

Precision Feeding Dairy Cow Pens by Predicting and Formulating for the Distribution of Dry Matter Intake

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Introduction

Precision nutrition is defined as minimizing the error between differences in nutrient requirements and nutrients provided. Knowing and supplying an exact ration for each dairy cow would maximize sustainability and milk production efficiency, less nutrients would be wasted, and cow performance would not be limited by dietary factors (Bewley, 2010; Meijer & Peeters, 2010; Maltz, 2020). This is not practiced; cows are fed by pen at an assumed constant DMI. Individually feeding cows for their energy needs does increase milk yield, solids, and energy-corrected milk per kg of ration dry matter (Maltz, 2013) but is not practical compared to the time and fuel-efficient large group feeding of a TMR (Schingoethe, 2017). Ration formulation should be adapted to precisely feed pens by setting the pen as the unit of feeding because dairy cows are managed by pen on commercial dairy farms.

The distribution of DMI in pens is not normal (Lucey and Rossow, 2023). Rations are formulated based on the ‘average cow’, which does not exist. The mean milk yield, composition, bodyweight, and BCS estimate DMI and energy for the ration solution. Therefore, half the cows will be underfed, and the other half overfed (Maltz, 2020), necessitating over-formulation to sustain high milk production (Linn et al., 2021). If the pen DMI were normal, feeding to this ‘average cow’ may strike a crude balance, but when not the case it will calculate an imprecise ration solution.

Measuring the individual DMI of cows within a pen is not practical in commercial settings (Seymour, 2019), so the true distribution is unknown. But machine learning technology can predict this shape with accuracy and precision from information on milk yield. The total DMI of the pen is then known from the predicted distribution shape and provides ration solutions that account for inter-cow variation within the pen.

This work compared two precision, and two imprecise ration solutions to the ideal ration for a Fresh, High, and Low production cow pen. The ideal ration was solved by least-cost linear programming with the observed DMI of each cow (**TRU**). The first precision ration was solved with DMI values predicted by machine learning for the Distribution Shape Model of DMI (**DSM**). The second precision ration used individual cow DMI values predicted by the NASEM DMI equation Model (**iNSM**; NASEM, 2021). Both imprecise ration solutions used the NASEM DMI equation but applied to a single representative cow rather than each individual. The **aNSM** predicted a DMI for the ration solution with each pen’s mean values, and the **fNSM** ration included an adjustment factor by using the 75th percentile values of the pen’s data for the DMI equation.

Materials and Methods

Pen selection and description

Three virtual pens were assembled from a database of 8,239 weekly observations of 443 individual lactating dairy cows. They were assembled by randomly selecting cows from this observation pool for the size of each pen, as per Lucey and Rossow (2023). The three pens were Fresh: fifty cows of week in milk (**WIM**) from one to three, High: one hundred and fifty cows of WIM from four to twenty-seven, and Low: one hundred cows of WIM from twenty-eight to forty-four. Only one observation per cow was included, and the WIM, and weekly average milk yield (kg) and DMI (kg) were required for inclusion. Some observations also included bodyweight (kg), BCS, milk fat (%), and milk protein (%), but were not excluded if these data were missing.

Distribution shape prediction of pen DMI

A machine learning pipeline (DSM) was used to predict the distribution of DMI for the three pens. This required the inputs pen size, parity category (primiparous, multiparous, or mixed), and descriptive statistics (mean, median, minimum, maximum, 5th, 25th, 75th, 95th percentile, standard deviation, skew and kurtosis) of milk yield and WIM. It predicted the distribution shape as Beta or Generalized Normal, and the parameters of the selected shape. The DMI was calculated as the area under this distribution curve.

Three NSM empirical predictions of pen DMI

The three NSM models used the NASEM 2021 DMI equation to calculate pen DMI but differed by what data was used as inputs. The iNSM used each cow's observed milk yield (kg), DMI (kg), milk fat (%), milk protein (%), parity, bodyweight (kg), BCS and DIM to calculate a DMI, and the sum was the pen DMI. The aNSM used the mean data from the pen for each input, and fNSM used the 75th percentile of the pen for the input variables, this calculated one DMI value for each pen, which was multiplied by the number of cows in that pen for a total.

Ration formulation program development

A least cost linear program was developed using the PuLP package (Roy, J., et al, 2005) in Python 3.12 (Python Software Foundation, <https://www.python.org/>) to solve rations to the nutrient requirements of dairy cows (Moraes et al., 2012). The ration objective function was to minimize cost (Eq. 1) where x is the amount (kg of DM) of feed i , and c is the cost (\$/kg of DM) of feed i , and n is the number of feeds available to the solution.

$$\text{Minimize } \text{COST} = \sum_{i=1}^n c_i x_i \quad \text{Eq. 1}$$

Every cow of each pen was assigned nutrient requirements for metabolizable energy (**ME**) Mcal/kg, Rumen-degradable protein (**RDP**) %, Rumen-undegradable protein (**RUP**) %, Crude protein (**CP**) %, and Neutral Detergent Fiber (**NDF**) % based on their days in milk, and parity (Table 21-1, NASEM 2021). A feed bank was available for the Fresh, High and Low pen based on common ingredient usage (Rossow and Aly, 2013), and the nutrient composition of each was the listed value of table 19-1 NASEM 2021. The listed digestible energy (DE) of the feeds was converted to metabolizable energy (ME) using equation 2-10 of the NRC 2001 (Eq. 2) where EE is ether extract of the feed as a percent of DM.

$$ME(Mcal/kg) = [1.01 \times DE - 0.45] + 0.0046 \times (EE - 3) \quad \text{Eq. 2}$$

Feed costs were obtained in \$/kg of DM from the Penn State feed prices for December 2023 (Penn State Feed Price List, 2023) and personal communication with a nutrition professional (Table 2).

Ration program constraints

Maximum inclusion limits on a kg/kg of DM were included for Corn Silage, Dried Distillers Grains, Molasses and Urea. The DMI was constrained to 2.5% above and below the predicted value for every solution where y is the cow's observed or predicted DMI and x is the DM in kg of feed i (Eq. 3).

$$y \times 0.975 \leq \sum_{i=1}^n x_i \leq y \times 1.025 \quad \text{Eq. 3}$$

The ration value of ME and proportions of CP, RDP, RUP, NDF and starch were constrained by Eq. 4. A minimum ME value was constrained to the nutrient requirement of Mcal/kg of DM. The CP was limited to a maximum of 20% kg DM, and RUP and RDP were constrained to minimums at the nutrient requirement (10% and 6.2 – 7.5% kg DM). The NDF was constrained between 25 and 35% kg DM, and starch between 18 and 33% kg DM.

$$u_t \leq \frac{\sum_{i=1}^n x_i \omega_{ti}}{\sum_{i=1}^n x_i} \leq q_t \quad \text{Eq. 4}$$

Where x_i is the amount of feed i , ω_{ti} is the nutrient t proportion of feed i in kg/kg DMI, u_t is the minimum proportion of nutrient t , and q_t is the maximum proportion of nutrient t .

The ration NDF as forage proportion was constrained between 19 and 25% of kg/kg DM of the solutions by Eq. 5. The feeds Legume hay-mature, Corn silage-typical, and Wheat straw were considered the forage feeds.

$$df \leq \frac{\sum_{i'=1}^3 x_{i'} f_{i'}}{\sum_{i=1}^n x_i} \leq ef \quad \text{Eq. 5}$$

Where df is the minimum and ef is the maximum ration proportion of NDF from forage as kg/kg DM, $x_{i'}$ is the amount of feed for the i' forage, $f_{i'}$ is the NDF proportion of the i' th forage, and x_i is the amount of feed i . The summation of variable $x_{i'}$ is the feeds that are considered forages and is a subset of x_i .

Pen Ration solutions

Combining individual cow ration solutions would incorporate different ingredients by cow, introducing low inclusions of certain ingredients. Single ration solutions for each pen were formulated to prevent this. For all models, the nutrient constraints other than DMI were a sum of the nutrient requirements for all cows within the pen. The % of CP, RDP, RUP, NDF and starch required by each cow were multiplied by their observed DMI to calculate the quantity required, then summed for the kg DM required by the pen. This total quantity of CP, RDP, RUP and NDF

were divided by the pen DMI of each model to calculate their % requirements. These requirements were the constraints to solve a single ration for each pen by all five models. All pen ration solutions for the models: DSM, iNSM, aNSM, and fNSM, were compared for their total values of Cost, DMI, and ME to the solution of TRU for a calculation of RMSE.

Results and Discussion

Pen ration solutions

Pen rations were formulated to their total nutrient requirement with each model (Table 1, 2 & 3). The TRU model used the observed DMI of each cow, so its solution was considered the ideal and most cost-effective. Formulating rations for individual cows is not applicable to commercial dairy management as they are fed by pens. Combining individual rations would affect the composition of a TMR; different ingredients may be present in different solutions and are diluted across the feed bunk at low levels. A single ration per pen is the common application of a TMR (Schingoethe, 2017), with some operations providing separate rations for cow types (e.g. Fresh, High, or Low), or feed the same ration to all pens, but at different quantities for different energy needs. The goal of this work was to provide a ration that can be applied similarly but formulated more precisely. The DSM predicted DMI with a distribution shape; the iNSM applied a DMI prediction equation to each cow. The aNSM and fNSM provided a single DMI for each pen which was multiplied by the number of cows; this assumes a constant DMI and represents industry usage of ration formulation when individual DMIs are not measured.

The DSM predicted a distribution very close to the TRU, and its pen ration was almost identical. The Fresh ration was formulated for 50 cows, and the DSM model under supplied the energy of this group by 6 kg DMI and 14 Mcal ME. In contrast the iNSM, aNSM, and fNSM over predicted this ration in cost by \$68, \$45, and \$78 more than TRU, and DMI and ME by up to 319 kg DM and 852 Mcal, while the DSM was \$2 more expensive. Maintaining energy balance in early lactation cows is important. However, all NSM models overpredicted the required ration, incurring monetary, and nutrient losses. If pens are overfed, the remainder can be fed to others, but the composition of the remainder is unknown, wasteful, and may promote feeding spoiled rations. The results of this work show that different constraint inputs lead to different combinations of ingredients, even for the same pen. Rations should always be formulated with the best-known requirements, especially for high-value ingredients and nutrients. It is important to note that the Fresh pen in this work consisted of cows between WIM 1 and 3, while the NASEM equation used for all three NSM models was derived from cow data of WIM 10 and greater, so higher inaccuracy in this pen's DMI is expected.

The High and Low pen ration solutions were again almost identical for the TRU and DSM models. The RMSE of cost, DMI and ME were less than 1 for the High pen between these two and ranged from 2.6 – 26.6 for the Low pen. For the iNSM model the cost of High ration was overpredicted by \$33/pen/d, which is a higher cost of \$0.22 per cow/d as 150 cows were in this pen. However, the aNSM and fNSM models overpredicted cost by \$66/pen/d, and \$169/pen/d. The difference in cost for the Low pen was \$3/pen for the DSM, \$21/pen, \$23/pen, and \$58/pen for the iNSM, aNSM, and fNSM. The difference in cost between iNSM and aNSM was lower than for the High pen. Less variation in DMI may exist in later lactation pens as cows are beyond their milking peak, showing that approximating a pen's requirements with a pen

descriptor, such as the mean or 75th percentile, is more appropriate in these pens, but still inaccurate when compared to the DSM.

These extra costs added unnecessary expense, especially as the number of cows per ration and the cost of the ration increases. The aNSM and fNSM models assumed a uniform DMI for the pens, ignoring distribution, and while the iNSM was closer to the TRU, is not as easily applied. The NASEM equation requires multiple cow inputs for its use: individual cow milk solids, BW, and BCS, which may not be routinely collected on dairies without the necessary infrastructure. But milk yield, parity and WIM were the only inputs of the DSM, which can be obtained when dairies record the milk yield of each cow. Using the NASEM based models incorrectly balanced the feed ingredients for each pen and did not offer precision feed utilization. Even if excess was fed as waste to other animal groups, nutrient wasting occurs as these would not be balanced correctly for the recipient groups.

Summary

It is understood that DMI is not a normal distribution for dairy cow pens. When the DSM model was applied, the nutrient requirements of a Fresh, High, and Low pen were accurately predicted. This was compared to models using the NASEM DMI equation for ration solutions. The model that applied the equation to each cow per pen (iNSM), to just the mean of the pen (aNSM), and the 75th percentile of the pen (fNSM) all overestimated the energy needs. Ration solutions using these models demonstrated that the DSM could provide a cost and ingredient composition close to the ideal ration, improving precision feeding and nutrient utilization.

Table 1. Fresh pen ration solutions.

n = 50	TRU	DSM¹	iNSM²	aNSM³	fNSM⁴
Cost, \$ ⁵	217	215	276	262	295
DMI, kg ⁶	890	884	1135	1077	1209
ME, Mcal ⁷	2366	2352	3019	2863	3218
CP, %	17.4	17.4	17.3	17.3	17.5
RUP, %	7.36	7.37	7.33	7.31	7.5
RDP, %	10	10	10	10	10
NDF, %	35	35	35	35	35
NDF % forage	19	19	19	19	19
Starch, %	25	25	25	25	25
Corn silage, typical, kg	413	411	527	500	561
Wheat silage, kg	77	77	97	92	109
Corn grain dry, kg	70	69	90	86	94
Corn gluten feed, kg	129	128	167	159	165
DDGS, kg	89	88	113	108	121
Molasses, kg	26	26	34	32	36
Urea, kg	0.45	0.44	0.57	0.54	0.60
Soybean meal, kg	84	84	106	99	122
Ration total, kg	890	884	1136	1077	1209

DMI = Dry Matter Intake

TRU = Observed DMI model

DSM = Distribution shape DMI model

iNSM = Individual NASEM equation model

aNSM = Average cow NASEM equation model

fNSM = 75th percentile cow NASEM equation model

ME = Metabolizable Energy

CP = Crude Protein

RUP = Rumen Undegradable Protein

RDP = Rumen Degradable Protein

NDF = Neutral Detergent Fiber

DDGS = Dried Distillers Grains with Solubles

¹ Ration constraint inputs from the Distribution Shape Model (DSM).

² Ration constraint inputs from the iNSM equation model.

³ Ration constraint inputs from the aNSM equation model that used the pen means.

⁴ Ration constraint inputs from the fNSM equation model that used the pen 75th percentile.

⁵ RMSE of 1.27, 59, 45, and 78 for the DSM, iNSM, aNSM and fNSM when compared to TRU Cost.

⁶ RMSE of 5.39, 245, 187, and 319 for the DSM, iNSM, aNSM and fNSM when compared to TRU DMI.

⁷ RMSE of 14, 652, 497, and 851 for the DSM, iNSM, aNSM and fNSM when compared to TRU ME.

Table 2. High pen ration solutions.

n = 150	TRU	DSM¹	iNSM²	aNSM³	fNSM⁴
Cost, \$ ⁵	858	858	891	924	1027
DMI, kg ⁶	3498	3498	3632	3771	4186
ME, Mcal ⁷	9324	9324	9683	10052	11161
CP, %	17.4	17.4	17.4	17.3	17.5
RUP, %	7.36	7.37	7.33	7.31	7.5
RDP, %	10	10	10	10	10
NDF, %	35	35	35	35	35
NDF % forage	19	19	19	19	19
Starch, %	25	25	25	25	25
Corn silage, typical, kg	1,624	1,623	1,686	1,751	1,943
Wheat silage, kg	264	264	274	283	319
Corn grain dry, kg	262	262	273	283	312
Corn gluten feed, kg	573	573	595	619	677
DDGS, kg	350	350	363	377	419
Molasses, kg	105	105	109	113	126
Soybean meal, kg	321	321	333	345	391
Ration total, kg	3,499	3,498	3,633	3,771	4,177

DMI = Dry Matter Intake

TRU = Observed DMI model

DSM = Distribution shape DMI model

iNSM = Individual NASEM equation model

aNSM = Average cow NASEM equation model

fNSM = 75th percentile cow NASEM equation model

ME = Metabolizable Energy

CP = Crude Protein

RUP = Rumen Undegradable Protein

RDP = Rumen Degradable Protein

NDF = Neutral Detergent Fiber

DDGS = Dried Distillers Grains with Solubles

¹ Ration constraint inputs from the Distribution Shape Model (DSM).

² Ration constraint inputs from the iNSM equation model.

³ Ration constraint inputs from the aNSM equation model that used the pen means.

⁴ Ration constraint inputs from the fNSM equation model that used the pen 75th percentile.

⁵ RMSE of 0.01, 33, 67, and 170 for the DSM, iNSM, aNSM and fNSM when compared to TRU Cost.

⁶ RMSE of 0.02, 135, 273, and 688 for the DSM, iNSM, aNSM and fNSM when compared to TRU DMI.

⁷ RMSE of 0, 360, 728, and 1837 for the DSM, iNSM, aNSM and fNSM when compared to TRU ME.

Table 3. Low pen ration solutions.

n = 100	TRU	DSM¹	iNSM²	aNSM³	fNSM⁴
Cost, \$ ⁵	535	538	556	558	593
DMI, kg ⁶	1988	1997	2067	2071	2203
ME, Mcal ⁷	5545	5472	5663	5674	6036
CP, %	18.7	18.7	18.7	18.7	18.7
RUP, %	7.7	7.7	7.7	7.7	7.7
RDP, %	11	11	11	11	11
NDF, %	35	35	35	35	35
NDF % forage	19	19	19	19	19
Starch, %	21	21	21	21	21
Corn silage, typical, kg	923	927	959	962	1,023
Wheat silage, kg	0	0	0	0	0
Corn grain dry, kg	0	0	0	0	0
Corn gluten feed, kg	750	754	780	781	832
DDGS, kg	0	0	0	0	0
Molasses, kg	60	60	62	62	66
Soybean meal, kg	255	256	265	265	283
Ration total, kg	1,988	1,997	2,066	2,070	2,204

DMI = Dry Matter Intake

TRU = Observed DMI model

DSM = Distribution shape DMI model

iNSM = Individual NASEM equation model

aNSM = Average cow NASEM equation model

fNSM = 75th percentile cow NASEM equation model

ME = Metabolizable Energy

CP = Crude Protein

RUP = Rumen Undegradable Protein

RDP = Rumen Degradable Protein

NDF = Neutral Detergent Fiber

DDGS = Dried Distillers Grains with Solubles

¹ Ration constraint inputs from the Distribution Shape Model (DSM).

² Ration constraint inputs from the iNSM equation model.

³ Ration constraint inputs from the aNSM equation model that used the pen means.

⁴ Ration constraint inputs from the fNSM equation model that used the pen 75th percentile.

⁵ RMSE of 2.61, 21.4, 22.5, and 58.1 for the DSM, iNSM, aNSM and fNSM when compared to TRU Cost.

⁶ RMSE of 9.71, 79.5, 83.4, and 215 for the DSM, iNSM, aNSM and fNSM when compared to TRU DMI.

⁷ RMSE of 26.6, 217, 228, and 590 for the DSM, iNSM, aNSM and fNSM when compared to TRU ME.

References

- Bewley, J. 2010. Precision Dairy Farming: Advanced Analysis Solutions for Future Profitability. The First North American Conference on Precision Dairy Management. Toronto, Canada. <https://www.precisiondairyfarming.com/>
- Linn, J., Hutjens, M., Shaver, R., Otterby, D., Howard, Terry., Kilmer, L., University of Minnesota Extension, 2021, Formulating dairy cow rations. Accessed Aug. 16, 2024. <https://extension.umn.edu/dairy-milking-cows/formulating-dairy-cow-rations>
- Lucey, P.M., and H.A. Rossow. 2023. Describing the distribution type of DM intake for dairy cow pens based on pen characteristics. *animal* 17:100888. doi:10.1016/j.animal.2023.100888.
- Maltz, E. 2020. Individual dairy cow management: achievements, obstacles and prospects. *Journal of Dairy Research* 87:145–157. doi:[10.1017/S0022029920000382](https://doi.org/10.1017/S0022029920000382).
- Meijer, R., and K. Peeters. 2010. The Use of Precision Dairy Farming in Feeding and Nutrition. The First North American Conference on Precision Dairy Management. Toronto, Canada. <https://www.precisiondairyfarming.com/>
- Moraes, L.E., J.E. Wilen, P.H. Robinson, and J.G. Fadel. 2012. A linear programming model to optimize diets in environmental policy scenarios. *J Dairy Sci* 95:1267–1282. doi:[10.3168/jds.2011-4651](https://doi.org/10.3168/jds.2011-4651).
- National Academies of Sciences, Engineering, and Medicine (NASEM)., 2021. Nutrient Requirements of Dairy Cattle: Eighth Revised Edition. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25806>.
- Penn State Feed Price List. 2023. Pennsylvania State University Cooperative Extension. Accessed June 9th, 2024. <https://extension.psu.edu/programs/files/feed-price-lists>
- Roy, J.S., Mitchell, S.A., Peschiera, F., PuLP: A Linear Programming Toolkit for Python (2.9.0), <https://pypi.org/project/PuLP/>
- Schingoethe, D.J. 2017. A 100-Year Review: Total mixed ration feeding of dairy cows. *Journal of Dairy Science* 100:10143–10150. doi:[10.3168/jds.2017-12967](https://doi.org/10.3168/jds.2017-12967).
- Seymour, D.J., A. Cánovas, C.F. Baes, T.C.S. Chud, V.R. Osborne, J.P. Cant, L.F. Brito, B. Gredler-Grandl, R. Finocchiaro, R.F. Veerkamp, Y. de Haas, and F. Miglior. 2019. Invited review: Determination of large-scale individual dry matter intake phenotypes in dairy cattle. *Journal of Dairy Science* 102:7655–7663. doi:[10.3168/jds.2019-16454](https://doi.org/10.3168/jds.2019-16454).