gestation and lactation instead of the same diet for both, reducing N and P excretion by 20-25% (Dourmad et al., 1999). Currently, few studies have focused on improving feeding strategies for lactating sows, even though sow requirements vary greatly. A precision feeding strategy might be useful for lactating sows because nutrient requirements per kg of diet vary greatly as a function of milk production and feed intake. For example, sows of parity 1 have greater requirements due to their lower feed intake. Nutrient requirements also vary by season due to the influence of temperature on feed intake and milk production. Gauthier et al. (2019) developed a decision support system based on InraPorc that could be incorporated in automated feeding equipment. Simulations compared a conventional feeding strategy to a precision feeding strategy; the latter could reduce mean lysine intake by 6.8%, P intake, and the number of under- or over-fed lactating sows.

3.3. Modeling mineral requirements

Minerals are a major component of pig nutrition. Because P is necessary for bone development and the metabolism of growing pigs, it must be supplied in pig diets. Dietary P of plant origin has low digestibility for pigs, but addition of P and/or phytase increases feed cost. The oversupply and low digestibility of P also results in high P excretion, which affects the environment. Therefore, models that predict mineral requirements are required to optimize mineral supply and minimize excretion (Brossard et al., 2017). Minerals have received little modeling attention because most models have focused on AA. Jondreville and Dourmad (2005) used a factorial approach to estimate P requirements for maintenance and production in different physiological stages, and it was later added to InraPorc for growing pigs (van Milgen et al., 2008) and sows (Dourmad et al., 2008). This approach considers the influence of the type of diet (pellets or mash) and the addition of phytase on digestibility. The model allows dietary P supply to be adjusted to pig performance and physiological status and predicts the influence of performance level on apparent digestible P requirements. However, P requirements for growth are estimated from animal BW gain, which has certain limitations. More mechanistic models have therefore been developed in which mineral content (P and calcium) can vary independently of protein and lipid mass (Letourneau-Montminy et al., 2015). These deterministic and mechanistic research models can be used to improve decision support tools to develop feeding strategies that minimize P excretion. These models must also consider that mineral requirements change during each physiological stage (e.g. an increase in calcium requirements at the end of gestation).

For gestating sows, recent simulations of a precision feeding strategy based on lysine requirements still report an important excess in phosphorus (Gaillard et al., submitted). This is partly because the implemented strategy was based on lysine requirements with only two diets. Hence, in such condition it was not possible to deal with the different dynamic of lysine and phosphorus requirements over the whole gestation. To modulate lysine and phosphorus supplies independently, one solution would be to calculate the proportions of the two mixed diets (High Lysine and Low Lysine) based on lysine and phosphorus requirements simultaneously, and therefore propose 3 different diets to combine for precision feeding instead of two (High Lysine + High P, Low Lysine + High P, Low Lysine + Low P). However, the strategy might be less efficient then for lysine and will need to be evaluated and compared with the present feeding strategy, based on lysine only, in terms of production, excretion, and costs.

Conclusion

Feed efficiency can be expressed as the ratio of mean daily weight gain to mean daily feed consumption during a given period. In practice, the inverse of this ratio is generally used for breeding animals and represents the efficiency in converting feed into weight gain (feed conversion ratio, FCR). Several factors influence FCR, such as feed spillage, feed digestibility, composition of weight gain, feed intake and nutrient utilization. The FCR can be decreased by selecting the appropriate form of feed and nutrient density and supply, and by reducing negative effects of environmental factors. Precision feeding is based on managing individual variability within a group and uses feeding technologies (e.g. sensors, feeders) to provide the right amount of feed, with the right composition, and at the right time, to a group of animals or to individuals. Predictive models of nutrient requirements and excretion, such as InraPorc, have been developed to select optimized feeding strategies. For growing pigs, precision feeding is a promising solution to reduce nutrient excretion by daily adjusting the supply of nutrients to individuals. Recent simulations results indicate that this might also be an appropriate feeding strategy for sows. Decision support models could be enhanced by improving sensors or considering factors such as ambient temperature and animal physical activity, which also influence energy utilization and consequently the FCR.

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Table 1. Mean of FCR of French pig farms in 2016 by production system. Source: IFIP (French Pork and Pig Institute, http://en.ifip.asso.fr/)

System	Breeder, sale at weaning	Traditional breeder	Breeder-Fattener	Fattener	Weaner-Fattener
Number of farms	80	15	1579	82	330
Number of sows	525	569	228	1831	2848
Overall performance					
Feed per sow, kg/year	1221	1251	1218		
Overall FCR, kg/kg	5.45	3.07	2.82	2.96	2.64
Feed cost, €/kg	1.456	0.904	0.680	0.660	0.635
Post weaning					
Feed intake, kg/piglet		33	42		42
FCR, kg/kg		1.78	1.68		1.68
Fattening					
Feed intake, kg/d			2.23	2.31	2.29
FCR, kg/kg			2.69	2.88	2.74

FCR: Feed Conversion Ratio

Table 2. Chemical and tissue composition of the empty BW gain (from Noblet et al., 1994)

Genotype	Piétrain	Large-White			Meishan
Sex	Male	Male	Female	Castrated	Castrated
Growth, g/d	804	881	726	751	458
Tissues, g/kg					
Muscles	580	472	450	420	242
Adipose tissues	181	206	253	309	430
Composition, %					
Water	61.6	58.5	55.0	51.0	39.2
Minerals	2.6	3.0	3.0	3.0	2.1
Proteins	17.4	16.7	15.9	16.0	11.1
Lipids	18.2	21.1	25.0	30.4	48.8
Energy, MJ/kg	11.2	12.3	13.8	15.6	22.1

Figure captions

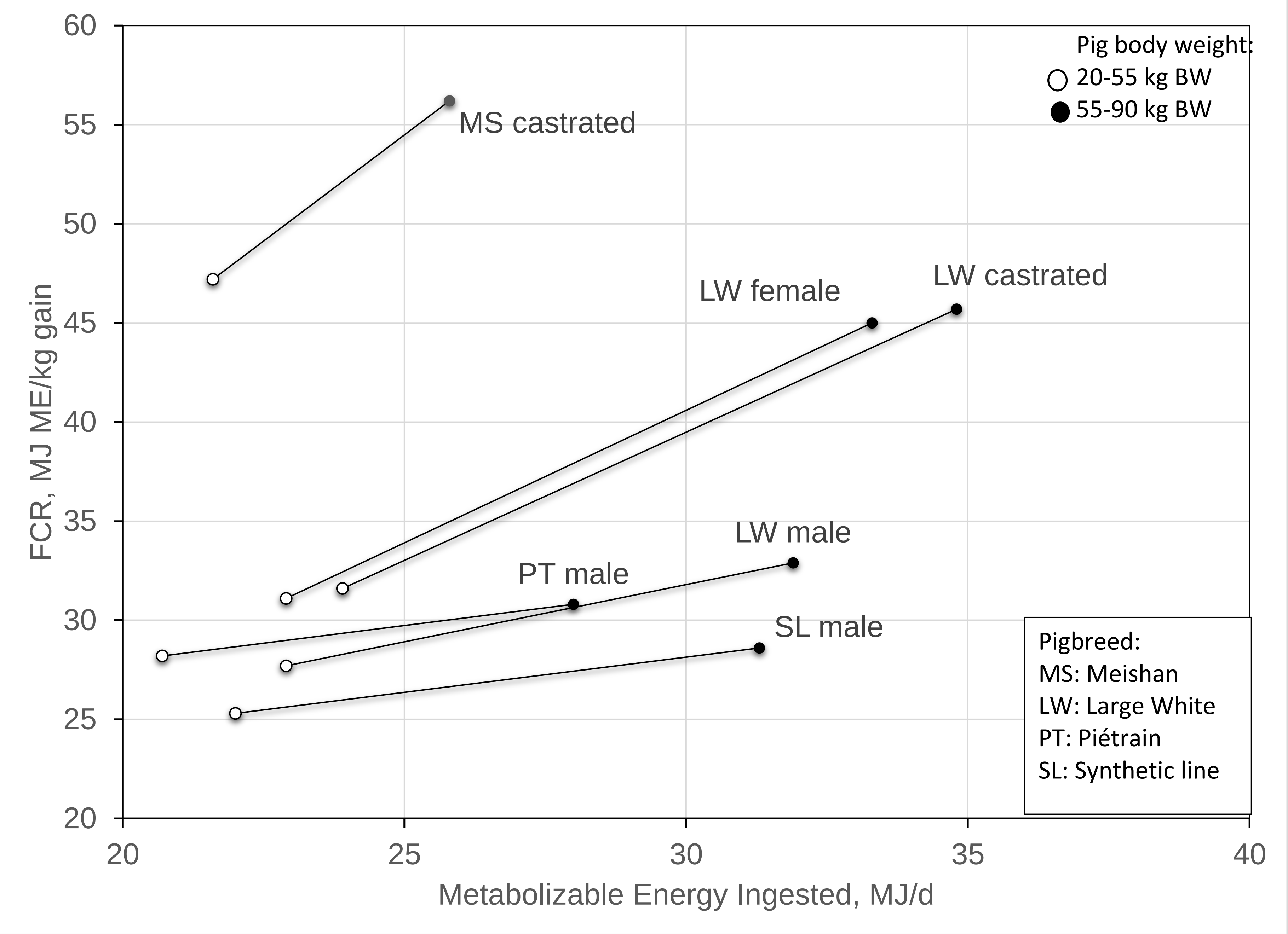
Figure 1. Relationship between feed conversion ratio (FCR) (MJ ME/kg gain) and ME ingested (MJ/d) for different breeds (MS = Meishan, LW = Large-White, PT = Piétrain, SL = Synthetic line of animals selected for their low adiposity) and sexes of pigs from 20-55 kg BW (open circles) and 55-90 kg BW (solid circles) (data from Noblet et al, 1994). ME = metabolizable energy.

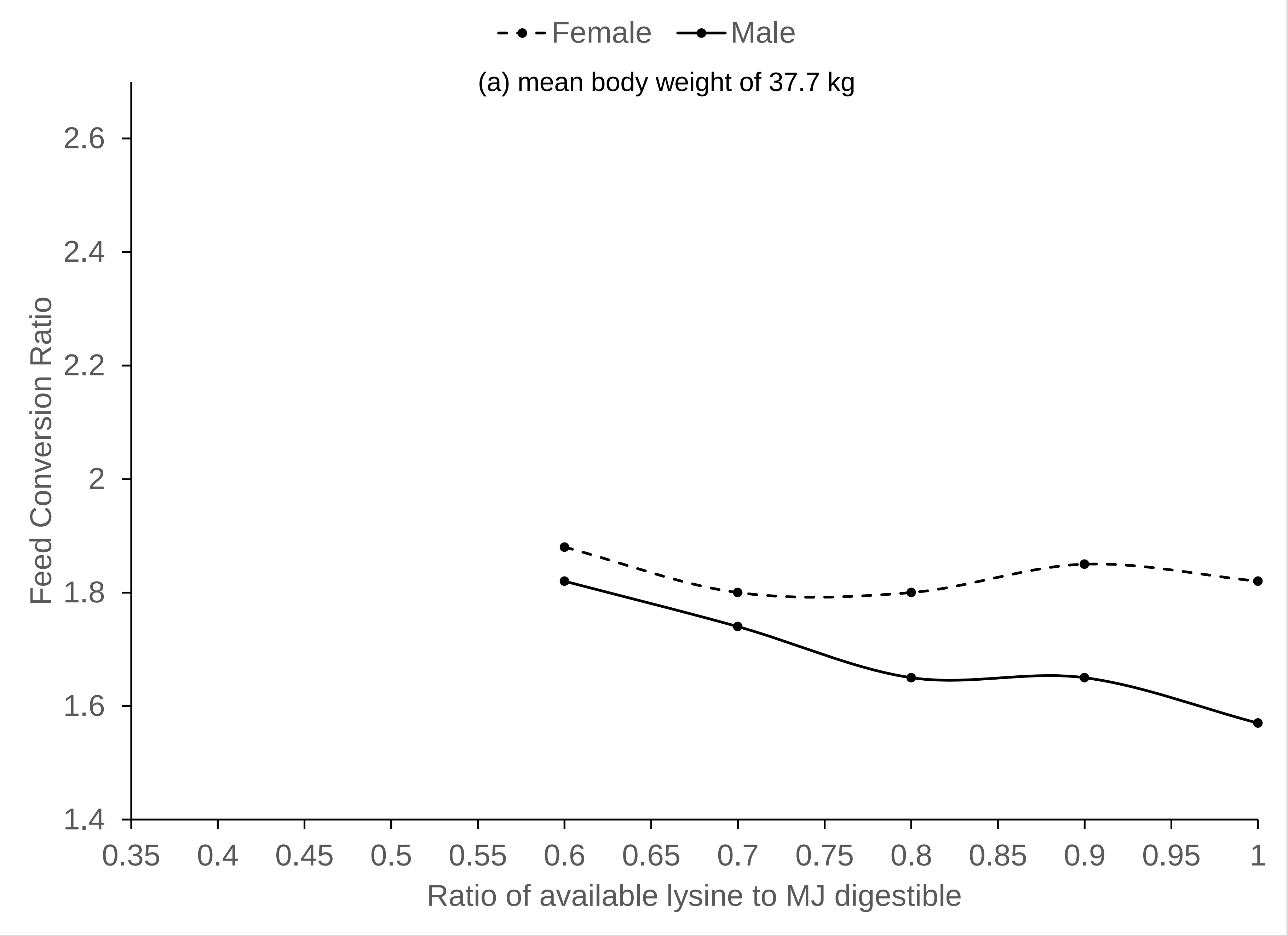
Figure 2. Effect of the ratio of available lysine to MJ digestible energy on mean feed conversion ratio (± 1 SEM) for (Large-White x Landrace) x Duroc female and male pigs with a mean body weight of (a) 37.7 kg and (b) 76.4 kg (Mullan et al., 2011)

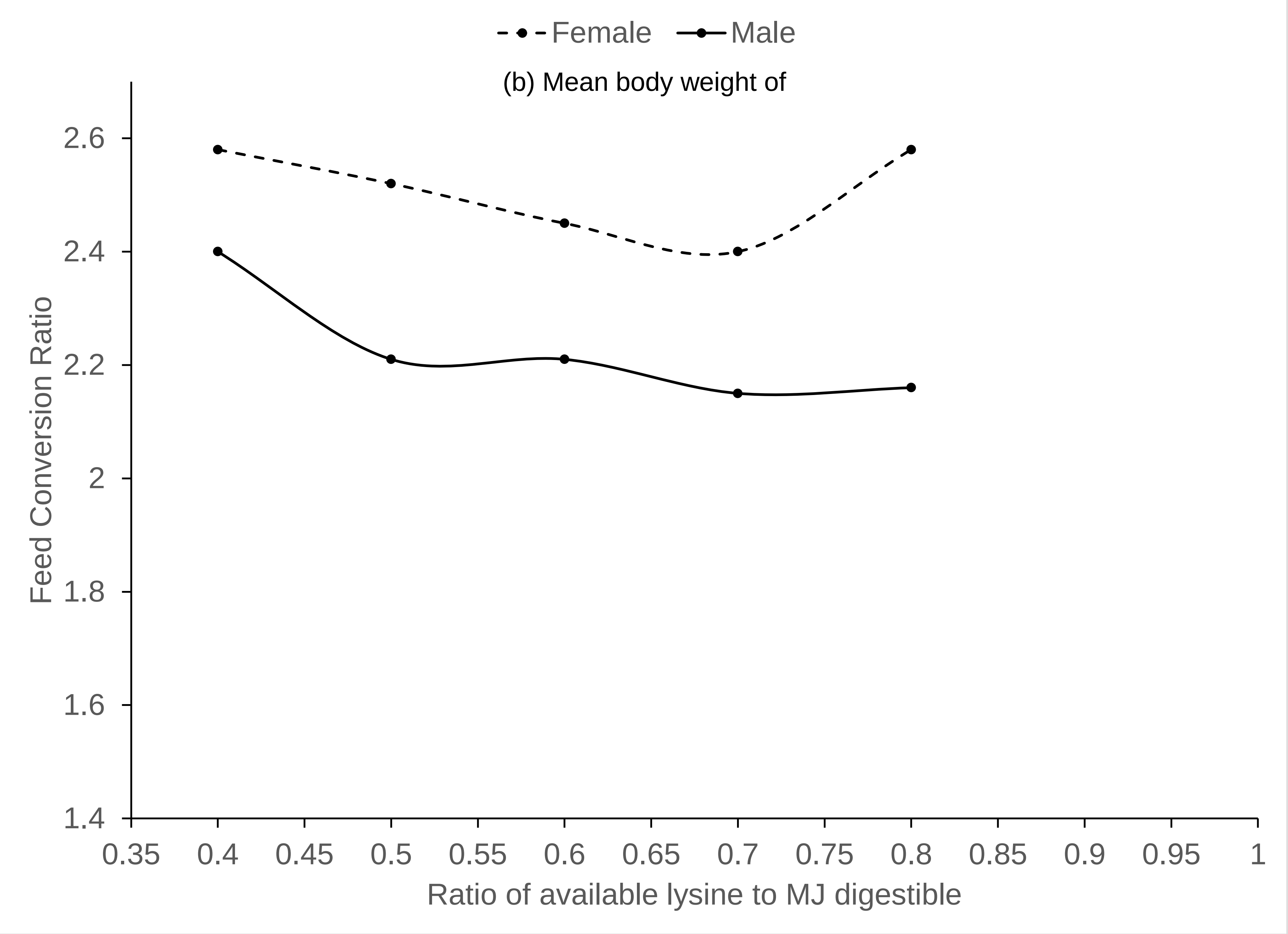
Figure 3. Principles of precision feeding (adapted from Allain et al., 2014)

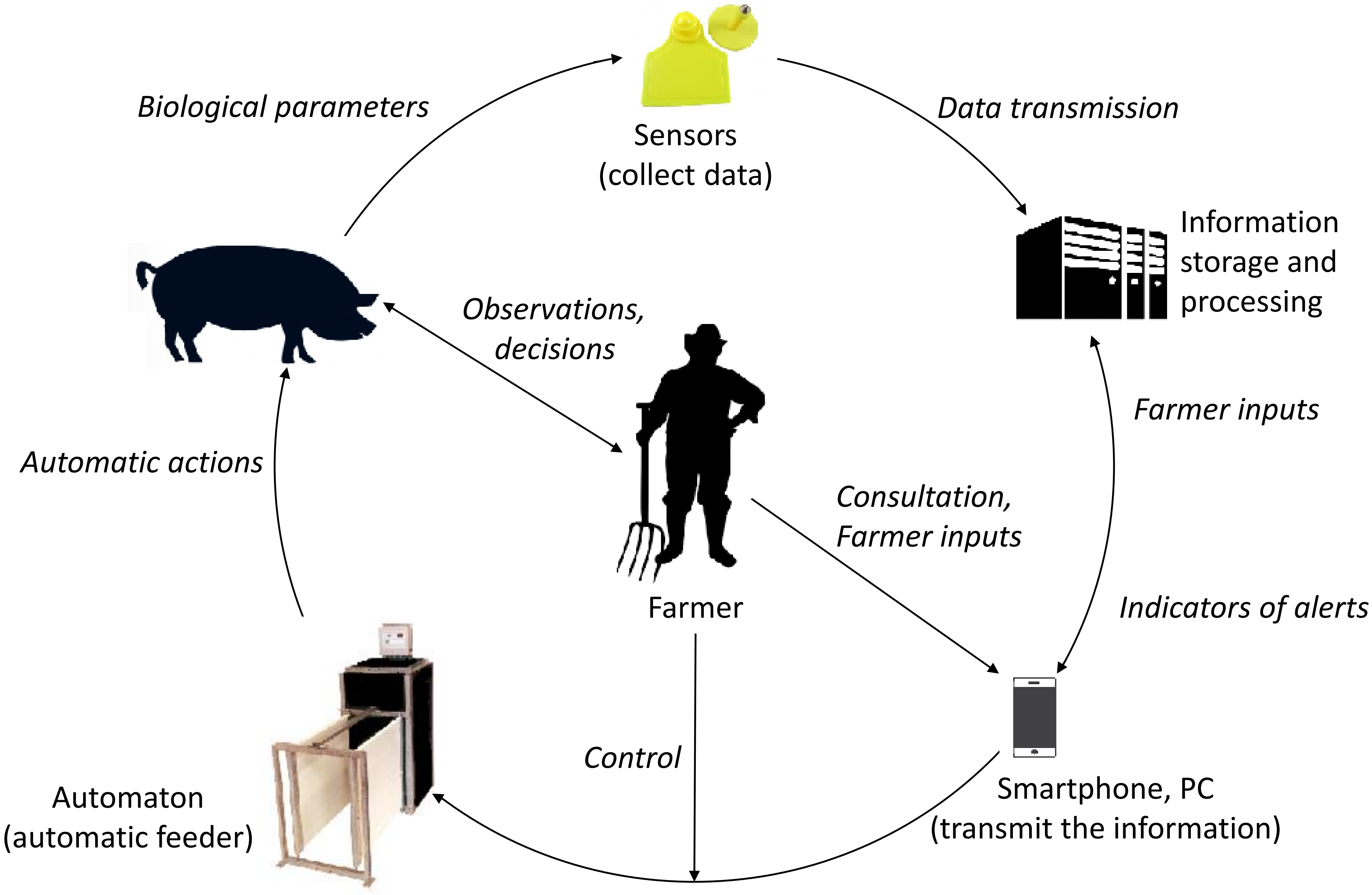
Figure 4. General outline of the Hauschild et al. (2012) model, with empirical and mechanistic model components used to estimate daily nutrient requirements for each individual in a pig population according to its measured growth and feed intake patterns (adapted from Hauschild et al., 2012). BW = body weight

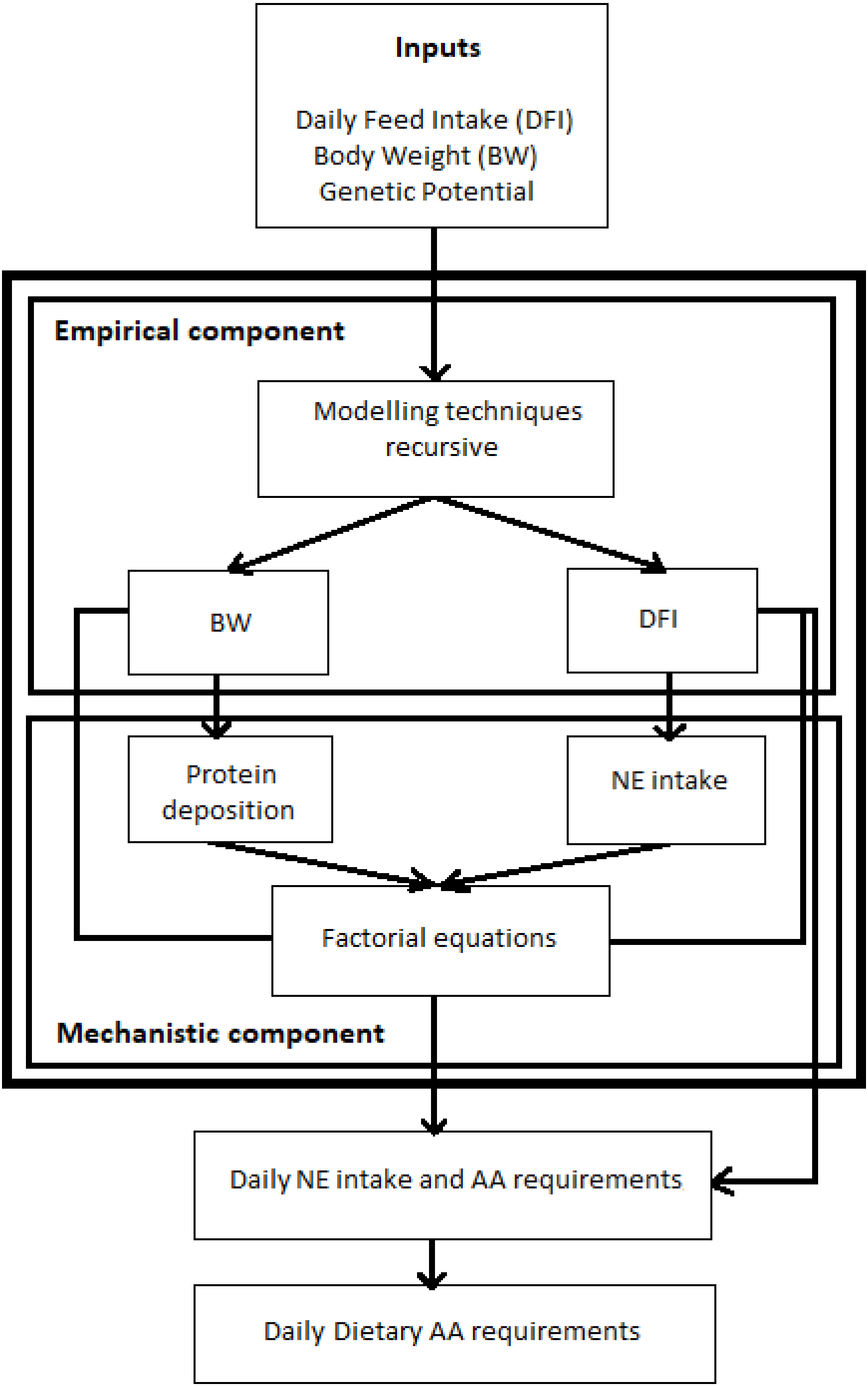
Figure 5. Configuration of the InraPorc decision making tool for sow nutrition (from Dourmad et al., 2008). BW = body weight


Pig body weight:
○ 20-55 kg BW
● 55-90 kg BW
MS castrated
LW female
LW castrated
LW male
PT male
SL male
Pigbreed:
MS: Meishan
LW: Large White
PT: Piétrain
SL: Synthetic line
FCR, MJ ME/kg gain
60
55
50
45
40
35
30
25
20
20
25
30
35
40
Metabolizable Energy Ingested, MJ/d

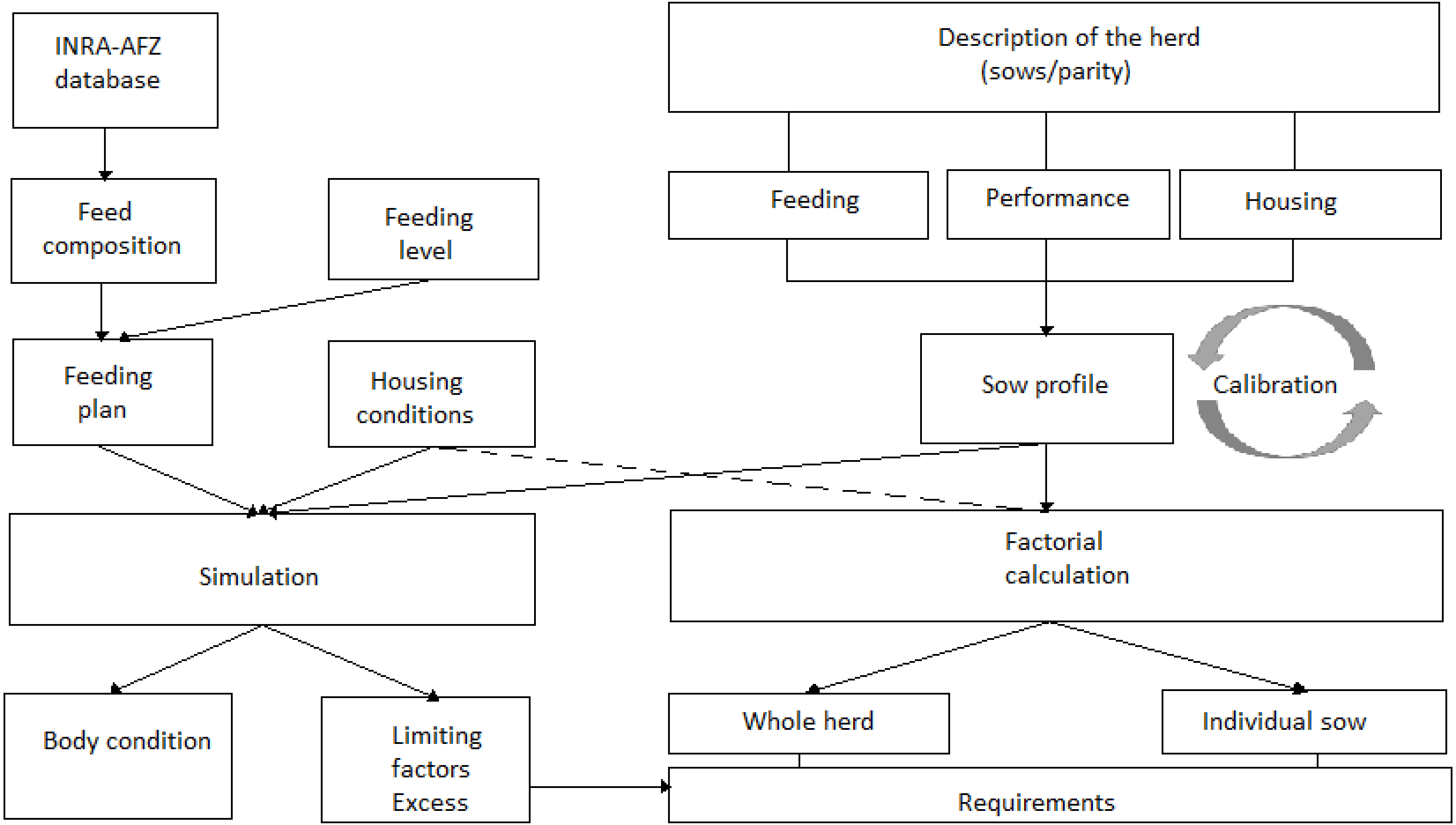

Female
Male
(a) mean body weight of 37.7 kg
Feed Conversion Ratio
2.6
2.4
2.2
2
1.8
1.6
1.4
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Ratio of available lysine to MJ digestible


Female
Male
(b) Mean body weight of
Feed Conversion Ratio
2.6
2.4
2.2
2
1.8
1.6
1.4
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Ratio of available lysine to MJ digestible


Biological parameters
Sensors
(collect data)
Data transmission
Information
storage and
processing
Observations,
decisions
Farmer inputs
Automatic actions
Consultation,
Farmer inputs
Farmer
Indicators of alerts
Control
Smartphone, PC
(transmit the information)
Automaton
(automatic feeder)



NE: Net Energy
AA: Amino Acid


INRA-AFZ database
Feed composition
Feeding level
Feeding plan
Housing conditions
Simulation
Body condition
Limiting factors Excess
Description of the herd (sows/parity)
Feeding
Performance
Housing
Sow profile
Calibration
Factorial calculation
Whole herd
Individual sow
Requirements