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

3

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9

10 **Highlights**

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

15

16

17 **Abstract**

18

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

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)

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

42

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

45

46

47 **Introduction**

48

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

70

71 **1. Feed and nutrient efficiency**

72

73 **1.1. Definition and measure of feed efficiency**

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

81 Genetic improvement has reduced the FCR for most of the conventional pig breeds (Bouquet,
82 2013). Nevertheless, producers still seek to minimize FCR. Selecting animals for increased
83 growth may lead to increased ingestion, whereas selecting for decreased ingestion may lead to
84 decreased growth. More recently, to avoid this selection difficulty, residual feed intake (RFI)
85 was used as another measure of efficiency. The RFI is calculated as an animal's daily feed
86 consumption minus the quantity of feed required to meet its theoretical energy requirements
87 (Bouquet, 2013). Pigs with high RFI are less energy efficient because they produce more heat,
88 mainly due to increased physical activity and basal metabolic rate (Barea, 2010). RFI has high
89 variability, but genetic selection can decrease it. Since RFI is not correlated with growth but is
90 positively correlated with feed intake and FCR, selecting animals for lower RFI should have
91 no influence on growth but would reduce ingestion. However, recent studies at IFIP (French
92 Pork and Pig Institute) showed that selecting for FCR results is still more economic than
93 selecting for RFI (Bouquet, 2013).

94 For fattening pigs, FCR is usually calculated from 10 weeks of age (around 30 kg of body
95 weight, BW) to slaughter (around 115 kg of BW). FCR can also be calculated from weaning
96 to around 10 weeks of age, or from weaning to slaughter (Gilbert, 2015). FCR for

97 reproductive sows is more difficult to assess. It can be expressed, as for fattening pigs, as the
98 amount of feed consumed over a given period divided by the BW gain of sows and piglets
99 (total BW of piglets at weaning plus net increase in sow BW) over the same period. Another
100 way to express FCR for sows would be as the amount of feed consumed per weaned piglet
101 produced.

102 FCR can be expressed in different units; kg feed/kg gain is the most common unit, but MJ
103 energy/kg gain is often used to consider variations in feed energy content. Cost of feed/kg
104 gain is another way to express FCR that is more similar to the economic efficiency (Gilbert,
105 2015). Ultimately, FCR is not determined by growth rate and feed intake, but by factors that
106 influence them, such as genetics, feeding practices, environmental conditions and health
107 status. For example, data obtained from a French pig farm survey (Table 1) indicate that FCR
108 depends on the breeding system and production period: herd FCR is greatest for the breeder-
109 sale-at-weaning system (5.45 kg) and lowest for the weaner-fattener system (2.64 kg/kg).
110 FCR is greater for the fattening period than for the post-weaning period, and these values vary
111 among farms.

112

113 **1.2. Factors that influence feed efficiency**

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

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

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

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

122 **Spillage.** In Eq. 1, increased spillage increases the FCR. Spillage can be reduced by
123 selecting feeder type. In the study of Pierozan et al. (2016), a linear dump feeder had less feed
124 waste and lower FCR than other types of feeders, such as conical semiautomatic feeders (2.41
125 and 2.44, respectively, $P = 0.04$). Comparisons between feeder types are limited due to their
126 diversity and the difficulty in developing trials to test the effect of feeder type on FCR, as it
127 requires modifying the feeders (Pierozan et al., 2016). Feeder characteristics (individual
128 shoulder protection, number of places per pig, and water supply) and localization in the pen
129 are essential when selecting a feeder to reduce feed waste (Averós et al., 2012). Averós et al.
130 (2012) reported that feeders with shoulder protection resulted in lower FCR than unprotected
131 feeders due to a reduction of pig aggressions at the feeder. Feed restriction may also help
132 reduce feed waste and improve FE (Patience et al., 2015). Another way to reduce spillage is to
133 feed pellets instead of mash diets. Indeed, the review of Vukmirović et al. (2017) reported a
134 general agreement on the fact that feeding pellets to pigs improved FCR, by improving DM
135 digestibility and reducing feed wastage, compared to feeding mash diets. However, size
136 particle is reduced during pelleting process, which can have negative effects on the
137 gastrointestinal tract health.

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

147 slightly as BW increases, whereas for female and castrated pigs, FCR increases more rapidly
148 with BW due to differences in feed intake and growth rate between sexes (Noblet et al., 1994)
149 (Fig. 1).

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

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

163 **Digestibility of feed and digestive efficiency of pigs.** In Eq. 2 and 3, FCR increases
164 as the indigestible portion of the feed increases. The digestibility of feed depends greatly on
165 its composition (Ponter et al., 2004) and on animal digestive capacity, which has been shown
166 to vary among pigs in interaction with feed composition (Noblet et al., 2013). For example, a
167 greater proportion of fiber in the diet is a challenge for digestion and results in high variability
168 in pig performance. Noblet et al. (2013) found that the digestibility of energy is influenced by
169 sire, which suggests that digestibility depends on heritable genetic variability. Kyriazakis
170 (2011) also reports that selecting pigs for digestive efficiency would improve nutrient
171 efficiency. Further research is needed to understand underlying mechanisms.

172 **Composition of weight gain (lean-to-fat ratio).** Eq. 2 and 3 indicate that the
173 chemical and tissue compositions of BW gain influence FCR. The chemical composition of
174 empty BW gain in minerals and protein (around 3% and 16-17% of empty BW, respectively)
175 (Table 2) is similar among breeds and sexes, except for certain traditional breeds whose
176 protein content is lower (Noblet et al., 1994). Conversely, the percentages of water and lipids
177 are largely related to genotype and sex, which influence the energy content of gain. Adipose
178 tissue yields around four times as much energy as muscle tissue (protein and lipid deposition
179 cost 9.1 and 29.2 MJ of ME per kg, respectively) because it contains less water. This results in
180 large differences in the energy content of BW gain among genotypes (e.g. 11.2 MJ/kg in
181 Piétrain males vs. 21.1 MJ/kg in Meishan castrates) and between sexes (12.3, 13.8, and 15.6
182 MJ/kg for Large-White males, females, and castrated males, respectively) (Noblet et al.,
183 1994). Over the past 40 years, most genetic improvement in FCR has been obtained by
184 reducing the proportion of lipids in BW gain. Selection for fast growing and lean animals has
185 increased the potential for protein deposition and reduced the amount of energy required to
186 achieve this potential, usually with little influence on feed intake (Gilbert, 2015).

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

194 **Nutrient utilization.** As previously mentioned, FCR is affected by the efficiency of
195 energy utilization, which depends on the energy content of BW gain and the effect of
196 maintenance requirements. Similarly, to the energy, the efficiency of utilizing nutrients, such

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

209 Up to 80% of P in feedstuff (cereals and seeds) is tightly bound in phytate, but pigs do not
210 produce enough phytase enzyme to degrade phytate, which encapsulates P, protein, and AA in
211 feedstuffs. Adding exogenous phytase is thus an effective way to improve the digestibility and
212 efficiency of utilizing P and, to some extent, other nutrients (Jondreville and Dourmad, 2005).

213 Adequate supplies of minerals and AA are needed to respectively maximize growth and bone
214 mineralization (Letourneau et al, 2016) and protein retention, and therefore minimize FCR.
215 The supply of an AA such as lysine influences FCR in different ways (Fig. 2). The lack of one
216 or more AA limits protein deposition as protein synthesis decreases. This results in an
217 increase in lipid deposition and consequently a decrease in growth rate and an increase in
218 FCR (van Milgen, 2008). When one AA is limiting, the other AA in excess are catabolized
219 and excreted as urea, reducing energy efficiency and increasing cost and waste. Similarly, an
220 excessive supply of nutrients increases nutrient excretion, fat deposition and FCR. Nutrient
221 requirements also depend on pig characteristics such as sex, age and genotype. For example,

222 entire males require more lysine than females (Fig. 2) and castrated males. In growing pigs,
223 the AA requirement relative to energy decreases as BW increases (Van Milgen et al., 2008,
224 Noblet et al., 2016). In sows, the AA requirement increases with the stage of pregnancy and is
225 greatest during lactation (Dourmad et al., 2008). Similar trends are observed for mineral
226 requirements of growing pigs and sows. This indicates the need to optimize each individual's
227 nutrient ingestion to maximize individual efficiency and reduce excretion. Taking into
228 account individual characteristics (age, breed, sex, BW) can be used to better feed to animals
229 up to their individual requirement. Nutrient ingestion can be optimized by using predictive
230 models of nutrient requirements (Brossard et al., 2017) (see section 3).

231

232 **1.3.Strategies to improve feed efficiency**

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

246 Genetic factors are also influencing the abundance of distinct bacterial species (Benson et
247 al., 2010). Several studies found a link between the porcine intestinal microbiome and FE
248 (McCormack et al., 2019a; Tan et al., 2017). While the effect of intestinal microbiota in
249 expressing FE has been confirmed, methods to phenotype the microbiota should be developed
250 to use this information on farms. McCormack et al. (2019b) reported the effect of fecal
251 microbiota transplantation (FMT), using fecal extracts from highly feed-efficient pigs, in
252 pregnant sows on the offsprings performance. The FE of the offsprings from a mother under
253 FMT was improved compared to the one of offsprings from a mother not under FMT (similar
254 feed intake but growth differences). However, the negative effect of FMT on the offsprings
255 growth limits the application of this procedure in commercial farms. Manipulations of
256 bacterial populations can also be used to improve digestibility and FE (Le Sciellour et al.,
257 2018) that would allow more flexibility regarding ration composition especially on the
258 amount of fibers. Niu et al. (2015) reported that several bacteria were correlated with apparent
259 crude fiber digestibility; of these, Clostridium is associated with dietary fiber metabolism.
260 They also found that the abundance and diversity of the gut microbiota in pigs increased and
261 changed with increasing age. Intestinal microbiota facilitates digestion of fiber, but its effects
262 on the variability in FE needs to be assessed and broken down into the fraction that depends
263 on animal genetics, the fraction that depends on breeding conditions and the fraction that sows
264 transmit to piglets at birth and during lactation.

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

269 **Removing external stressors.** Black et al. (2001) reported that removing one or more
270 stressors, or reducing their influence, improves pig performance because the stressors may

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

285 **Adequate nutrient supply.** As previously indicated, feed and nutrient efficiency depend
286 partly on nutrient utilization, which is based on adjusting nutrient supply to requirements.
287 Therefore, one way to improve FE is to refine this adjustment by estimating animal
288 requirements more accurately. Two methods are generally used to estimate nutrient
289 requirements for pigs: empirical and factorial. Briefly, requirements in the empirical method
290 correspond to those of a population for a given performance target and time interval.
291 However, the estimated requirements cannot be extrapolated to other situations because they
292 vary as a function of animal characteristics and environments (Pomar et al., 2003). In contrast,
293 nutrient requirements in the factorial method are estimated for an average animal at a given
294 stage. However, pig performance depends on pig characteristics (genetic, age, weight, sex,
295 social status and health), feed characteristics (feed allowance, nutrient composition and

296 digestibility), and housing conditions (ambient temperature and space allowance) (Noblet and
297 Quiniou, 1999). Models based on the factorial approach have been developed to simulate
298 performance of a single animal and can predict nutrient requirements and appropriate feeding
299 strategies (e.g., van Milgen et al., 2008). However, because they are based on an average
300 animal, feeding strategies based on this approach means that many animals are inevitably
301 underfed or overfed (Pomar et al., 2003). Individual variability influences the efficiency of
302 nutrient utilization (Pomar et al., 2003, Brossard et al., 2009). In addition, the fact that
303 nutrient requirements change over time needs to be considered to predict them more
304 accurately. Precision feeding requires developing new feeding strategies to refine the
305 adjustment of nutrient supply to requirements.

306

307 **2. Individual variability, the key point of precision feeding**

308

309 **2.1.Precision feeding: definition, objectives, advantages**

310 Precision feeding is one way to better consider individual variability in nutrient requirements
311 within a group. It involves using technology to provide the right amount of feed, with the
312 right composition and at the right time, to a group of animals or to individuals (Pomar et al.,
313 2009). Precision feeding aims to improve characterization of individuals (feed intake, growth
314 potential, body condition, physical activity, health, etc.) or small groups to better adapt the
315 quantity, quality and timing of feed supplied to them. It also aims to improve efficiency by
316 reducing farm costs, reducing excretion, and monitoring quality (Fig. 3). Applying precision
317 feeding and doing so accurately requires assessing the nutritional potential of feed ingredients
318 and nutrient requirements of each animal to formulate balanced diets accurately to minimize
319 nutrient deficiency or excess (Pomar et al., 2009).

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

337

338 **2.2.Variation in nutrient requirements**

339 Two main sources of variation in nutrient requirements must be considered: variations over
340 time and differences between animals. Nutrient requirements vary over time (Andretta et al.,
341 2014) and among growing pigs in a group receiving the same feed (Pomar et al., 2007,
342 Brossard et al., 2009), due to sex (castrated or entire males, females), age (different nutritional
343 requirements), weight and individual potential. Nutritional requirements of sows also vary
344 with individual characteristics such as physiological status, age, weight and prolificacy

345 (Dourmad et al., 2017). Sows of parity 1, 2, or 3 continue to grow while gestating, whereas
346 sows of parity 4 or more have already reached their mature weight, which means that their
347 requirements are limited to maintenance, gestation and rebuilding body reserves used up
348 during gestation. These between-animal variations influence the population response, the
349 efficiency of nutrient utilization, and consequently the optimal nutrient supply for the
350 population (Pomar et al., 2003, Brossard et al., 2009). Therefore, stochasticity has been
351 introduced into models to address variability, simulate responses of groups of pigs (Pomar et
352 al., 2003) and define strategies to improve on-farm nutrient efficiency (Brossard et al., 2017).
353 These variations among animals and over time show the relevance of developing more
354 individualized feeding strategies (see section 3).
355 In growing pigs, Cloutier et al. (2015) reported that the factorial method used to estimate
356 individual daily lysine requirements was able to accommodate the small genetic differences in
357 feed intake without a specific correction for genetic differences. This method can be used in
358 precision feeding systems without adjustments for small genetic differences but should be
359 studied further for larger genetic differences in feed intake and protein deposition patterns.

360

361 **2.3. Feeding technologies and real-time data**

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

365 **Technology and individual data collection.** Farm animals can be identified by
366 radiofrequency (RFID), which makes data collection reliable and simplifies management of
367 individuals (Cornou and Kristensen, 2013). Using RFID and sensors automates farm
368 equipment, which can transfer real-time data to a farmer or an automated decision support
369 system that can make rapid management decisions (Fig. 3). Cornou and Kristensen (2013)

370 listed several sensors used in pig production and how their data can be used to support
371 decisions. Automatic identification of an animal is the first step in monitoring production
372 efficiency and is performed on pig farms usually by placing an ear-tag containing an RFID
373 chip on each animal to recognize the animal, for example at the feeder. Electronic feeding
374 stations can record the number, time and duration of the visits, and the quantity of feed
375 ingested by each pig. In commercial herds, only sows are individually identified at electronic
376 feeding stations. Individual identification is uncommon for fattening pigs due to its cost,
377 although the technology is available for selection herds. Several technologies exist that
378 automatically record BW: foreleg weighing systems (Ramaekers et al., 1995), image analysis
379 (Parsons et al., 2007), the walk-through using machine vision (Banhazi et al., 2011) and
380 photogrammetry to determine pigs' three-dimensional shapes (Wu et al., 2004). Knowing the
381 body composition might also be required to individualize the diet, especially in gestating
382 sows. Body composition can be determined by analyzing images or videos or measuring
383 backfat thickness with ultrasound; however, this last technique is performed manually and
384 would need to be automated. Pig activity, which may also be of interest, can be automatically
385 recorded using photocells, force sensors for sows housed in crates (Oliviero et al., 2008), and
386 accelerometers for sows in loose housing or crates (Cornou and Lundbye-Christensen, 2012).
387 Finally, pig temperature influences FE and can be automatically recorded using an ear-based
388 temperature sensor or estimated using an image-analysis procedure based on the pig's
389 thermoregulatory behavior (Wouters et al., 1990).

390 **Data processing.** The sensors described above provide large amounts of data on a daily
391 basis. The biological characteristic of interest needs to be extracted from each measurement.
392 First, the data are cleaned by removing abnormal values, which requires defining thresholds.
393 Then, the characteristic of interest is generally extracted by smoothing the data; the amount of

394 smoothing is based on the objective (Friggens and Robert, 2016). These data will then serve
395 as inputs to models to predict animals' nutrient requirements.

396

397 **3. Models and applications of precision feeding**

398

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

405

406 **3.1. Fattening pigs**

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

416 The Hauschild et al. (2012) model was evaluated using data from a previous trial (Pomar et
417 al., 2007) that tested the influence of a daily 3-phase or multiphase feeding strategy on pig
418 efficiency. Daily feed intake and BW trajectories of an animal could be predicted 1 day or 7

419 days in advance, respectively, with an average mean absolute error of 12% and 1.8%,
420 respectively. The mechanistic component of the Hauschild model has been used in two animal
421 trials (Zhang et al., 2012, Cloutier et al., 2015). In the Zhang et al. (2012) trial, the model
422 accurately predicted SID Lys requirements of pigs of 25-55 kg BW, but underpredicted the
423 requirements of heavier animals. In the Cloutier et al. (2015) trial, the model was used to
424 predict individual daily SID Lys requirements and to consider the influence of small genetic
425 differences on them. Three trials evaluated the overall approach of estimating real-time AA
426 requirements and the effect of switching from conventional to precision feeding systems in
427 growing-finishing pig operations on productive performance, nutrient utilization, body
428 composition and environmental costs (Andretta et al., 2014, Pomar et al., 2014, Andretta et
429 al., 2016). Pomar et al. (2014) found that a daily phase-feeding strategy (mixing two feeds)
430 reduced N intake by 7.3%, P intake by 3.3%, N excretion by 11.7%, P excretion by 1.9% and
431 feed cost by 1.3% compared to those of a 3-phase feeding strategy. Andretta et al. (2014)
432 found that a multiphase individual feeding strategy reduced SID AA intake by 27%, P
433 excretion by 27% and N excretion by 20% compared to those of a 3-phase feeding strategy.
434 Andretta et al. (2016) found that an individual feeding strategy (in which the mixing
435 proportions of two feeds were updated daily to meet 100% of the lysine requirement) reduced
436 SID Lys intake by 26%, N excretion by 30% and feeding cost by 10% compared to those of a
437 group-feeding strategy. These three trials show that using precision feeding techniques to feed
438 growing-finishing pigs with diets that are tailored daily is an effective approach to reduce
439 nutrient excretion without compromising performance. It confirms that combining precision
440 feeding with real-time modeling of requirements can improve the efficiency of use of feed
441 and nutrient, and to some extent the economic result. However, this requires more
442 sophisticated equipment (e.g. equipment for feed storage and distribution, smart feeders,
443 weighing scale), with more supervision, inducing additional costs that were generally not

444 considered in the economic evaluation. Predictive models require further improvements, such
445 as including health factors (environmental stressors, pathogen levels), and prediction of
446 technical, economic and environmental effects of precision feeding on commercial farms. For
447 example, Monteiro et al. (2016) used the InraPorc decision support tool
448 (https://inraporc.inra.fr/inraporc/index_en.html) to predict production data that they then used
449 as input data for life cycle assessment to compare environmental effects of four pig feeding
450 strategies. They predicted that an individual feeding strategy yielded the lowest life cycle
451 effects for pig fattening in all situations (in France and Brazil). Finally, this technology needs
452 to be implemented and validated on commercial farms. Current technology can feed pig
453 groups based on their weight, but automatic feeders with a decision support tool are not yet
454 commercially available.

455

456 **3.2. Sows in gestation and lactation**

457 Mechanistic models such as InraPorc (Dourmad et al., 2008) and the model of Hansen et al.
458 (2014) were developed to simulate energy and nutrient partitioning of reproductive sows on a
459 daily time step. These models represent sows as the sum of multiple compartments: body
460 protein, body lipids, body minerals and the uterus (Dourmad et al., 2008) (Fig. 5). Equations
461 describing nutrient utilization by sows were used to build InraPorc, which predicts daily
462 nutrient and energy flows from feed to storage in the body and then excretion. InraPorc
463 simulates daily utilization of key nutrient pools by a sow. InraPorc also predicts energy and
464 AA requirements of sows based on production objectives, as well as changes in body
465 composition due to a given feeding strategy or housing condition (Gaillard et al., 2019a).

466 Dourmad et al. (2015) used InraPorc to simulate and evaluate two-phase and multiphase
467 feeding strategies during gestation. Simulations results indicate that compared to one-phase
468 feeding, the two-phase and multiphase strategies could respectively reduce crude protein (CP)

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

487 On most farms, sows are fed different diets for gestation and lactation instead of the same diet
488 for both, reducing N and P excretion by 20-25% (Dourmad et al., 1999). Currently, few
489 studies have focused on improving feeding strategies for lactating sows, even though sow
490 requirements vary greatly. A precision feeding strategy might be useful for lactating sows
491 because nutrient requirements per kg of diet vary greatly as a function of milk production and
492 feed intake. For example, sows of parity 1 have greater requirements due to their lower feed
493 intake. Nutrient requirements also vary by season due to the influence of temperature on feed

494 intake and milk production. Gauthier et al. (2019) developed a decision support system based
495 on InraPorc that could be incorporated in automated feeding equipment. Simulations
496 compared a conventional feeding strategy to a precision feeding strategy; the latter could
497 reduce mean lysine intake by 6.8%, P intake, and the number of under- or over-fed lactating
498 sows.

499

500 **3.3. Modeling mineral requirements**

501 Minerals are a major component of pig nutrition. Because P is necessary for bone
502 development and the metabolism of growing pigs, it must be supplied in pig diets. Dietary P
503 of plant origin has low digestibility for pigs, but addition of P and/or phytase increases feed
504 cost. The oversupply and low digestibility of P also results in high P excretion, which affects
505 the environment. Therefore, models that predict mineral requirements are required to optimize
506 mineral supply and minimize excretion (Brossard et al., 2017). Minerals have received little
507 modeling attention because most models have focused on AA. Jondreville and Dourmad
508 (2005) used a factorial approach to estimate P requirements for maintenance and production
509 in different physiological stages, and it was later added to InraPorc for growing pigs (van
510 Milgen et al., 2008) and sows (Dourmad et al., 2008). This approach considers the influence
511 of the type of diet (pellets or mash) and the addition of phytase on digestibility. The model
512 allows dietary P supply to be adjusted to pig performance and physiological status and
513 predicts the influence of performance level on apparent digestible P requirements. However, P
514 requirements for growth are estimated from animal BW gain, which has certain limitations.
515 More mechanistic models have therefore been developed in which mineral content (P and
516 calcium) can vary independently of protein and lipid mass (Letourneau-Montminy et al.,
517 2015). These deterministic and mechanistic research models can be used to improve decision
518 support tools to develop feeding strategies that minimize P excretion. These models must also

519 consider that mineral requirements change during each physiological stage (e.g. an increase in
520 calcium requirements at the end of gestation).
521 For gestating sows, recent simulations of a precision feeding strategy based on lysine
522 requirements still report an important excess in phosphorus (Gaillard et al., submitted). This is
523 partly because the implemented strategy was based on lysine requirements with only two
524 diets. Hence, in such condition it was not possible to deal with the different dynamic of lysine
525 and phosphorus requirements over the whole gestation. To modulate lysine and phosphorus
526 supplies independently, one solution would be to calculate the proportions of the two mixed
527 diets (High Lysine and Low Lysine) based on lysine and phosphorus requirements
528 simultaneously, and therefore propose 3 different diets to combine for precision feeding
529 instead of two (High Lysine + High P, Low Lysine + High P, Low Lysine + Low P).
530 However, the strategy might be less efficient than for lysine and will need to be evaluated and
531 compared with the present feeding strategy, based on lysine only, in terms of production,
532 excretion, and costs.

533

534 **Conclusion**

535 Feed efficiency can be expressed as the ratio of mean daily weight gain to mean daily feed
536 consumption during a given period. In practice, the inverse of this ratio is generally used for
537 breeding animals and represents the efficiency in converting feed into weight gain (feed
538 conversion ratio, FCR). Several factors influence FCR, such as feed spillage, feed
539 digestibility, composition of weight gain, feed intake and nutrient utilization. The FCR can be
540 decreased by selecting the appropriate form of feed and nutrient density and supply, and by
541 reducing negative effects of environmental factors. Precision feeding is based on managing
542 individual variability within a group and uses feeding technologies (e.g. sensors, feeders) to
543 provide the right amount of feed, with the right composition, and at the right time, to a group

544 of animals or to individuals. Predictive models of nutrient requirements and excretion, such as
545 InraPorc, have been developed to select optimized feeding strategies. For growing pigs,
546 precision feeding is a promising solution to reduce nutrient excretion by daily adjusting the
547 supply of nutrients to individuals. Recent simulations results indicate that this might also be
548 an appropriate feeding strategy for sows. Decision support models could be enhanced by
549 improving sensors or considering factors such as ambient temperature and animal physical
550 activity, which also influence energy utilization and consequently the FCR.

551

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557

558

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807

808 **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

809 FCR: Feed Conversion Ratio

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

Genotype Sex	Piétrain		Large-White		Meishan
	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

811

812 **Figure captions**

813

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

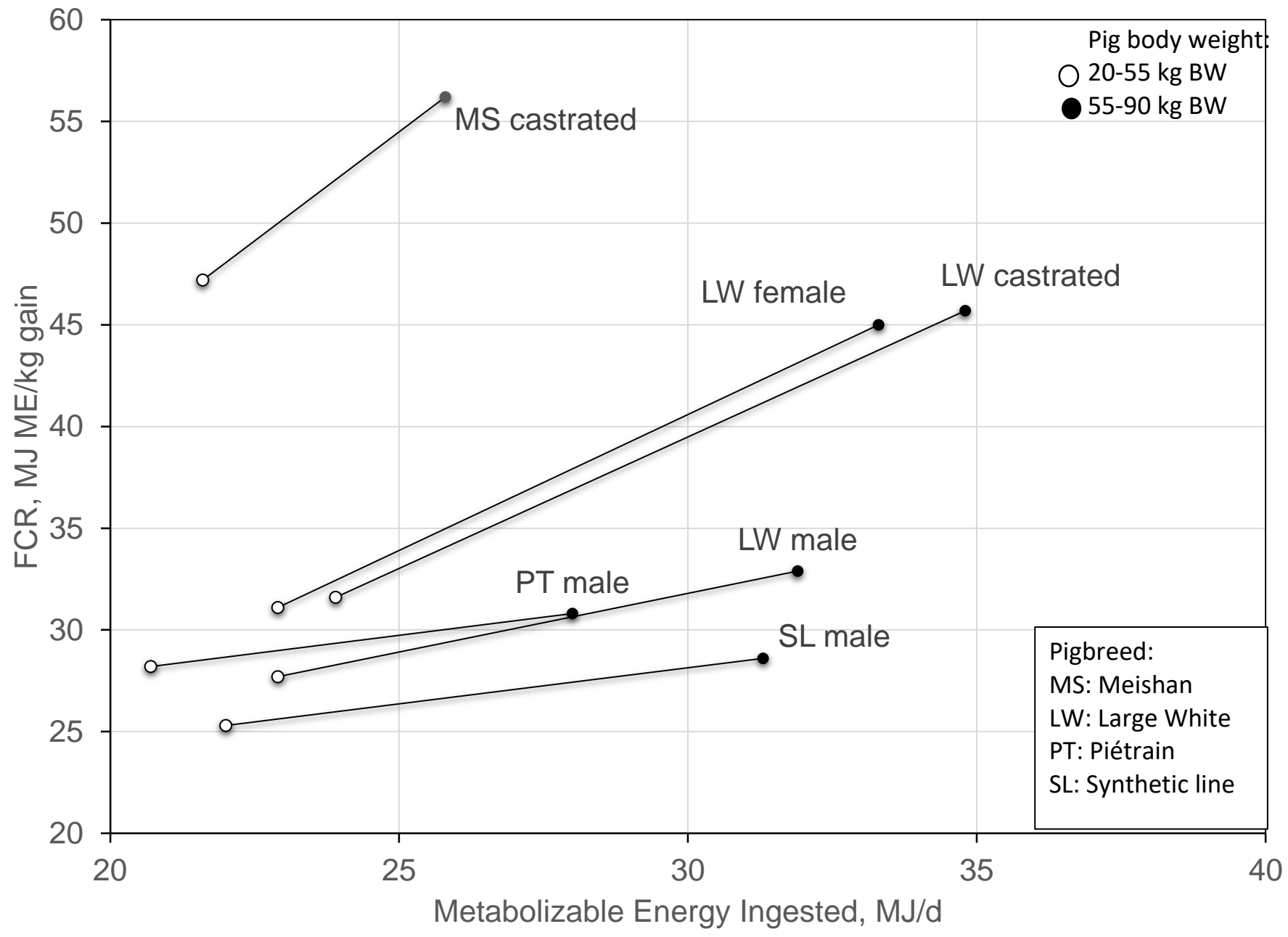
819 **Figure 2.** Effect of the ratio of available lysine to MJ digestible energy on mean feed
820 conversion ratio (± 1 SEM) for (Large-White x Landrace) x Duroc female and male pigs with
821 a mean body weight of (a) 37.7 kg and (b) 76.4 kg (Mullan et al., 2011)

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

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

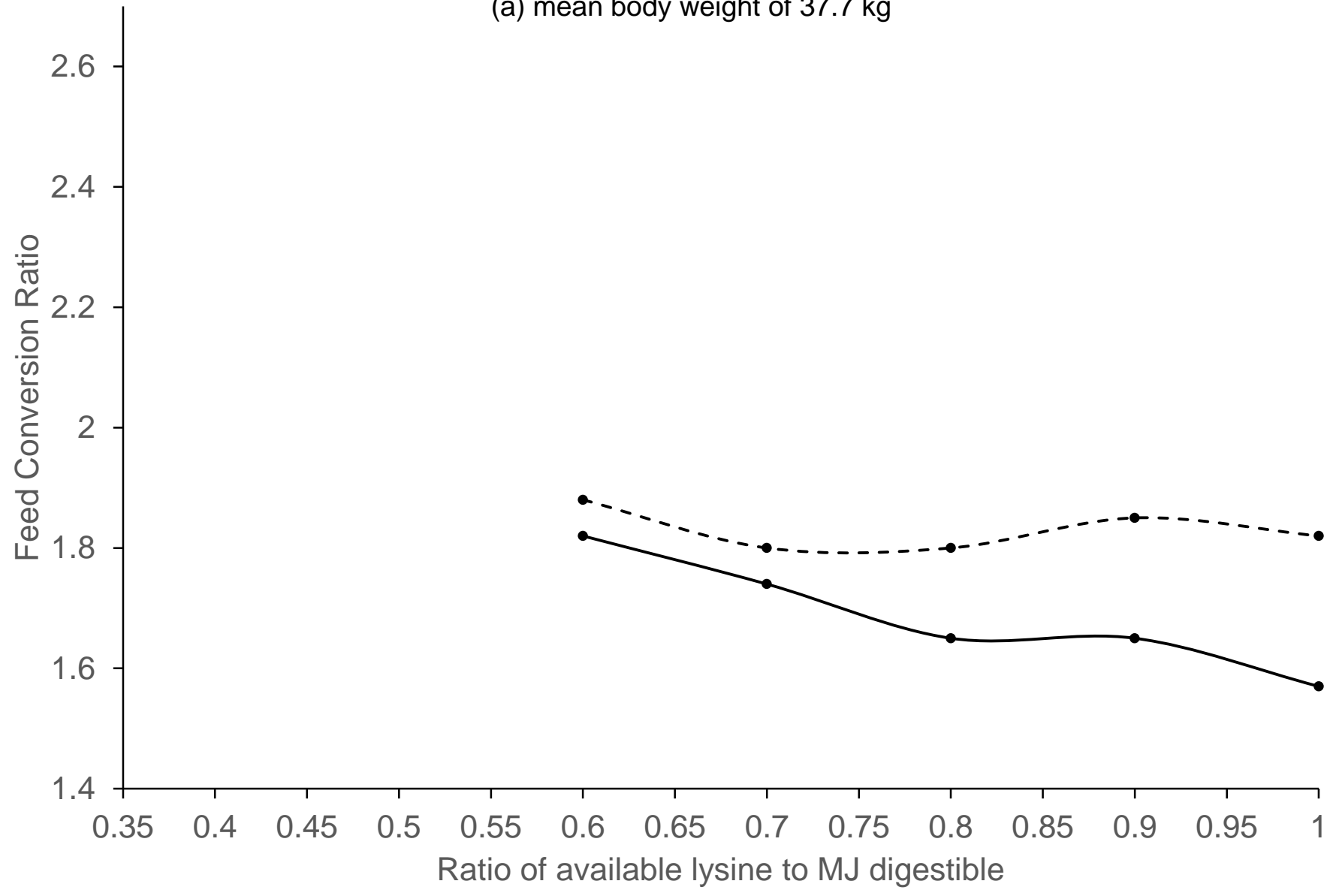
827 **Figure 5.** Configuration of the InraPorc decision making tool for sow nutrition (from
828 Dourmad et al., 2008). BW = body weight

829



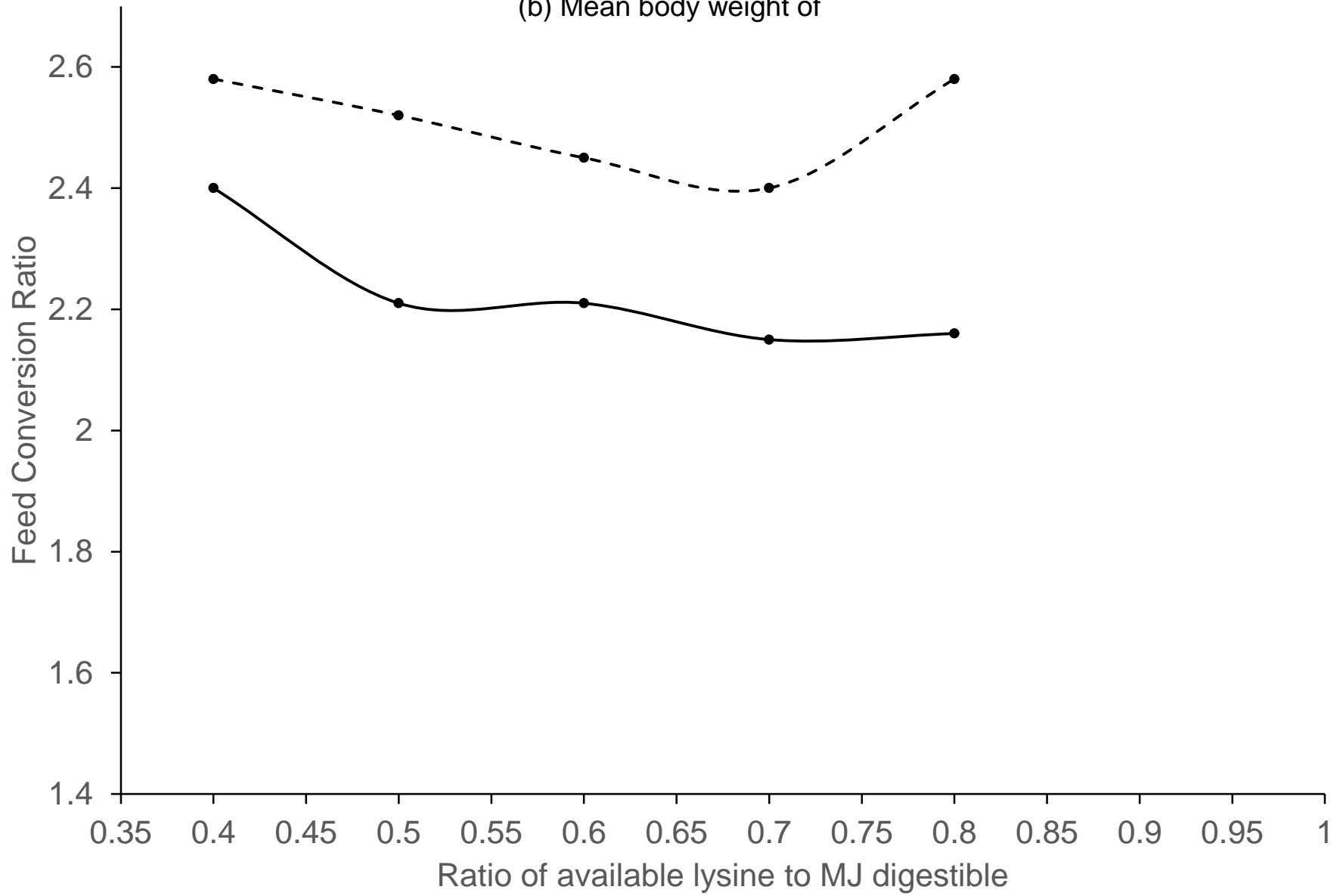
-●- Female -●- Male

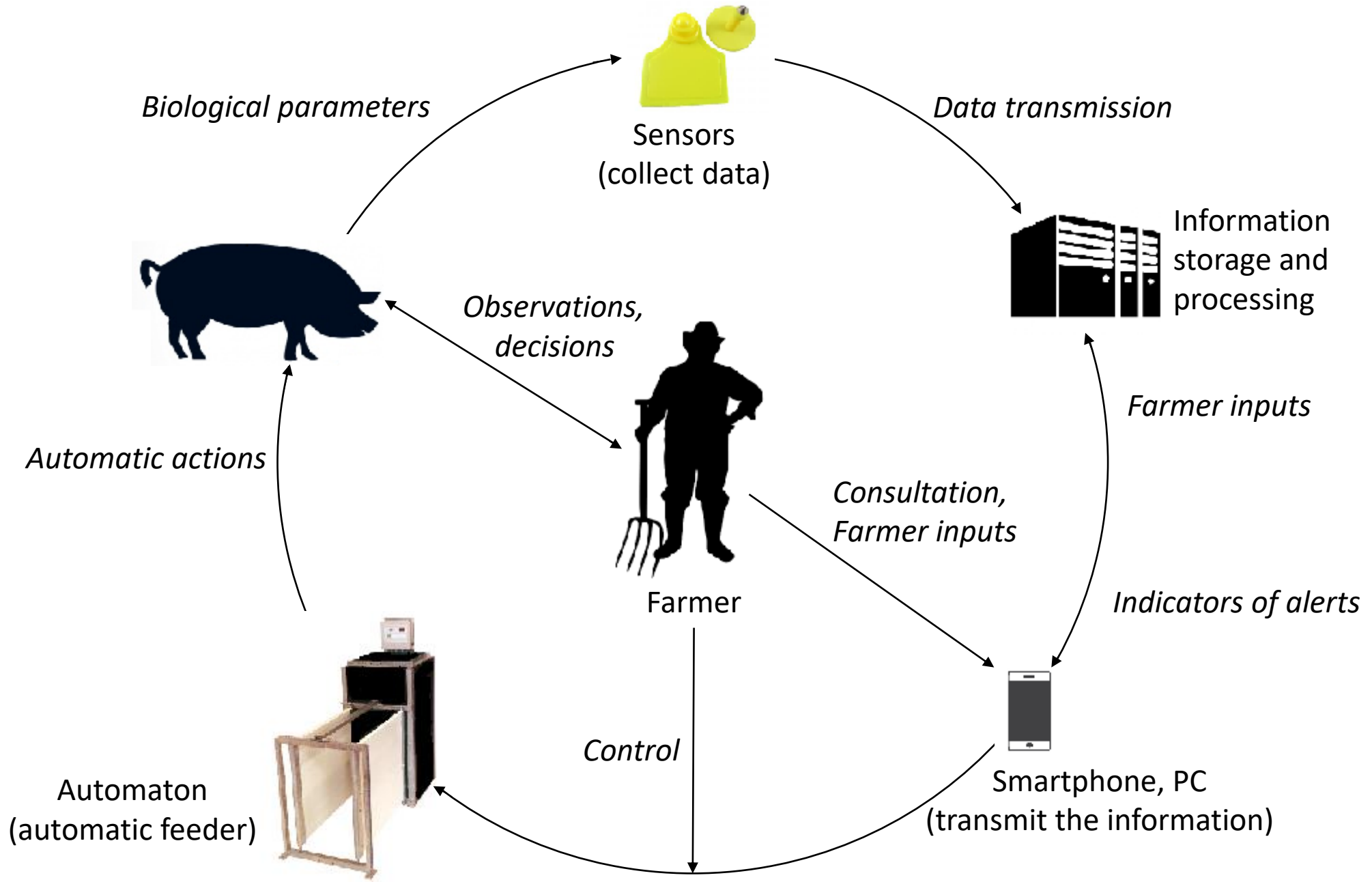
(a) mean body weight of 37.7 kg

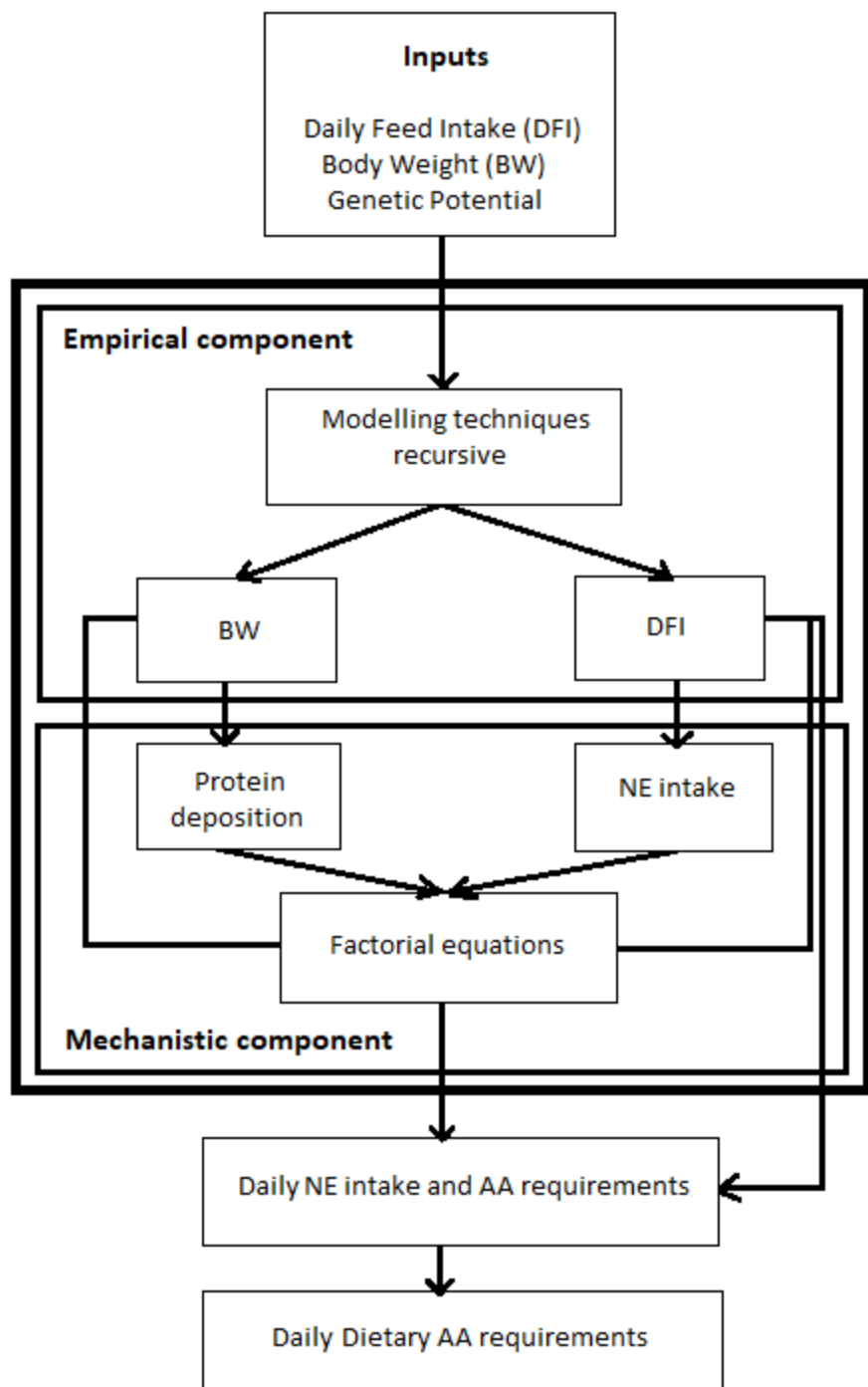


-•- Female —•— Male

(b) Mean body weight of







NE: Net Energy
AA: Amino Acid

