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Precision feeding of lactating sows: implementation and evaluation of a decision support system in farm conditions

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Abstract

Precision feeding (PF) aims to provide the right amount of nutrients at the right time for each animal. Lactating sows generally receive the same diet, which either results in insufficient supply and body reserve mobilization, or excessive supply and high nutrient excretion. With the help of online measuring devices, computational methods, and smart feeders, we introduced the first PF decision support system (DSS) for lactating sows. Precision (PRE) and conventional (STD) feeding strategies were compared in commercial conditions. Every day each PRE sow received a tailored ration that had been computed by the DSS. This ration was obtained by blending a diet with a high AA and mineral content (13.00 g/kg SID Lys, 4.50 g/kg digestible P) and a diet low in AAs and minerals (6.50 g/kg SID Lys, 2.90 g/kg digestible P). All STD sows received a conventional diet (10.08 g/kg SID Lys, 3.78 g/kg digestible P). Before the trial, the DSS was fitted to farm performance for the prediction of piglet average daily gain (PADG) and sow daily feed intake (DFI), with data from 1,691 and 3,712 lactations, respectively. Sow and litter performance were analyzed for the effect of feeding strategy with ANOVA, with results considered statistically significant when $P < 0.05$. The experiment involved 239 PRE and 240 STD sows. DFI was similarly high in both treatments (PRE: 6.59, STD: 6.45 kg/d; $P = 0.11$). Litter growth was high (PRE: 2.96, STD: 3.06 kg/d), although it decreased slightly by about 3% in PRE compared to STD treatments ($P < 0.05$). Sow body weight loss was low, although it was slightly higher in PRE sows (7.7 vs. 2.1 kg, $P < 0.001$), which might be due to insufficient AA supply in some sows. Weaning to estrus interval (5.6 d) did not differ. In PRE sows SID Lys intake (PRE: 7.7, STD: 10.0 g/kg; $P < 0.001$) and digestible P intake (PRE: 3.2, STD: 3.8 g/kg; $P < 0.001$) declined by 23% and 14%, respectively, and feed cost decreased by 12%. For PRE sows, excretion of N and P decreased by 28% and 42%, respectively. According to these results, PF appears to be a very promising strategy for lactating sows.

Lay Summary

In lactating sows, nutrient requirements among individual animals vary greatly. With a single diet, lactating sows are likely to be either underfed, which results in body reserve mobilization, or overfed, which results in nutrient excretion. Precision feeding (PF) is a new feeding strategy that aims to provide the right amount of nutrients at the right time for each animal. In this study, we focus on the implementation and the evaluation of a decision support system (DSS) that delivers daily tailored diets to lactating sows. Two experimental treatments were compared: a precision feeding strategy based on the DSS (PRE treatment; 239 sows), and a conventional feeding strategy (STD treatment; 240 sows). Digestible lysine intake and digestible phosphorus intake were reduced by 23% and 14% in PRE sows, respectively, and feed cost by 12%, compared to STD sows. Excretion of nitrogen and phosphorus also decreased for PRE sows by 28% and 42%, respectively. Sow body weight loss was low, although slightly higher in PRE sows, which might be due to insufficient amino acid supply in some sows. PF appears to be a very promising strategy for matching nutrient supply to the specific nutrient requirements of lactating sows.

Key words: decision support system, lactating sow, machine learning, nutrient excretion, precision feeding, production cost

Abbreviations: DDGS, dried grains with soluble; DFI, daily feed intake; DSS, decision support system; FTU, Phytase unit; LADG, litter average daily gain; LSB, litter size at birth; LSW, litter size at weaning; LWB, litter weight at birth; LWW, litter weight at weaning; MAE, mean absolute error; MAPE, mean absolute percentage error; ME, metabolizable energy; N, nitrogen; PADG, Piglet average daily gain; RDBMS, relational database management system; RMSE, root mean square error; RMSEP, root mean square percentage error; RSD, residual standard deviation; SID, standardized ileal digestible; STTD, standardized total tract digestible

Introduction

The feeding of lactating sows is of economic importance since it affects sow productivity, milk production, and piglet performance. In commercial farms, about 15% to 17% of total feeding costs are dedicated to the feeding of sows (Solà-Oriol and Gasa, 2017). As far as environmental impacts are concerned, about 80% of P and 70% of N intake in lactating

sows may be excreted in feces and urine (Jongbloed et al., 1999; Jondreville and Dourmad, 2005), thus having strong implications for the use of non-renewable resources and the possible release of pollutants into the environment. Feeding is also strongly related to animal welfare, with studies demonstrating that body reserve mobilization during lactation should be limited (Quesnel, 2005) by providing appropriate

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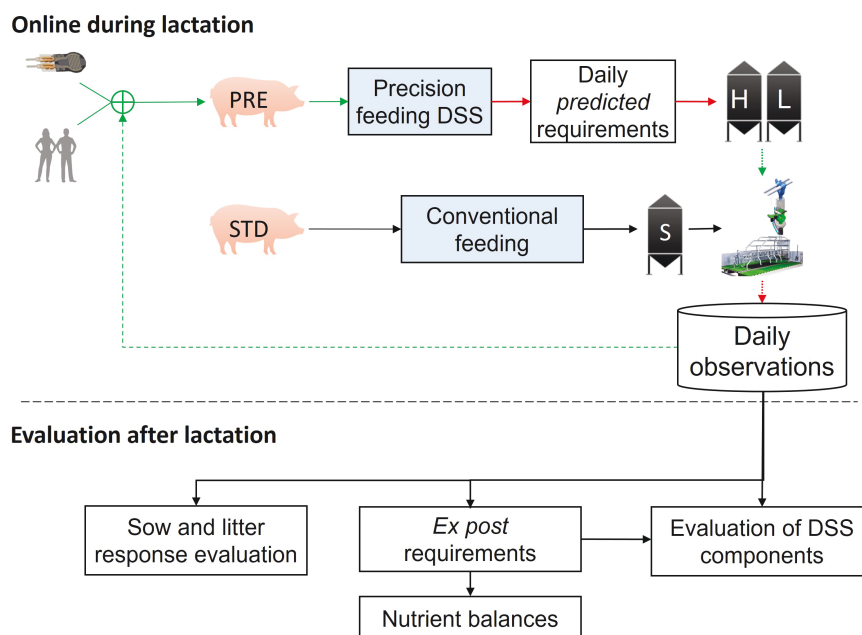


Figure 1. General description of the online experimental plan with precision feeding strategies at the individual level (PRE) and conventional feeding (STD), and the evaluation of sow and litter performance, nutrient supplies, ex post requirements, balances, and predictive performance of Decision Support System (DSS) components. H, L, and S stand for high, low, and standard diets, respectively.

feeding during lactation, in order to improve sow reproductive performance and longevity. Other studies have indicated that enriched fiber diets during late gestation were able to stimulate feed intake after farrowing and to improve sow behavior (Guillemet et al., 2006). For lactating sows, nutrient supply must thus match nutrient requirements as closely as possible in order to enhance the overall sustainability of swine farming systems, while achieving production objectives and being in line with society's animal welfare concerns.

Conventional feeding systems during lactation are based on a close to ad libitum delivery of a single diet. The diet composition is optimized to span the nutrient requirements of all sows over the entire lactation period, while limiting costs at the herd level. Nutrient requirements are generally estimated in a retrospective manner from the average performance of the herd (Dourmad et al., 2008; NRC, 2012). However, sizeable variations in nutrient requirements were reported in time and among sows (Gauthier et al., 2019), indicating that conventional feeding strategies may lead to individual nutrient excess or deficiency. At the same time, new capabilities are being offered to farmers to make more efficient decisions with the help of new sensors and technologies (Wathes et al., 2008). It is now possible to individually identify animals and perform more measurements on-farm in order to evaluate each sow's production potential. This is currently driving the research toward precision feeding systems, which aim to provide the right amount of nutrients at the right time for each animal (Pomar and Remus, 2019).

Recently, data-driven and real-time mathematical models of daily nutrient use during lactation have been developed based on nutritional knowledge acquired in past decades (Gauthier et al., 2019). The effects of milk production and feed intake were identified as being the main drivers of nutrient requirement variability during lactation and among sows. As an adequate proxy for milk production, Gauthier et al. (2022) proposed a way to efficiently train a predictive algo-

rithm for on-farm estimation of litter weight at weaning. Similarly, from the large amounts of data that can be collected by smart electronic feeders, Gauthier et al. (2021) developed a new predictive algorithm for sow daily feed intake during lactation.

Based on these studies, a new Decision Support System (DSS) that follows the principles of precision feeding is proposed, in order to predict individual daily nutrient requirements during lactation on the basis of expected litter growth and sow appetite. The support system then delivers a daily tailored ration based on these requirements, by mixing two diets with different concentrations of digestible proteins, amino acids, and minerals. The objectives of this study are to describe the main features of this DSS, and to evaluate a precision feeding strategy based on the DSS in comparison with a conventional feeding strategy, in terms of sow and litter performance, nutrient intake and excretion, and feed cost.

Materials and Methods

The animal data used in this paper were obtained from a commercial farm using commercial feeding devices. All sows and piglets were cared for according to the recommended code of practice of the National Farm Animal Care Council (2014).

General approach

The general approach of this study is illustrated in Figure 1. Two experimental treatments were compared: a precision feeding strategy (PRE) and a conventional feeding strategy (STD). Sows were allocated to treatments according to their parity and body weight before farrowing. Each PRE sow received a daily tailored ration obtained from a blend of two diets: a diet with a high AA and mineral content (High: 13.00 g/kg SID Lys, and 4.50 g/kg digestible P) and a diet low in AAs and minerals (Low: 6.50 g/kg SID Lys, and 2.90 g/kg digestible P). A detailed composition of the

Table 1. Ingredients and composition of high and low experimental diets for precision feeding, and the standard diet (STD) for conventional feeding, on an as-fed basis

	High	Low	STD
Ingredient, g/kg			
Barley	-	94.33	42.45
Corn	527.34	752.02	628.45
Corn DDGS ¹	50.00	25.00	38.75
Soybean meal 46%	336.94	52.14	208.78
Canola meal 36%	20.00	46.20	31.79
Soybean oil	23.09	-	12.70
Calcium carbonate	19.50	15.11	17.52
Dicalcium phosphate 21%	8.44	2.00	5.54
Salt	4.61	4.95	4.76
DL-Methionine 99%	1.34	0.10	0.78
L-Lysine 78%	3.49	3.39	3.44
Threonine	1.27	0.71	1.02
L-Tryptophan	0.16	0.26	0.20
Phytase 750 FTU ²	0.30	0.29	0.30
Choline chloride 60%	1.00	1.00	1.00
Trace minerals and vitamins	2.50	2.50	2.50
Composition			
Crude Protein %	22.53	12.33	17.94
SID Lys, g/kg ³	13.00	6.50	10.08
Total P, g/kg	5.70	3.20	4.58
STTD P, g/kg ⁴	4.50	2.90	3.78
Total Ca, g/kg	11.70	8.00	10.04
Metabolizable Energy, MJ/kg	13.46	13.23	13.36
Net Energy, MJ/kg	10.57	10.57	10.57

¹Dried Grains with Solubles²Phytase unit³Standardized Ileal Digestible⁴Standardized Total Tract Digestible

two diets is given in [Table 1](#) on an as-fed basis. The proportion between High and Low diets was estimated online on a daily timescale for each PRE sow. Based on the principles of precision feeding, using real time measurements on sow and litter and tuned for the nutritional requirements of lactating sows, the DSS predicted the optimal daily ration to be given to each sow. This was done by 1) predicting her piglet average daily gain (PADG) according to her parity and current litter size, with these data being used to predict energy and protein output in milk, 2) calculating her daily nutrient requirements, and 3) predicting her appetite based on her previous daily feed intakes (DFIs). This information was then transferred to an individual electronic feeder (Gestal Quattro, JYGA Technologies, Québec, Canada), which handled feed mixing and distribution. STD sows, on the other hand, received the same conventional diet (STD) during the entire lactation period. This diet was obtained by mixing the High and Low diets in a fixed proportion (55% and 45%, respectively, to achieve 10.08 g/kg SID Lys and 3.78 g/kg digestible P, the content of the conventional lactation diet used on the farm). Real-time data were collected by the farmers (sow body weight and backfat thickness, litter size, and piglet body weight) and by the smart feeders, and then stored in a relational database management sys-

tem (RDBMS) for online operations (PRE only), and evaluation (PRE and STD).

At the end of the experiment, the historical data collected from the experiment were analyzed. Based on measurements at farrowing, weaning, and estrus, sow and litter response were first evaluated according to their feeding strategy. Daily observations were then processed with a nutritional model for the ex post assessment of nutrient requirements and the calculation of P and N balance over the lactation period. Finally, in order to evaluate the performance of the DSS, the predictions of the DSS's various components were evaluated against the observed values (PADG, DFI). The ex ante and ex post calculations of nutrient requirements (SID Lys and STTD P) were also compared.

The following sections describe the DSS and how it was tailored with farm data, animal management during the experiment, and calculations and statistical methods for evaluation.

Description of the decision support system Components.

The DSS handled individual data collection and management at sow and litter levels. The DSS was composed of a RDBMS (MySQL 8.0) containing the different data related to the description of the experiment, the performance of sows and their litters, DFI recordings collected by the electronic feeders, and data produced by the DSS. Each sow was identified with a unique number. Entries related to lactating sows, litters, and DFI were accessible through a web interface (Django 3.0), to enable farmers to access it in real time for data collection and verification. Entries related to DFI were automatically retrieved from the electronic feeder.

The DSS included machine learning algorithms to process the collected data and make predictions. The first machine learning algorithm predicted PADG from sow parity and litter size, according to past farm performance. Piglet growth was considered as a proxy for milk production to modulate the real-time estimation of daily nutrient requirements ([Gauthier et al., 2022](#)). Because sows were fed ad libitum during lactation, a second machine learning algorithm was trained to predict DFI based on previous feeding behaviors of sows on the farm, in combination with the DFI values collected online on each sow ([Gauthier et al., 2021](#)).

The DSS also relies on precise knowledge of nutrient use by each sow, via a data-driven and real-time mathematical model ([Gauthier et al., 2019](#)). This model, based mainly on the InraPorc model ([Dourmad et al., 2008](#)), uses a factorial approach to estimate daily maintenance costs and milk production costs for each sow, while taking into account the expected PADG, and litter size. It also predicts sow body reserve mobilization, and energy and amino acids that sows release during postpartum uterine involution, which also supply some nutrients.

Predicted DFI and estimated nutrient requirements made it possible to formulate a daily ration containing the expected daily SID Lys supply, and this "decision" was transmitted to the electronic feeders for application.

Training the two predictive algorithms.

In order to train the litter growth predictive algorithm, a database was built with data from 1,691 lactations collected at the farm between July 2019 and March 2020, according to the procedure described by [Gauthier et al. \(2022\)](#). The database

contained data relative to sow parity, litter size at birth (LSB), litter size at weaning (LSW), litter weight at birth (LWB), litter weight at weaning (LWW), and lactation length. A linear regression model was trained with fixed effects of LSW and sow parity (P1: 1, P2: 2, P3+: 3 and beyond) on Litter Average Daily Gain (LADG), computed as the litter weight gain between weaning and birth divided by the lactation length. The following equations were obtained:

$$\text{LADG}_{\text{P1}} = 388.92 \times \text{LSW} - 10.69 \times \text{LSW}^2 - 521.35$$

$$\text{LADG}_{\text{P2}} = 437.18 \times \text{LSW} - 11.08 \times \text{LSW}^2 - 718.92$$

$$\text{LADG}_{\text{P3+}} = 466.27 \times \text{LSW} - 12.33 \times \text{LSW}^2 - 882.44$$

with an overall r^2 of 0.45.

To train the feed intake predictive algorithm, daily feed intake data were collected at the farm between January 2018 and July 2020 on a total of 3,712 sows. The sows' feed intake trajectory curves at the farm were extracted from the training database using the k -Shape learning algorithm (Paparrizos and Gravano, 2016), associated with $k = 2$, selected as being the best cluster value according to Silhouette and Calinski Harabasz scores (Gauthier et al., 2021). The mean feed intake in the training database was 5.78 kg. Online daily prediction of feed intake first required each PRE sow to be assigned to the closest feed intake trajectory curve, which had been previously identified by means of the shape-based distance (Paparrizos and Gravano, 2016). One-day-ahead feed intake was then predicted from the feed intake values of the sow in the two previous days, according to the method used by Gauthier et al. (2021). On day 1, when there was no previous feed intake information available, the prediction was replaced by 2.43 kg, the mean feed intake in the training database. On day 2, the online prediction was computed according to the closest feed intake behavior and the real feed intake on day 1.

Online process.

The software was developed using Python 3 (Python Software Foundation, Beaverton, OR), and used cron (Unix) software for daily scripts automation. Computations that changed the feed composition were planned to take place between midnight and the first meal of each day, which occurred at 06:00. During the computation process, the individual feed intake from the previous day was first collected to assess the true nutrient intake and predict the next feed intake for the coming day. Changes in the number of suckled piglets, due to possible piglet mortality or fostering, were used to trigger a new prediction of the milk nutrient output. Based on these predictions, nutrient requirements were then predicted, and the optimal blend between High and Low diets was computed in order to meet the predicted requirement in SID Lys. Finally, this daily ratio between the two feeds was sent to the automated feeder to be applied to each sow on that particular day.

Animal management

The trial took place between July and November 2020 in 12 successive farrowing batches. Within each batch, sows from the two feeding strategies were bred over the same week and transferred at the same time to the same farrowing house, and

were fed close to ad libitum by allowing them to eat extra amount of 15% compared to daily historical data. Sows were assigned to one of the feeding strategies according to their parity, their body weight, and backfat depth before farrowing. Pairs of similar sows were identified and randomly assigned to the PRE and the STD groups, so that average parity, body weight, and backfat depth before farrowing were matched as closely as possible in the two feeding strategies. The experimental treatments were applied from the onset of lactation. In total, 479 sows were included in the experiment (239 and 240 sows in the PRE and STD treatments, respectively). The sows were crossbred Landrace x Large-White (Line 276, Fast Genetics, Saskatoon, Canada).

The PRE sows received a variable proportion of High and Low diets, as determined by the DSS, while STD sows were given the STD diet obtained by mixing High and Low diets (55% and 45%, respectively), which corresponded to the standard commercial lactation diet. High, Low, and STD diets were iso-caloric on a net-energy basis (10.57 MJ/kg) but were different in terms of AA and mineral concentration. A detailed composition of the diets and their nutrient values is given in Table 1 on an as-fed basis.

Animal response measured during lactation in sows and piglets was entered into the database through the web interface. On the day of farrowing, sow parity, body weight, and backfat thickness were recorded, and litter size and individual piglet weight were measured. During lactation, litter size was recorded each day to account for possible cross-fostering and piglet death. Occasional sow feed refusal was weighted each day and removed. Daily feed intake was automatically recorded by the feeder. Individual piglet weight was measured one day prior to weaning. Sow body weight and backfat thickness were measured on weaning day.

Evaluation and statistical methods

Evaluation and statistical analyses were conducted using Python 3, with statsmodels (0.12.1), and SciPy (1.3.3) packages (Figure 1). An ANOVA was first carried out to evaluate the effect of the feeding strategy on sow and litter performance, with results considered statistically significant when $P < 0.05$. Tested variables were related to sow (body weight and backfat thickness before farrowing, after farrowing, and after weaning, and weaning-to-estrus interval) and litter performance (sizes and weight at birth and at weaning, and average daily gain of piglets and litter over lactation). Sow body weight after farrowing was computed from body weight before farrowing and piglet weight at birth, in line with Dourmad et al. (1997).

Ex post requirements were evaluated after lactation with a nutritional model (Gauthier et al., 2019) from individual data on sows and litters collected during the experiment. An ANOVA was then carried out to evaluate the effect of treatments on ex post requirements and intakes. All statistical analyses were calculated based on a statistical significance cut-off of $P < 0.05$. Tested variables were ex post ME, SID Lys, and STTD P requirements and intakes, DFI, and the percentage of High feed delivered. Daily nutrient supplies were compared to ex post nutrient requirements, on daily and weekly timescales. A global comparison was performed between precision and conventional feeding strategies to assess differences in N and P balances. Each balance was calculated considering the total ingestion of nutrients minus the amount of nutrients exported in milk. N mobilization was also taken into account,

considering it as a source of nutrients as N ingested, and assuming that 15% of body weight loss consisted of proteins. The feed cost during the trial was also compared between feeding strategies based on the amounts consumed and the price of each diet.

The DSS's predictions were compared with several metrics against observations (PADG, DFI) and ex post calculated requirements (SID Lys and STTD P). The metrics used were the coefficient of determination (r^2), the mean error, the mean absolute error (MAE) and the mean absolute percentage error (MAPE), the root mean square error (RMSE), and the root mean square percentage error (RMSEP). A comparison between training data and observed performance of LADG and DFI was also carried out.

Results

Sow and litter performance during lactation

Overall sow and litter performance according to treatment is presented in Table 2. Lactation length did not differ between PRE (20.2 d) and STD (20.3 d, $P = 0.52$) feeding strate-

Table 2. Influence of the feeding strategy on sow and litter performance

	Strategy ¹		Statistics ²	
	PRE	STD	RSD	P-value
Number of sows	239	240		
Lactation length, d	20.2	20.3	1.0	0.52
Parity	3.59	3.64	1.89	0.80
Body weight, kg				
Before farrowing	292.7	291.2	37.0	0.66
After farrowing	261.9	260.8	36.1	0.73
After weaning	254.2	258.6	36.5	0.19
Loss during lactation	-7.7	-2.1	17.3	***
Back fat, mm				
Before farrowing	15.6	15.7	3.6	0.68
After weaning	12.2	12.3	3.0	0.68
Loss during lactation	-3.4	-3.4	2.7	0.92
Litter size				
At 24 h	13.7	13.7	1.3	0.80
At weaning	12.0	12.0	1.6	0.66
Litter weight, kg				
At birth	21.1	20.8	3.1	0.32
At weaning	75.5	77.1	12.3	0.14
Litter heterogeneity				
At birth	0.302	0.301	0.076	0.90
At weaning	1.150	1.171	0.327	0.50
Piglet weight, kg				
At birth	1.55	1.52	0.22	0.23
At weaning	6.29	6.47	0.86	*
Weight gain				
Per litter, kg/d	2.96	3.06	0.53	*
Per piglet, g/d	247	257	41	*
Weaning to estrus, d ³	5.8	5.3	5.2	0.39

¹PRE, precision feeding strategy; STD, standard feeding strategy

²Data were analyzed with ANOVA that included the effect of feeding strategy (***: $P < 0.001$, *: $P < 0.05$).

³Calculated with 184 PRE sows, and 177 STD sows

gies, and the average parity was also similar in PRE (3.59) and STD (3.64, $P = 0.80$) sows. Body weight did not differ between treatments before farrowing (PRE: 292.7 kg, STD: 291.2 kg, $P = 0.66$), after farrowing (PRE: 261.9 kg, STD: 260.8 kg, $P = 0.73$), nor after weaning (PRE: 254.2 kg, STD: 258.6 kg, $P = 0.19$). Sow body weight loss during lactation was significantly greater in PRE (7.7 kg) than in STD sows (2.1 kg, $P < 0.001$). Backfat thickness did not differ between treatments before farrowing (PRE: 15.6 mm, STD: 15.7 mm, $P = 0.68$), nor after weaning (PRE: 12.2 mm, STD: 12.3 mm, $P = 0.68$), and backfat loss during lactation was the same in both groups (3.4 mm, $P = 0.92$).

Litter and piglet performance at birth were comparable in both feeding strategies. Litter size after cross-fostering was equal to 13.7 piglets in both groups ($P = 0.80$). Similar average litter weight at birth (PRE: 21.1 kg, STD: 20.8 kg, $P = 0.32$), similar heterogeneity, i.e., standard deviation of piglet's weights at birth within a litter (PRE: 0.302, STD: 0.301, $P = 0.90$), and similar individual piglet weights (PRE: 1.55 kg, STD: 1.52 kg, $P = 0.23$) were also observed in the two feeding strategies.

At weaning, litter size was similar between treatments (12.0 piglets, $P = 0.66$). Litter weight at weaning was also comparable (PRE: 75.5 kg, STD: 77.1 kg, $P = 0.14$) between feeding strategies. No differences were found between treatments for litter heterogeneity of piglet weight at weaning (PRE: 1.15 kg, STD: 1.17 kg, $P = 0.50$). However, piglet weight at weaning was about 3% lighter in the PRE treatment (6.29 kg) than in the STD treatment (6.47 kg, $P < 0.05$).

The average litter daily weight gain was significantly different depending on the feeding strategy. It was lower by about 3% in the PRE treatment (2.96 kg/d) than in the STD treatment (3.06 kg/d, $P < 0.05$). The average piglet daily weight gain was also significantly smaller in PRE sows than in STD sows, with 247 and 257 g/d, respectively ($P < 0.05$).

Weaning to estrus interval was computed on 184 PRE (5.8 \pm 5.5 d on average) and 177 STD (5.3 \pm 4.9 d on average) sows, and did not differ between treatments ($P = 0.39$).

Ex post nutrient requirements and intake Average requirements across lactation.

The average ex post nutrient requirements and intake during lactation are presented in Table 3. Feed intake did not differ between feeding strategies (PRE: 6.59 kg/d, STD: 6.45 kg/d, $P = 0.11$). The ex post ME requirement was significantly lower in PRE sows (110.1 MJ/d) than in STD sows (113.1 MJ/d, $P < 0.05$), whereas ME intake did not differ between feeding strategies (PRE: 87.5 MJ/d, STD: 86.2 MJ/d, $P = 0.26$). Metabolizable energy intake represented a significantly greater proportion of the ME requirements in PRE (79.6 %) than in STD (76.3 %) sows ($P < 0.05$).

The ex post SID Lys requirement was significantly lower in PRE sows (8.1 g/kg) compared to STD sows (8.5 g/kg, $P < 0.05$). The SID Lys intake was lower and more variable in PRE (7.7 g/kg \pm 0.98) than in STD sows (10.0 g/kg \pm 0.12, $P < 0.001$). The dietary SID Lys content of the STD diet met the requirement of 84.7% of the STD sows. The ex post STTD P requirement was slightly lower ($P < 0.05$) in PRE sows (3.0 g/kg) compared to STD sows (3.1 g/kg). The STTD P intake was lower ($P < 0.001$) and more variable in PRE sows, and was lower (3.2 g/kg \pm 0.24) compared to STD sows (3.8 g/

kg \pm 0.03). The dietary STTD P content of the STD diet met the requirement of 88.4% of the STD sows. The proportion of High feed in the ration was significantly different between PRE (19%) and STD (54%, $P < 0.001$) sows.

Nutrient supply dynamic over lactation.

Different amounts of High feed were delivered depending on the feeding strategy, with variations across time (Figure 2). STD sows received 54.0% (\pm 4.3) of High feed in their diet, while PRE sows received on average 19.0% (\pm 21.1) of High feed in their diet. In detail, this proportion was 20.5% (\pm 21.4) during first week of lactation, 21.2% (\pm 21.7) during second week, and 14.0% (\pm 18.9) during third week of lactation. The mean proportions of High feed were highest on day 1 (26.1% \pm 7.3) and 7 (24.7% \pm 22.1). This proportion subsequently showed a slow decrease, down to 12.0% (\pm 19.7) on day 19.

Differences between SID Lys supplies and ex post requirements were compared on a daily timescale (Figure 3), and a weekly timescale

Table 3. Influence of the feeding strategy on the ex post nutrient requirements and nutrient intake, on average during lactation

	Strategy ¹		Statistics ²	
	PRE	STD	RSD	P-value
Number of sows	239	240		
Feed intake, kg/d	6.59	6.45	0.96	0.11
Metabolizable energy				
Requirement, MJ/d	110.1	113.1	14.9	*
Intake, MJ/d	87.5	86.2	12.8	0.26
Intake, % of requirement	79.6	76.3	14.0	*
SID ³ Lys				
Requirement, g/kg	8.1	8.5	1.7	*
Intake, g/kg	7.7	10.0	0.7	***
STTD ⁴ P				
Requirement, g/kg	3.0	3.1	0.6	*
Intake, g/kg	3.2	3.8	0.2	***
Feed High, %	19.0	54.0	10.8	***

¹PRE, precision feeding strategy; STD, standard feeding strategy

²Data were analyzed with ANOVA that included the effect of feeding strategy (***: $P < 0.001$, *: $P < 0.05$).

³Standardized Ileal Digestible

⁴Standardized Total Tract Digestible

(Figure 4). On average, STD sows received more SID Lys than their requirement. Over the first 5 d, the daily excess decreased from 11.2 (\pm 12.5) g/d down to 3.0 (\pm 10.3) g/d. Then it increased almost linearly by 1.3 g/d ($P < 0.001$) up to day 20 (23.6 \pm 17.7 g/d). On average, PRE sows received slightly less SID Lys than their requirement, except on day 1. From day 2 to day 5, the daily deficiency in SID Lys increased from 2.3 (\pm 7.7) up to 5.3 (\pm 7.9) g/d. Then it decreased slowly and almost linearly by 0.2 g/d ($P < 0.001$) down to 3.2 g (\pm 18.3) on day 20. On a weekly timescale (Figure 4), the proportions of sows receiving adequate (\pm 5% of the requirement), deficient (5% to 15% or >15%), or excess amounts (5% to 15% or <15%) of SID Lys according to average ex post requirements differed according to an χ^2 test between PRE and STD feeding strategies in week 1 ($P < 0.001$), 2 ($P < 0.001$), and 3+ ($P < 0.001$). The proportions of STD sows with a SID Lys supply exceeding their requirement by more than 15% were 55.4%, 55.4%, and 75.4%, in weeks 1, 2, and 3+, respectively. The proportions of STD sows receiving adequate amounts of SID Lys (i.e., \pm 5% of the requirement) were 13.3%, 13.8%, and 11.3%, in weeks 1, 2, and 3+, respectively. More PRE than STD sows exhibited a SID lysine deficit, with 33.1%, 30.1% and 28.5% of the sows receiving less than 85% of their requirement in weeks 1, 2, and 3+, respectively. The proportion of PRE sows receiving adequate amounts of SID Lys (i.e., \pm 5% of the requirement) was 20.1%, 22.6%, and 24.7%, in weeks 1, 2, and 3+, respectively.

Differences between STTD P supplies and ex post requirements were also compared on a daily timescale (Figure 3). STD sows received higher supplies of STTD P than their requirements. During the first 5 d, the daily excess decreased from 2.7 (\pm 4.8) g/d down to 1.0 (\pm 3.8) g/d. Then, it increased almost linearly by 0.6 g/d ($P < 0.001$) up to 10.5 (\pm 6.6) g/d on day 20. PRE sows also received higher supplies of STTD P than their requirement, except on day 2. This excess increased slowly and almost linearly by 0.3 g/d ($P < 0.001$) from day 6 (0.4 \pm 3.4) to day 20 (3.3 \pm 7.8).

Nitrogen and phosphorus balance

The N and P balance over lactation is presented in Table 4. Nitrogen intake was lower, by about 20.1%, in PRE sows compared to STD sows, the difference being almost the same for SID Lys intake (-23.2%). Nitrogen in milk was slightly lower, by about 3%, in PRE than STD sows, whereas N mobilized from body reserves was higher (9.0 vs. 2.5 g/d). This resulted in a 28.0% reduction in N excretion in PRE compared to STD sows.

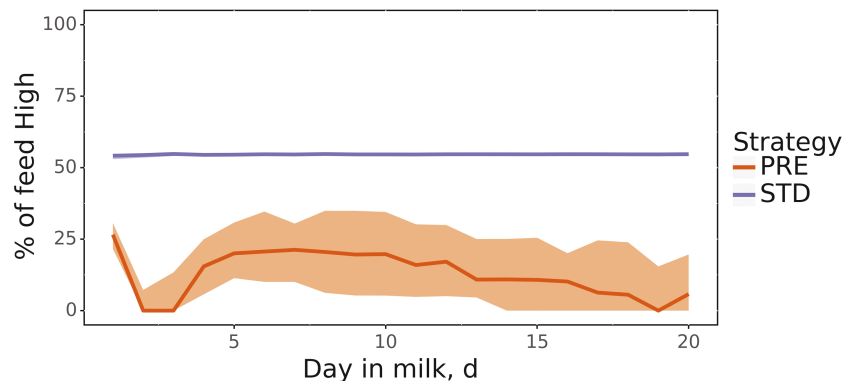


Figure 2. Influence of the stage of lactation on the delivered amounts of High feed according to the feeding strategy (PRE: precision feeding, STD: standard feeding). Lower bound, line, and upper bound are the first quartile, the median, and the third quartile of the amounts of delivered High feed, respectively.

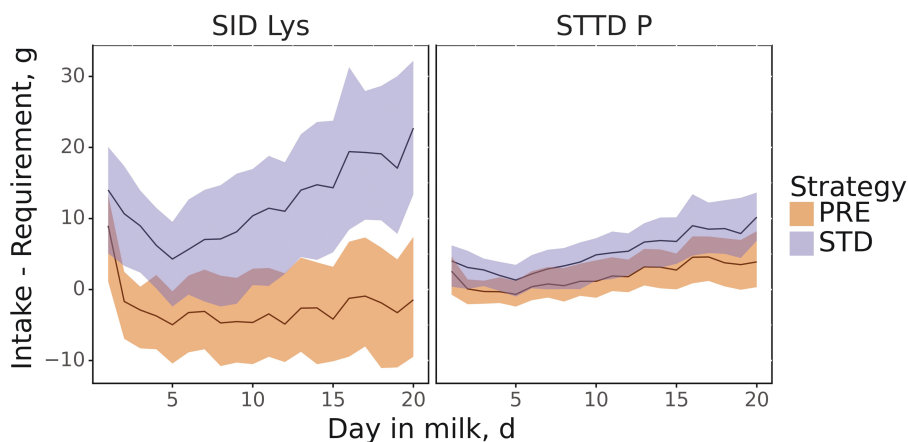


Figure 3. Influence of the feeding strategy (PRE: precision feeding, STD: standard feeding) on the estimation of the daily difference between daily nutrient supplies and daily ex post nutrient requirements (left: SID Lys, right: STTD P). Lower bound, line, and upper bound are the first quartile, the median, and the third quartile of the amounts of delivered High feed, respectively.

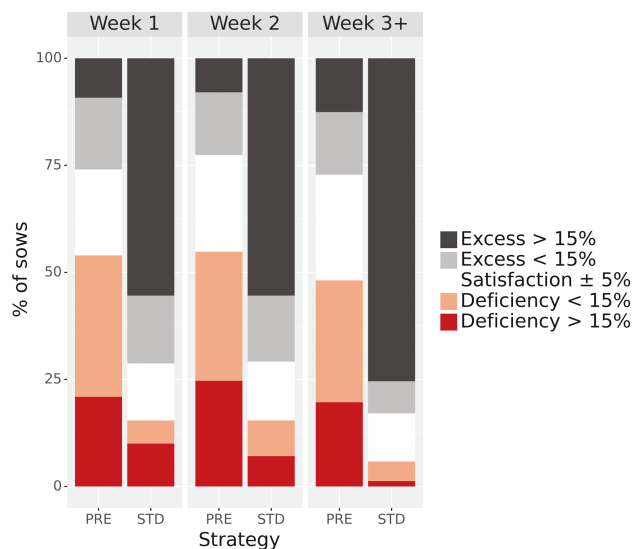


Figure 4. Influence of the feeding strategy (PRE: precision feeding, STD: standard feeding) on the proportion of sows receiving adequate, deficient, or excess amounts of SID Lys according to average ex post requirement per week.

P intake was lower, by about 19.3%, in PRE sows compared to STD sows, the difference being almost the same for STTD P intake (−14.3%). P in milk was slightly lower, by about 3%, in PRE than STD sows. This resulted in 42.2% reduction in P excretion in PRE compared to STD sows.

Feed cost formulated on the basis of feed ingredient prices in July 2020 was cheaper by 11.7% in the PRE (CA\$265.04/t) than in the STD feeding strategy (CA\$300.22/t). However, because of slightly higher feed consumption in PRE sows, the extent of the difference was slightly lower when expressed per sow per lactation (−10%, CA\$35.28 vs CA\$39.31 per sow for PRE and STD treatments, respectively).

Evaluation of DSS components

The performance of the different components of the DSS were evaluated in PRE sows by comparing DSS predictions against

Table 4. Influence of the feeding strategy (PRE: precision feeding, STD: standard feeding) on SID Lys and STTD P intake, and N and P balances¹

	Strategy ²		Variation, %
	PRE	STD	
Number of sows	239	240	
Feed intake, kg/d	6.59	6.45	2.2
SID Lys intake, g/d	49.8	64.8	−23.2
STTD P intake, g/d	20.9	24.4	−14.3
N Balance, g/d			
Ingested ³	147.6	184.7	−20.1
In milk ⁴	84.5	87.1	−3.0
From body reserves ⁵	9.0	2.5	262.5
Excreted ⁶	72.1	100.1	−28.0
Excreted, % ⁷	49.2	54.0	−8.8
P Balance, g/d			
Ingested ³	23.8	29.4	−19.3
In milk ⁴	16.7	17.2	−3.0
Excreted ⁶	7.1	12.2	−42.2
Excreted, % ⁷	29.5	40.5	−27.2
Feed cost, \$/t	265.04	300.22	−11.7

¹SID, standardized ileal digestible; STTD, standardized total tract digestible

²PRE, precision feeding strategy; STD, standard feeding strategy

³Calculated from feed intake and N or P content of feed

⁴Estimated by the Decision Support System from litter size and litter growth

⁵Calculated from sow body weight and backfat loss according to [Dourmad et al. \(1997\)](#)

⁶Calculated from: (Nutrient intake + nutrient from body reserves - nutrient in milk)

⁷Nutrient excretion (%) was calculated from: (Nutrient intake + nutrient from body reserves - nutrient in milk) / Nutrient intake

observed values (PADG, DFI), and by comparing the ex ante against ex post calculations of nutrient requirements (SID Lys and STTD P; [Table 5](#)). Predictions of DFI were strongly correlated with observations ($r^2 = 0.76$). The observed DFI was, however, slightly higher than expected, with a difference of 0.11 kg/d (+1.7%). DFI showed an almost linear increase over the lactation period ([Figure 5](#)). At day 1, the mean

prediction of DFI was lower than the mean observed DFI, with 2.43 (\pm 0.00) and 3.56 (\pm 1.15) kg, respectively. The MAE of DFI prediction is 0.77 kg/d, which represents 11.6% of the observed DFI of sows. For piglet growth, predictions of PADG were weakly correlated with observations ($r^2 = 0.12$). Observed PADG was greater than predicted values by 10 g/d (i.e., by 4.2%). The corresponding MAE of prediction is 31 g/d, which represents 12.4% of the observed mean PADG. The predicted daily SID Lys requirement was strongly correlated with the ex post requirement ($r^2 = 0.77$), but it was on average 4.5 g/d lower (i.e., 8.6% lower) than the ex post requirement, with a relative MAE of 12.8%. The predicted SID Lys requirement per kg feed was significantly correlated with observations ($r^2 = 0.24$), with a difference of -0.5 g/kg (i.e., 6.3% lower) and a MAE of 1.3 g/kg (i.e., 15.9%).

Discussion

General structure of the DSS

The DSS presented here mainly relies on a nutritional model and on machine learning algorithms to process the flow of data produced on-farm during lactation. This makes it possible to take multiple sources of variability in nutrient requirements into account, and to provide nutrient recommendations at the individual level in real time. This system thus introduces an important paradigm shift compared to conventional nutrient recommendations, which are generally determined at the herd level and, in most cases, on average for the entire lactation period. To our knowledge, this DSS is the first of its kind for the precision feeding of lactating sows; however, similar approaches have already been explored for fattening pigs (Hauschild et al., 2012) and gestating sows (Dourmad et al., 2017).

Evaluation of feeding strategies

On average, sow feed intake amounted to 6.5 kg/d. Comparable performance was reported in the literature, for example 6.5 and 5.8 kg/d in Gauthier et al. (2019), and 6.3 kg/d in Hojgaard et al. (2019). Pedersen et al. (2016) found a higher feed intake of 6.9 kg/d, but this was for a longer lactation period, which could explain this difference.

Loss of back fat, generally associated with energy deficiency (Noblet, 1990), was relatively low (3.4 mm), showing no difference between feeding strategies. This is in line with the similar energy intake observed for both strategies.

This value is also comparable to findings from Strathe et al. (2017), who reported a loss of 2.9 mm. Body weight loss was higher in the precision feeding strategy (7.7 kg) than in the standard strategy (2.1 kg). Body weight loss during lactation is frequently associated with a higher risk of reproductive failure after weaning (Quesnel, 2005). However, the higher body weight loss in the precision feeding strategy did not increase the weaning-to-estrus interval of sows, probably because this loss remained rather small. Indeed, from a previous review, Pedersen et al. (2016) reported that highly prolific sows fed ad libitum may lose between 10 and 30 kg of body weight during lactation, and Gourley et al. (2020) recorded a body weight loss of 8.5 kg. The significant difference in body weight loss observed in the present study might be related to lower AA supply to sows in the precision feeding strategy (Strathe et al., 2020), due to the DSS's weak performance in predicting the variability of litter growth and milk production.

Litter average daily gain (LADG) was high with an average of 3.0 kg/d. According to recent studies, LADG was found to fall between 2.6 kg/d and 3.0 kg/d (Gauthier et al., 2019; Gourley et al., 2020). However, a significant and slight reduction of 3% in LADG was observed in sows fed under the precision feeding strategy compared to the control. Because of a similar feed intake in both feeding strategies, this difference is likely due to insufficient AA supply. Sows fed under the precision feeding strategy, for which milk production was underestimated, may have mobilized a greater amount of body proteins to fulfill the high requirements of demanding litters (Trottier et al., 2015). This was not the case for STD sows, which received AAs in excess compared to their requirements. This agrees with the greater body weight losses observed in the precision feeding strategy.

The analysis of ex post requirements also indicates 1) that SID Lys requirements may have been higher than predicted, and 2) that the daily balance in SID Lys between intake and requirement was generally slightly negative. This is even more important if we consider that the potential SID Lys requirement is the one observed with the standard feeding strategy, in which nutrient supply is likely to exceed sows' nutrient requirements. Given the components of the DSS, both an overestimation of feed intake and an underestimation of litter growth could result in an underestimation of the AA requirements. Because feed intake tended to be slightly underestimated, the underestimation of litter growth is likely to be the main reason. This is partly related to the fact that the litter performance in the database used to train the predictive algorithm is slightly lower than the performance achieved during the experiment. As discussed in the

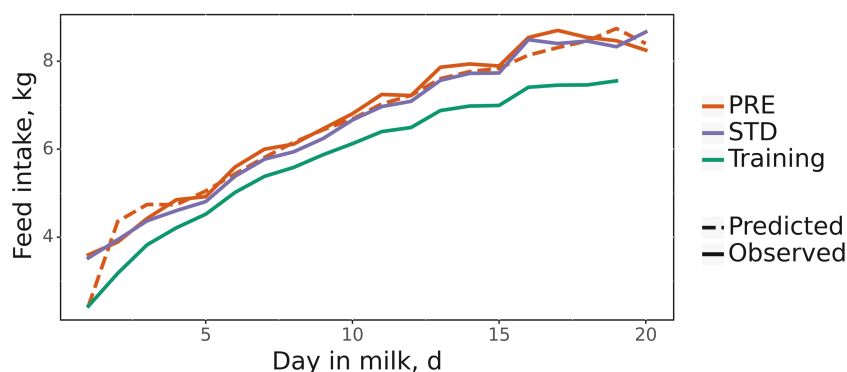


Figure 5. Influence of the stage of lactation on observed feed intake (precision and standard feeding strategies), and predicted feed intake (precision feeding strategy).

following subsection, careful attention must be paid to training the algorithm to predict litter growth, which is highly sensitive to the training database.

From a dynamic point of view, the DSS made it possible to better take the variability in nutrient requirements into account over the lactation period. Except for the first day when there was no prediction available, the percentage of High feed strongly increased during the first week of lactation and subsequently decreased slightly. This is related to an increase in nutrient requirements due to milk production that is faster than the increase in the sows' feed intake capacity (Hansen et al., 2012). After the peak in nutrient exportation in milk, the reduction of the proportion of High feed in the diet for PRE sows results from the increase in feed intake, while milk production tended to plateau or even decrease. Sows within the STD feeding strategy received the same feed throughout their lactation, thus their daily balance in SID Lys was only influenced by the evolution of their nutrient requirements. On the other hand, for sows in the precision feeding strategy, nutrient requirements and diet composition evolved simultaneously, leading to a more constant and almost nil balance between requirement and supply. As for STTD P, this balance was positive and showed a similar trend in both feeding strategies. This might be due to the diet tailoring process, which was done only according to SID Lys requirements.

In the STD feeding strategy, nutrient supplies made it possible to meet the requirements of most sows at the herd level (SID Lys: 84.7% of the sows, STTD P: 88.4% of the sows),

but led to a higher excretion of N and P in feces and urine. The precision feeding strategy made it possible to reduce N and P excretion by 28.0% and 27.2%, respectively. These values may be compared to the 38% reduction in N and P excretion found in growing pigs (Pomar et al., 2011). For a similar approach in gestating sows, Gaillard et al. (2020) found a reduction in N and P excretion of 16.7% and 15.4%, respectively. The present study also reports an 11.7% reduction in feeding cost, which could confirm the economic benefits of precision feeding strategies reported for growing pigs (10.5%, Pomar et al., 2011) and gestating sows (3.6%, Gaillard et al., 2020). Precision feeding thus seems to be a promising strategy for reducing feeding cost and nutrient excretion in lactating sows. However, it is expected that these reductions depend on the standard diet used in conventional feeding strategy. The richer and the more expensive the standard diet is, the bigger the reduction in nutrient excretion and feeding cost.

Recommendations for future usage of the DSS in practice

The analysis of the respective performance of each component of the DSS revealed important points for future implementation of precision feeding systems in lactating sows. We propose a ranking of these observations by order of importance and some recommendations to enhance the performance of the DSS.

- a) The LADG predictive algorithm suffered from concept drift, which is a situation where the underlying structure of data

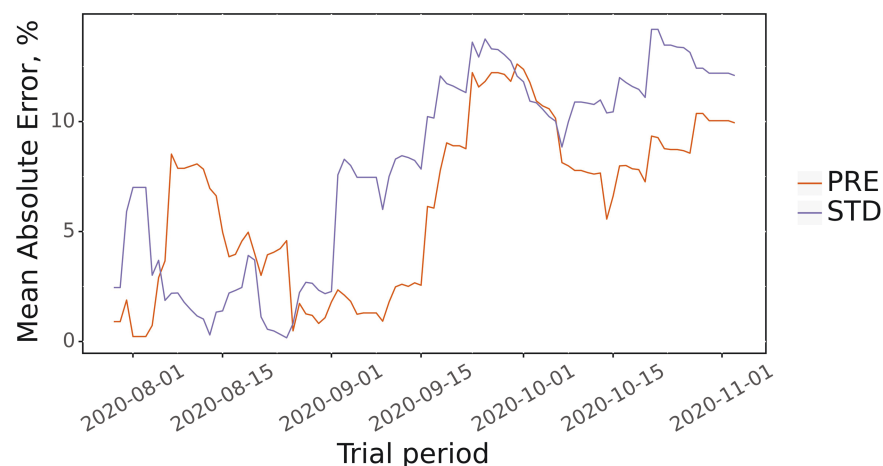


Figure 6. Illustration of concept drift that occurred over time for the prediction of litter average daily gain (LADG). The PRE curve corresponds to the predictive error made online for PRE sows during the experiment. The STD curve corresponds to the predictive error obtained by predicting LADG after the experiment for further analysis.

Table 5. Evaluation of the decision support system for the daily predictions of feed intake, proteins in milk, and SID Lys requirements¹

	N	Pred.	Obs.	r^2	ME	MAE	MAPE, %	RMSEP, %
Feed intake kg/d	4,589	6.49	6.60	0.76	-0.11	0.77	11.6	16.1
PADG, g/d	4,589	237	247	0.12	-10	31	12.4	15.6
SID Lys, g/d	4,589	48.0	52.5	0.77	-4.5	6.7	12.8	16.2
SID Lys, g/kg ²	4,247	7.4	7.9	0.24	-0.5	1.3	15.9	20.3

¹N, number of values; Pred., predicted value; Obs., observed value; r^2 , coefficient of determination; ME, mean error; MAE, mean absolute error; MAPE, mean absolute percentage error; RMSEP, Root Mean Square Error in Percentage; SID, standardized ileal digestible.

²Outliers were removed from predicted and observed SID Lys requirements in g/kg, where an outlier is defined as an observation that falls below $Q_1 - 1.5 \times (Q_3 - Q_1)$ or above $Q_3 + 1.5 \times (Q_3 - Q_1)$, with Q_1 and Q_3 being the first and third quartiles, respectively.

learned during the training process becomes inapplicable at the time the prediction is made (Žliobaite et al., 2016). This process may have been incremental in our case with most changes occurring between early and late September 2020 (Figure 6). Interestingly, the predictive error after this period remained lower on average in the precision feeding strategy, which may be due to greater body protein mobilization, as mentioned earlier. This component could be improved by adding environmental attributes (such as outdoor and indoor temperatures) to the training process of the algorithm. It could also be improved by using online adaptive learning techniques that would refit part of the model, for example, with new data acquired after weaning a batch of sows (Gama et al., 2014).

- b) The predictive feed intake algorithm is another aspect that could contribute to a better match between nutrient supply and requirements. Compared to the predictive LADG algorithm, this second algorithm did not seem to be affected by concept drift. This prediction was in fact established from herd historical data and sow live data (Gauthier et al., 2021), which increased its robustness. First, it would be of interest to explore the structure of daily variations in feed intake behaviors that can be extracted by a time series clustering algorithm. If this structure is meaningful, a seasonal component might be added to the prediction (Cleveland et al., 1990).
- c) For the nutritional model, some data may not be available in every commercial farm, such as body weight and backfat thickness. A solution would be to use mean sow weight and backfat thickness, according to their parity or age. However, we strongly recommend the use of a reliable weighing device to improve the estimation of maintenance costs for sows.

Direct evaluation of the nutritional mathematical model is no easy task since it is related to the prediction of several biological mechanisms. Safety margins at the individual level could thus be considered to offset the imprecision in some of parameters of the nutritional model. The level of this margin would result from a compromise between risks (increasing excretion and feed costs) and benefits (securing nutrient supply, improving performance and welfare). This is especially the case for predicting PADG, for which a large part of the variability (about 50%) cannot be predicted by the algorithm (Gauthier et al., 2022).

Finally, the human-machine interface could be enhanced to provide useful information to farmers. Some data might also be of interest for different precision farming applications. It would thus be useful to connect the DSS with a Management Information System for each farrowing house. This would simplify the tedious task of data entry for farmers.

Conclusion

Feeding sows with a tailored diet is a promising strategy for matching nutrient supply to nutrient requirements at the individual level in real time. The proposed DSS makes it possible to reduce N and P excretion and feeding cost, while better satisfying individual requirements. Litter growth performance is high, although it is slightly lower, by about 3%, compared to the conventional strategy. Sow body weight loss increased slightly with precision feeding, but it remained low

and the sows' reproductive performance after weaning was not affected. These effects appear to be mainly related to an underestimation of litter growth in some sows, leading to insufficient AA supply. This prediction needs to be revised in the future to address concept drift challenges.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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