IMPROVING NUTRITIONAL ACCURACY AND ECONOMICS THROUGH MULTIPLE RATION-GROUPING MANAGEMENT

by

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LITERATURE REVIEW

1.1. Introduction

One of the most critical challenges dairy farms face today are narrow profit margins (Bewley et al., 2015) together with increasing price volatility and uncertainty. Additional challenges affecting dairy farm management include environmental regulations and consumers demands for social sustainability and animal welfare (Spilke and Fahr, 2003, Bewley et al., 2015). To fulfill these consumer demands and environmental regulations while achieving farm profitability, it is required to improve farm management efficiency. Systematizing data collection and analysis is a potential strategy to enhance management efficiency supporting improved decision-making (Bewley et al., 2015).

Precision dairy farming plays an important role in improving dairy production sustainability (Chase, 2018). Precision dairy farming is defined as the actions of measuring and recording physiological, behavioral, and production performance from dairy cattle using automated systems to improve production, economic, social, and environmental sustainability (Spilke and Fahr, 2003, Bewley, 2010). The adoption of new technologies to implement precision dairy farming generates constant real-time data streams (Liang et al., 2018). These massive data streams include on-farm data from milking, feeding, reproduction, and weather condition records, along with off-farm records such as milk and feeds market prices. However, these data streams are individually collected and processed by different software (Liang et al., 2018). To facilitate analysis of the global farm situation and generate more effective and efficient decision-making process on farms, it is essential to integrate these different data streams (Liang et al., 2018). Collecting real-time massive data allows the dairy farmer to monitor and identify significant physiological and behavior abnormalities of the cows (Bewley et al., 2015). By detecting these abnormalities, dairy farmers have the chance to make opportune decisions that may result in greater productivity and profitability (Meijer and Peeters, 2010).

Improving dietary nutritional accuracy is part of the process to enhance precision dairy farming. Dietary nutritional accuracy is defined by Cerosaletti and Dewing (2008) as "the continual process of providing adequate, not excess, nutrients to the animal requirement and deriving a majority of nutrients from homegrown feeds through the integration of feeding and forage management for the purpose of maintaining environmental and economic sustainability." Real-time monitoring of weather conditions, feedstuff composition, mixed and delivered total mixed rations (TMR), nutritional requirements, and dry matter intake (DMI) of lactating cows, along with greater diet formulation frequency improve nutritional accuracy of diets, productivity, and generate economic benefits (White and Capper, 2014).

White and Capper (2014) studied the interaction between climate and diet formulation frequency. They reported economic benefits when diets were formulated more frequently considering changes of cows energy requirements related to varying climate conditions. When diets are formulated on a weekly basis, returns over costs may increase by $25,000 per year for a 300-cow operation (White and Capper, 2014). Also, Maltz et al. (2013) reported an improvement in milk yield when diets matched individual cows' requirements over the lactation curve. They performed a study feeding 58 cows through the early and mid-lactation stages (from 1 to 19 weeks) with a single control diet (NE_L: 1.64

Mcal/kg of DM; CP: 16.2%) and a treatment diet (NE_L: ranged from 1.59 to 1.63 Mcal/kg of DM; and CP: ranged from 16.1 to 16.2%). This treatment diet better matched the diet to the individual nutritional requirements of the cow. Results showed 0.86 kg/cow per d more concentrate use in treatment than control diet. However, the treatment group cows produced 3.3 kg/d more milk, 3.2 kg/d more fat corrected milk (FCM), and 2.8 kg/d more energy corrected milk (ECM) per cow than did cows in the control group.

Improvement in nutritional accuracy of diets can also be accomplished through cow grouping management (Kalantari et al., 2016, Barrientos et al., 2018, Bach, 2019). This concept is known as nutritional grouping (NG) and consists of grouping cows with similar nutritional requirements and providing an adjusted diet to each group (Cabrera et al., 2012). Nutritional grouping strategy facilitates improved allocation of nutrients due to decreased variance of nutritional requirements within each group (Cabrera et al., 2012, Kalantari et al., 2016, Wu et al., 2019). As a result, dietary nutritional accuracy increases due to improving the match of diet to cow's nutritional requirement (Grant and Albright, 2001).

1.2. Grouping factors and feeding management

Grouping management is an important aspect to consider for enhancing cow productivity, health, and farm profitability. When cows are grouped, they have better production performance, welfare, and health than when they are alone. Cows in groups show greater DMI due to social stimulation behavior (Albright, 1993). Grouping management also affects feeding behavior of dairy cows, which consequently improves milk production and economics of the farm (Sniffen, 1991). When grouping cows, it is important to consider factors such as group size and number of groups, bunk space, facility design, days in milk

(DIM), age, stage of cows, and cows' social interaction and behavior (Grant and Albright, 2001).

Many factors are used to determine the number of cows per group; these include cow characteristics (social interaction, body size and condition, age, and DIM), facility capacities (stocking density per pen and in milking parlor's holding area, feed bunk space, and number of lying spaces), and barn conditions (stall size and design, and environmental conditions of the barn). Batchelder (2000) performed a study comparing the effect of head gates versus no head gates and 0 or 30% overcrowding of free stalls and bunk space. Results showed that cows in head gate pens had a decrease from 3 to 6% DMI for both 0 and 30% overcrowding, compared to no head gates. Immediately after post-milking, 45 to 66% of non-overcrowding cows ate, whereas only 28 to 30% of cows in overcrowded groups ate. For the no-overcrowd group, 32 to 43% of cows ate at feeding time, whereas for the overcrowd group, only 21 to 27% of cows ate at feeding time. From an observation period of every 15 minutes during 24 h, on average, 28% (maximum 32%) of cows were ruminating in the overcrowd group, whereas 37% (maximum 55%) of cows were ruminating in no-overcrowd groups. In contrast to the above findings, Bolinger et al. (1997) reported that headlocks do not affect milk yield, somatic cell score (SCS), or daily DMI. They found that, after restrained in headlocks, cows spent more time laying down, less time eating, and are more aggressive, although their DMI is not affected. Grant and Albright (2001) recommend that group density can be optimized by minimizing waiting time for milking (less than 45 minutes to 1 hour, milking 2 to 3 times a day), providing palatable feed at high frequency, and adequate fence-line feeding design.

Days in milk and age of cows are relevant factors to be considered on grouping cows (Grant and Albright, 2001). It has been shown that cows in the first 5 week of lactation have the fastest rate of increase in DMI, around 1.5 to 2.2 kg of DM/week (Kertz et al., 1991). Additionally, the rate of increase in DMI is 15% greater for multiparous cows than for primiparous cows (Kertz et al., 1991). This could be explained by the social structure of cow groups. Hierarchical dominance is observed in cow groups, primarily at feed bunks (Grant and Albright, 1995). This hierarchical dominance is correlated with age, body size, and seniority of the group (Dickson et al., 1970). Hence, new cows in the group are less dominant and their DMI is negatively affected if feed quantity or bunk space is constrained (Grant and Albright, 2001). Nevertheless, hierarchical dominance is diminished in large groups of cows (Zwald and Shaver, 2012). Albright (1978) reported that cows can only recognize around 100 other animals. In large groups, cows will rather be laying down or eating than spending energy in stabilizing hierarchy position (Albright, 1978).

Competition for feed, water, and other sources, and herd health are factors that influence DMI. Cows that experience extreme environmental and social changes during transition period are more susceptible to metabolic disorders and abnormal feeding behavior. Grouping transition cows separate from later lactation cows is recommended in order to facilitate their adaptation to the postpartum environment (Grant and Albright, 1995). Offering unlimited feed does not remove feeding competition but could avoid decreased DMI (Olofsson, 1999). It is recommended to have between 0.61 to 0.76 meters of bunk space per cow with unlimited access to feed during the day (Grant and Albright, 2001). Additionally, body size matters when grouping cows. Primiparous cows are smaller and have lower hierarchical dominance in comparison to mature cows. A separate group assigned for primiparous cows improves their DMI and milk production (Grant and Albright, 2001).

Several studies have shown that shifts of cows between groups disrupt groups hierarchy and may affect the DMI and milk productivity of the new cows in the group (i.e., Smith et al., 1978). However, the dominance hierarchy among the group is reestablished between 3 to 7 days after moving (Grant and Albright, 2001). Zwald and Shaver (2012) measured the effect of pen change in daily milk yield during the first 10 days post-movement. Farm A consisted of a group of 152 cows that did not change pens and 154 that were moved. Farm B had 142 cows that did not move pens, and 137 cows that moved. The reported results showed that moving cows to different groups does not cause a significant decrease in milk yield. In a trial of 100 cows managed with 3-grouping and 1-grouping management as control, Clark et al. (1977) found no significant difference in milk yield 5 days after cows were changed to a different group once a month. In contrast, Smith et al. (1978) measured the effect of 1 and 2-group management with low forage (56%) and high forage (84%) diets. They reported that moving cows in the 2-group management decreased milk yield by 2 kg/cow per d in the first week after moving and the milk yield decreased persisted longer for multiparous cows than primiparous cows.

1.3. Nutritional grouping

1.3.1. Nutritional Grouping methods

In a grouping simulation study, Williams and Oltenacu (1992) suggested that NE_L and CP requirements per kg of DMI and per kg of neutral detergent fiber (NDF) intake capacity are the most appropriate factors for grouping cows. McGilliard et al. (1983) used ranking cluster as a method for grouping cows according to their NE_L and CP requirements. The first step of this method is to standardize NE_L and CP concentration requirements ($u = 0, \sigma^2 = 1$). This is done by subtracting the average NE_L and CP concentration requirements of the herd from the individual cow NE_L and CP requirement and dividing it by the standard deviation of the NE_L and CP concentration requirements. Then, the standardized values are ranked, and cows are grouped by percentile rank. With this method, the group sizes are equal over time and allows the farm manager to use one or multiple nutritional requirement as grouping variables (McGilliard et al., 1983).

Different than the ranking cluster method, Cabrera et al. (2012) suggested an iterative searching of global maximum income over feed cost (IOFC) as a method to perform NG. This method allocates cows by nutrient requirements to a pre-determined number of groups and size of those groups, then maximizes the global income over feed cost (IOFC) of the herd. The maximum IOFC is calculated using Eq.1:

$$Max(IOFC) = \sum G_{group} = \left(IOFC_{group}\right) \quad [1]$$

Where:

$IOFC_{group} = \left(Milk_{group}\right)(Milk\ Price) - \left(FeedCost_{group}\right),$

$FeedCost_{group} = \left(83\%tileCP_{group}(CPPrice)\right) + \left(83\%tileNEl_{group}(NElPrice)\right),$

$IOFC = Income\ over\ feed\ cost,$

$G = Total\ number\ of\ groups: 2, 3, or\ 4$

Following the iterative search of global maximum IOFC method, Wu et al. (2019) suggested the OptiGroup as a method to implement NG. OptiGroup consists of finding the cows group arrangement that maximize the global IOFC of the herd using a mixed-integer nonlinear programming optimization algorithm. The objective equation of the model is maximizing IOFC as follows in Eq. 2:

$Max(IOFC) =$

$$\sum_{i=1}^{n}\left(P_{milk}\sum_{i=1}^{N_j} g_{ji}MY_i - C_{NE}\sum_{i=1}^{N_j} g_{ji}DMI_iNE_{L,diet,j} - C_{CP}\sum_{i=1}^{N_j} g_{ji}DMI_iCP_{diet,j}\right) \qquad [2]$$

Subject to:

$\sum_{i=1}^{N} g_{ji} = 1$; every cow belongs to one group $g_{ji} \in \{0,1\}$

$N_1 = N_2\ for\ 2\ groups\ or\ \ N_1 = N_2 = N_3\ for\ 3\ groups$

$NE_{L,diet,1} = NE_{L,diet,2} for\ 2\ groups\ or\ \ NE_{L,diet,1} = NE_{L,diet,2} = NE_{L,diet,3}\ for\ 3\ groups$

$CP_{diet,1} = CP_{diet,2} for\ 2\ groups\ or\ \ CP_{diet,1} = CP_{diet,2} = CP_{diet,3}\ for\ 3\ groups$

Where:

j = group number; n = number of groups (2 or 3); i = cow number; N_j = number of cows in group j; P_{milk} = Price of the milk; g_{ji} = cow i in group j; MY_i = Milk yield of cow i; C_{NE} = Cost of NE_L nutrient by unit; DMI_i = Estimated dry matter intake of cow i; $NE_{L,diet,j}$ = NE_L density in the diet of group j; C_{CP} = Cost of crude protein nutrient by unit; $CP_{diet,j}$ = Crude protein percentage in the diet of group j.

A different approach for implementing NG strategy is using K-means analysis. Forgey (1965) developed the K-means clustering algorithm, an unsupervised machine learning algorithm used to find subgroups in an observation dataset. This method identifies which observations are similar and categorizes them into a pre-specified number of subgroups. The algorithm looks for observations with minimum variability within clusters and maximum dissimilarity between clusters. The variability is measured as distance between observations or as correlation-base distance. There are Euclidean and Manhattan methods that measure distance between observations and Pearson, Kendall, and Spearman methods that measure the correlation-base distances. The Euclidean method measures the distance between two vectors x and y of length n $d_{euc}(x,y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$. Similarly, the

Manhattan method measures distance between two vectors x and y of length n, but uses $d_{man}(x,y) = \sum_{i=1}^{n} |(x_i - y_i)|$. Pearson method is done by $d_{cor}(x,y) = 1 - \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}}$, where x and y are the vectors with length n. Spearman method uses the same equation as Pearson, but with ranked vectors $d_{cor}(x,y) = 1 - \frac{\sum_{i=1}^{n}(x_i'-\bar{x}')(y_i'-\bar{y}')}{\sqrt{\sum_{i=1}^{n}(x_i'-\bar{x}')^2 \sum_{i=1}^{n}(y_i'-\bar{y}')^2}}$, where $x_i' = rank(x_i)$ and $y_i' = rank(y_i)$. Kendall method measures the correspondence between the ranking of x and y variables following $d_{kend}(x,y) = 1 - \frac{n_c - n_d}{\frac{1}{2}n(n-1)}$, where n is the length of x and y, $\frac{1}{2}n(n-1)$ is the total number of possible pairings of x with y observations, n_c (concordant pairs (c)) is the number of y_i that are larger than each y_i and n_d (discordant pairs (d)) is the number of y_i that are lower than each y_i. The most common method to measure distance is Euclidean. However, the method to be used depends on the type of data or purpose. K-means clustering is performed in 4 steps: 1) Set the number of groups (k). 2) Calculate the means of each cluster. 3) Assign the observations to the closest mean of the cluster according to the Euclidean distance from the observation to the mean of the cluster. And 4) calculate the mean of each cluster (center) iteratively repeating step 3 until the algorithm finds the minimum total variation between observations and the center of the cluster. The standard K-means algorithm used in step 4 is Hartigan-Wong algorithm, which uses Euclidean distance to determine the total within-cluster variation between the observations and center of each cluster. Hartigan-Wong algorithm follows $\sum_{k=1}^{k} W(C_k) = \sum_{k=1}^{k} \sum_{x_i \in C_k} (x_i - u_k)^2$, where k is the number of groups; x_i is the observation that belongs to the cluster C_k; and u_k is the average values of the observations that belongs to the cluster C_k. The final clusters have minimum variance between observations within the groups. The number of clusters (k) are pre-determined, however, the number of observations may be dissimilar between clusters. This possible difference in number of observations among clusters can be a limitation if the number of cows per group has to be constrained due to the barn facility design.

1.3.2. Optimal factors to consider for grouping cows

In a simulation grouping study, McGilliard et al. (1983) compared grouping by their percentage CP requirements and NE_L requirements per kg of expected DM with grouping cows by daily milk yield, FCM, and dairy merit ($FCM/BW^{0.75}$). The analysis showed that using ranking cluster method for NG resulted in lower within group variance of CP: $\sigma^2 = 2.14$ and NE_L: $\sigma^2 = 0.0137$) than grouped by milk yield (CP: $\sigma^2 = 2.84$ and NE_L: $\sigma^2 = 0.0204$), by FCM (CP: $\sigma^2 = 2.65$ and NE_L: $\sigma^2 = 0.0192$), and by dairy merit (CP: $\sigma^2 = 2.39$ and NE_L: $\sigma^2 = 0.0177$). Later, Kalantari et al. (2016) did a NG study using NE_L and MP as factors for grouping cows. They reported productive and economic benefits using 2 and 3-nutritional groups management.

1.3.3. Formulation of diets for nutritional grouping

Lead factor is an important conversion factor to formulate an optimum diet for a group of cows (St-Pierre and Thraen, 1999). Lead factor was defined as the mean plus one standard deviation ($mean + 1 \times SD$) or 83rd percentile milk yield value of a group of lactating cows in Stallings and McGilliard (1984) and St-Pierre and Thraen (1999). The cow that has the closest milk yield to the lead factor is used as reference to calculate cow's CP and NE_L requirement, according to her body weight and milk components (protein, fat, lactose). $Mean + 1 \times SD$ and 83rd percentile methods are sensitive to herd size, season, and milk performance (Stallings and McGilliard, 1984). According to Stallings and McGilliard

(1984), 83rd percentile is the best method to calculate lead-factor values for balancing dairy diets. Even though 83rd percentile method does not yield the most economical diet, it promotes the increase of milk production and minimizes the overfeeding of cows with low milk yield (Stallings and McGilliard, 1984). In other studies, optimal NE_L and MP requirements per nutritional group have been calculated using $Mean + 1 \times SD$ of the group's NE_L and MP requirement distribution (Cabrera et al., 2012, Kalantari et al., 2016, Wu et al., 2019). With this optimal NE_L and MP requirement per group, they calculated the diet's cost and the IOFC of each nutritional group. In a similar approach St-Pierre and Thraen (1999) have suggested the use of differenciated lead factor per group, which depends on the number of groups. For example, when aggregating cows in 3 groups the lead factor to be multiply by the milk yield and calculate the NE_L to formulate a diet per group are 1.15 for group 1, 1.21 for group 2, 1.29 for group 3. The lead factor to be multiply by the milk yield and calculate the CP to formulate a diet per group are 1.11 for group 1, 1.17 for group 2, and 1.24 for group 3. These lead factors from St-Pierre and Thraen (1999) are derived from ecomic optimization and have similar magnitude to the 83rd percentile method suggented by Stallings and McGilliard (1984). However, the lead factors from St-Pierre and Thraen (1999) are lower for the lowest milk production groups. For example, when aggregating cows in 3 groups, Stallings and McGilliard (1984) suggested a lead factor of 1.14 for group 1, 1.10 for group 2, and 1.21 for group 3.

1.3.4. Benefits of nutritional grouping management for milk production

Nutritional grouping management yields groups of cows with less variable nutritional requirements (Kalantari et al., 2016, Barrientos et al., 2018, Wu et al., 2019). This facilitates a better allocation of diet nutrients across groups and, therefore, greater nutritional accuracy of diets (Cabrera and Kalantari, 2016, Kalantari et al., 2016, Barrientos et al., 2018). Greater dietary nutritional accuracy decreases the proportion of underfed and overfed cows in the herd (Kalantari et al., 2016, Bach, 2019). Using NG strategy, cows with low nutritional requirements get less dense and cheaper diets while cows with high nutritional requirements get denser and more expensive diets (Bach, 2014, Kalantari et al., 2016). Feeding multiple rations that better match nutritional requirements enhances the potential milk productivity of high production cows and decrease over-conditioning of lower milk yield cows (Allen, 2009).

A potential increase in milk yield of high production cows due to greater nutritional accuracy of diets using NG can be speculated based on results of several studies. In comparison with 65:35 forage: concentrate ratio diet, Okine et al. (1997) reported a tendency of increased milk yield by 11% ($p>0.05$) and FCM by 14% ($p>0.04$) when late-lactation (>200 DIM) cows were fed with 50:50 forage: concentrate ratio diet. In another study, feeding mid-lactation (90±33.6 DIM) cows with 80:20, 65:35, 50:50, and 35:65 forage: concentrate ratio diets, Moorby et al. (2006) reported a significant linear increase on milk yield ($P<0.001$) as the fermentability of the diets increased. The results showed up to nearly 8 kg/cow per d greater on milk yield when cows were fed with 35:65 rather than 80:20 forage: concentrate ratio diet. Hernandez-Urdaneta et al. (1976) reported that feeding early-lactation (4 to 28 DIM) cows a 40:60 forage: concentrate ratio diet contributed to an increase of 2.8 kg/cow per d milk yield compared to early-lactation cows fed with a 60:40 ratio diet.

1.3.5. Economic benefits of nutritional grouping management

Grouping cows according to their CP and NE_L requirements per kg of DM and NDF intake capacity improves IOFC due to increased milk yield (Williams and Oltenacu, 1992). Williams and Oltenacu (1992) study showed that per cow and per year IOFC for 3-nutritional groups management was $21 (8,000 kg of milk production at 305-d), $33 (9,000 kg of milk production at 305-d), and $40 (10,000 kg of milk production at 305-d) greater than 2-nutritional groups management. St-Pierre and Thraen (1999) reported that NG strategy decreased the variance of the nutritional requirements within the groups, which improved the allocation of nutrients and increased milk yield. As a result, the IOFC increased by $43.80/cow per yr when cows were aggregated in 2-nutritional groups and $76.65/cow per yr when cows were aggregated in 3-nutritional groups. Cabrera et al. (2012) performed a simulation NG study using a ranking and iterative method for maximizing global IOFC of the herd. Using a dataset from 30 Wisconsin herds, they showed that 3-nutritional groups increased IOFC by $396/cow per yr. Kalantari et al. (2016) evaluated the economic impact of nutritional grouping in five commercial dairy herds using a stochastic Monte Carlo simulator model. Using the datasets from the farms included in the study, the simulator scheduled the events that could happen to cows on each of their reproductive cycles. The aggregation of cows in nutritional groups was performed using the ranking and iterative method for maximum global IOFC of the groups suggested by Cabrera et al. (2012). In a first step, cows were categorized into two subgroups, obligated and optional. Obligated subgroup was assigned to dry and postpartum (< 21 DIM) cows which were subdivided into two nutritional groups. Dry cows were fed a constant NE_L of 1.7 Mcal/kg of DM and MP of 7g / 100 g of DM diet. Early cows were fed a constant NE_L of 1.28 Mcal/kg of DM diet and the provided

MP was calculated based on the 83rd percentile of the MP requirement of the group. Optional subgroup was set for the cows with more than 21 DIM. This subgroup was used to evaluate the implementation of NG management. Cows from optional subgroup were aggregated into groups according to their NE_L and MP nutritional requirements once per month. The study showed that the gain of IOFC for 2 nutritional groups was $39/cow per yr, for 3 nutritional groups was $46/cow per yr, and for 4 nutritional groups was $47/cow per yr when diets were formulated to the $Mean + 1 \times SD$ of the groups' MP requirements. Wu et al. (2019) performed a NG simulation study using a mixed-integer nonlinear programming optimization algorithm (OptiGroup). A database comprised of seven Wisconsin dairy farms was used to simulate the implementation of NG and measure its economic impact. The study compared 1-nutritional group as control with 2 and 3-nutritional groups contrasting the clustering method and the newly developed OptiGroup method. They found that the IOFC for 2-nutritional groups was $40/cow per yr and for 3-nutritional groups was $59/cow per yr greater than 1-group strategy with the clustering method. Using OptiGroup method, the IOFC for 2-nutritional groups increased to $48/cow per yr and for 3-nutritional groups to $71/cow per yr greater than the 1-group strategy.

1.3.6. Environmental benefits of nutritional grouping

When the number of nutritional groups increases, the total percentage of captured N in milk increases, benefiting the environment (St-Pierre and Weiss, 2015, Kalantari et al., 2016). Less N is excreted as waste when low production cows are fed a diet that better matches their nutritional requirements (Allen, 2009). Kalantari et al. (2016) found that N efficiency increased by 2.7%, on average, when cows are aggregated in 3-nutritional groups and fed with diets that supply 1SD over the average MP requirement of each nutritional group. This improvement in N efficiency was explained by a better match of MP supplied in the diet to the group's MP requirement (Kalantari et al., 2016). St-Pierre and Thraen (1999) reported that N efficiency increased by 5.8% and N excretion decreased 3.7% when cows were grouped in 3-nutritional groups using the clustering method suggested by McGilliard et al. (1983). Decreasing 2% of CP concentration in diets for 120 days per lactation, decreases N excretion by 9.07 kg/cow per yr (Allen, 2009).

1.3.7. Current grouping management on dairy farms

Grouping cows and feeding one diet for all the groups or feeding a diet for each group is a common practice in dairy farms. Contreras-Govea et al. (2015) surveyed farmers from WI and MI to quantify the percentage for dairy farms in those states that provide one or multiple diet formulas for lactating cows, identify the criteria used for grouping cows, and the drawbacks on adopting nutritional criteria for grouping management. According to Contreras-Govea et al. (2015), in WI and MI states, 26% and 42.5% of dairy farms use a single diet for feeding the whole group of lactating cows, respectively. The survey also showed that the main criteria for grouping lactating cows are lactation category (first lactation cows and mature cows) and stage of lactation (early cows and all other cows), whereas nutrition requirements are not commonly used for grouping cows. In both states, lactation category is the first, stage of lactation is the second, and milk production is the third most important factor used for grouping and feeding cows.

1.4. Conclusions

Several studies have shown that NG strategy increases nutritional accuracy of diets, and therefore, improve nutritional precision dairy farming. Increased diets' nutritional accuracy could prevent nutrient loss, decrease diet cost, and potentially increase milk yield.

Cows age and body size, their social interaction, barn design, and feed availability are essential factors to consider when grouping cows. A nutritional grouping strategy can be implemented using ranking clusters, iterative search of global maximum IOFC, OptiGroup, and K-means analysis. However, the algorithm to be used depends of the farm's facilities and goals. Nitrogen and other nutrients excretion as waste can be reduced by implementing NG strategy due to better allocation of diet nutrients. Decreased nutrient losses and greater nutritional accuracy of the dietary groups generate savings. Moreover, the implementation of NG strategy may increase milk yield due to greater diet's nutritional accuracy. Thus, diet cost savings and potential increase on milk yield improve IOFC. Even though grouping is a common practice in dairy farms, dairy farmers rarely implement NG strategy due to the potential implementation complexity. The aim of this research is to develop a mathematical application tool that facilitates the implementation of NG management in commercial dairy farms.

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CHAPTER II

IMPROVING NUTRITIONAL ACCURACY AND ECONOMICS THROUGH MULTIPLE RATION-GROUPING MANAGEMENT

2. Abstract

The objective of this study was to develop a model application to systematize nutritional grouping (NG) management in commercial dairy farms. The model has 4 sub-sections: (1) real-time data stream integration, (2) nutritional parameters' calculation, (3) grouping algorithm, and (4) output reports. A simulation study in a commercial Wisconsin dairy farm was used to evaluate our NG model. In this dairy farm, lactating cows (N=2,374±185) are weekly regrouped in 14 pens according to their parity and lactation stage for which 9 diets are provided. Diets are seldom reformulated and nutritional requirements are not factored to allocate cows to pens. The same 14 pens were used to simulate the implementation of NG using our model following closely the current farm criteria, but also including predicted nutritional requirements (net energy (NE_L), metabolizable protein (MP)), and milk yield in an attempt to generate more homogenous groups of cows for improved diet accuracy. The goal the simulation study was to implement a continuous weekly system for cows' pen allocation and diet formulation. The predicted MP and NE_L requirements from the NG were used to formulate the diets with a commercial diet formulation software using the same feed ingredients, feed prices, and other criteria as the current farm diets. Diet MP and NE_L densities were adjusted to the nutritional group requirements. Results from the simulation study indicate that NG model facilitates the implementation of NG strategy and improves the diet accuracy. The theoretical diet cost and predicted nitrogen (N) supply with

NG decreased for low nutritional requirement groups and increased for high nutritional requirement groups compared with current farm groups. The overall average N supply in diets for NG management was 15.14 g/cow per d less than the current farm grouping management. The average diet cost for the current farm management was $3,250/cow per yr, whereas this was $3,219/cow per yr for NG, which resulted in a theoretical $31/cow per yr diet cost savings.

Key words: Feed cost, diet accuracy index, nutritional grouping, real-time data integration

2.1. Introduction

Nutritional grouping management can improve nutritional accuracy of diets, reduce nutrient losses, and increase income over feed cost (IOFC) in dairy farms (Cabrera et al., 2012, Kalantari et al., 2016, Wu et al., 2019). Available on-farm data streams, computer and feeding systems, and existing farm grouping protocols offer an opportunity to facilitate the implementation of NG.

Grouping lactating cows into multiple pens is a common practice in dairy farms (Robinson, 2003, Contreras-Govea et al., 2015). Nevertheless, nutritional requirements are not usually considered for grouping cows (Contreras-Govea et al., 2015). In a survey of dairy farms in WI and MI, Contreras-Govea et al. (2015) reported that parity, DIM, keeping pens full, and milk yield are the principal factors used for grouping cows. They also reported that one of the main reasons of minimizing the number of rations for lactating cows were the desire to keep feeding management simple.

Nutritional grouping yields groups of cows with more homogenous nutritional requirements. This facilitates a better allocation of diet nutrients and therefore dietary nutritional accuracy (Kalantari et al., 2016, Barrientos et al., 2018, Bach, 2019). Dietary nutritional accuracy can be defined as feeding cows closer to their nutritional requirements (Cerosaletti and Dewing, 2008). If dietary nutritional accuracy is low, the proportion underfed and overfed cows increases (Kalantari et al., 2016, Bach, 2019). Underfed cows suffer under-conditioning, which decreases milk productivity and reproductive performance (Roche et al., 2009, Roche et al., 2013). In contrast, overfed cows suffer over-conditioning (Kalantari et al., 2016), which increases the risk of metabolic disorders in the next lactation (Cameron et al., 1998, Roche et al., 2009).

Better nutritional accuracy would increase milk productivity and reduce nutrient excretion (Kalantari et al., 2016). Maltz et al. (2013) demonstrated that feeding individual diets that match nutritional requirement of a cow could increase milk yield by 3.3 kg/cow per d compared to a single group diet in early lactation cows. On the other hand, decreasing CP and RUP concentration of diets of mid and late lactation cows did not impact milk production, but reduced N excretion (Kalscheur et al., 1999).

Better nutritional accuracy of NG would also reduce overall feed costs (Kalscheur et al., 1999, VandeHaar et al., 2016) and increase IOFC (Kalantari et al., 2016, Wu et al., 2019). Multiple NG simulation analyses have shown productive and economic benefits when lactating cows are grouped according to their nutritional requirements (St-Pierre and Thraen, 1999, Allen, 2009, Bach, 2014, Kalantari et al., 2016). Nevertheless, there is not an available application that could help dairy farmers to systematically implement NG. Likewise, there is not an application to collect, integrate, manage, analyze dairy farm data to support improvements in decision-making process related to farm management (Liang et al., 2018) such as NG. The development of a model that collects. integrates, and analyzes relevant continuous data streams could provide the opportunity to implement NG in a practical, efficient, and accurate way in dairy farms.

To fulfill these technological gaps and to address the need for improving nutritional accuracy of diets and farm profitability, this study provides an innovative mathematical model designed to facilitate the implementation of NG in commercial dairy farms. The model is tested with a simulation study applied to a commercial dairy farm.

2.2. Materials and Methods

Research was performed following 2 main steps: 1) developing a prescriptive model for implementing NG strategies in dairy farms and 2) evaluating the developed model by a simulation analysis with data from a commercial dairy farm, a simulation study. Analyses and model development were built under R studio® programming language environment version 3.5.3 (R Foundation for Statistical Computing, Vienna, Austria).

2.2.1. Prescriptive model development

The model was developed to systematize NG management in commercial dairy farms. The model has 4 sub-sections: (1) real-time data stream integration, (2) nutritional parameter calculations, (3) grouping algorithm, and (4) outputs reports.

Data integration

This sub-section was designed to import and combine data from different data sources of a farm. It involved cleaning up potential unknown characters of the merging reference variables using "str_replace_all" function in R studio®. All continuous data from the feeding, and cow's profile recording systems are merged to a single dataset using file date, cow ID, and/or group ID as merging reference variables. The integrated dataset is stored in an Excel® file and used later for calculating the nutritional parameters. The required data variables to run the nutritional grouping model are specified in Table 1. All observations are in number format except the date. This data integration is prepared to automatize the uptake the different data streams to generate the required inputs for implementing NG management without supervision on a weekly or monthly interval, according to farm goals.

Nutritional parameters calculations

Deterministic nutritional parameters for DMI (kg of DM/cow per d), NE_L (Mcal/cow per d), and MP (g/cow per d) are calculated based on NRC (2001) equations. These parameters are in function of BW, milk yield, milk protein and fat content, and DIM.

Body weight. Because of the limited availability of BW records in dairy farms, the model includes an algorithm to calculate the daily individual cow's BW according to average herd BW by parity and stage of lactation following Kalantari et al. (2016). Average BW for primiparous and multiparous are used as reference to calculate the inflexion BW changes at 42 and 336 DIM for primiparous and at 63 and 336 DIM for multiparous.

Dry matter intake. The predicted daily DMI per cow is calculated as a function of BW, fat corrected milk (FCM) and week of lactation (WOL) (NRC, 2001), Eq. 1.

$$DMI_i = \left(0.372 \times FCM_i + 0.0986 \times BW_i^{0.75}\right) \times \left(1 - e^{\left(-0.192 \times (WOL + 3.67)\right)}\right) \qquad [1]$$

Where, DMI_i is the predicted dry matter intake in kg/d for cow *i*. FCM_i is the fat corrected milk per cow *i*: $FCM_i = 0.4 \times MY + 15 \times MY \times (CP_{milk}/100)$. BW_i is the predicted body weight for cow *i*. The calculated DMI_i are adjusted to have the same average as the actual pen DMI. To adjust the individual cow's DMI, the actual DMI average per pen is divided by the calculated average DMI_i per pen, then the result is multiplied by the individual cow's DMI_i.

Net energy. Total NE_L (Mcal/cow per d) requirement is calculated in function of net energy for maintenance (NE_M), net energy for milk production (NE_l), and net energy for growth (NE_G) that are calculated from NRC (2001), Equations 11-3, 2-16, and 11-2, respectively.

Metabolizable protein. Total MP requirement is a function of MP for maintenance (MP_M), MP for milk production (MP_L), and MP for growth (MP_G) and are calculated from NRC (2001), Equations in pp. 68.

Diet accuracy index. To measure the nutritional accuracy of the diets, we developed a diet accuracy index (DAI). The DAI contrasts the nutrient requirement versus the nutrient offered in the diet and is calculated as an absolute value. Diet accuracy is inversely related to the magnitude of the calculated DAI value as the nutritional accuracy of the diet increases as the DAI value get closer to zero, Eq. 2.

$$DAINE_{PEN} = \frac{\sum_{i=1}^{n_{PEN}} \left| \frac{DietNE_{PEN}}{ActualDMI_{PEN}} - \frac{NE_i}{DMI_i} \right|}{n_{PEN}}; DAIMP_{PEN} = \frac{\sum_{i=1}^{n_{PEN}} \left| \frac{DietMP_{PEN}}{ActualDMI_{PEN}} - \frac{MP_i}{DMI_i} \right|}{n_{PEN}} \quad [2]$$

Where $DAINE_{PEN}$ is the DAI for NE_L and $DAIMP_{PEN}$ is the DAI for metabolizable protein in the pen (PEN). The NE_L supplied by the diet assigned to pen is $DietNE_{PEN}$ and NE_i is the calculated NE_L requirement for cow *i* allocated to pen PEN (Mcal/cow per d). The metabolizable protein supplied by the diet assigned to a pen is $DietMP_{PEN}$ and MP_i is the calculated metabolizable protein requirement for cow *i* allocated to pen PEN (g/cow per d). The number of cows in the analyzed pen is n_{PEN}.

2.2.2. Nutritional grouping algorithm

Kalantari et al. (2016) used a ranking method to aggregate cows according to their MP and NE_L requirements as a proxy of the clustering method proposed by McGilliard et al. (1983). We followed that approach, but different than Kalantari et al. (2016), our model was kept flexible to additionally accommodate possible farm group requirements such as state of lactation (postpartum, early, peak, late lactation), parity, or milk yield. After the cows are grouped, the model provides a list of cows for each nutritional group, which depends on the size and number of nutritional groups.

Setting the size and number of nutritional groups. The number of cows per group is constrained by the maximum allowed number of cows per pen whereas the number of nutritional groups is limited by the farm goals, which are defined by the farm decision-maker.

Categorizing parity and stage of lactation variables. Dairy farmers may want to group or maintain grouping of cows according to parity, stage of lactation (Contreras-Govea et al., 2015) or other criteria. Our model is able to accommodate these forced grouping requirements by using conditional statement functions. Once these are imposed, nutritional grouping is accommodated.

Algorithm for grouping cows nutritionally. The model is designed to group cows according to continuous variables such as milk yield, MP and NE requirements, or other potential meaningful variables for nutritionally grouping cows. The first step on this model subsection is normalizing each continuous variable. Second, summing up the normalized variables per cow (norm). Third, calculate the percentile rank for each cow using the variable norm. Then, aggregating cows in groups by their percentile rank according to the desired number and size of groups.

Movements of cows across groups

The model tracks the number of cows that are moved in and out of each group by using conditional statements. So, it is possible to quantify the total number of cows moved in each regrouping period and follow the flow of cows in groups and pens across time.

Diet formulation

The optimum MP and NE_L requirements per group (unit/kg DM) are calculated using a percentile of milk yield distribution method as suggested by Stallings and McGilliard (1984). Then, the model allows the user to set the desired percentile of the milk yield distribution to be used as reference value to calculate the optimum MP and NE_L requirement per nutritional group. As required by any diet formulation software, the model selects the cow that has the minimum absolute difference to that percentile value. In this section, before this optimum MP and NE_L are calculated, 10% in each tail of the milk yield distribution per group are removed to avoid nonrealistic optimum MP and NE_L requirement values that could be generated by outliers.

2.2.3. Simulation study: Evaluating the nutritional grouping model

A simulation study with data from a large-scale commercial dairy farm of Holstein cows located in Wisconsin was used to evaluate the performance of the proposed model during a period of 9 weeks. The merged dataset included data from Dairy Comp 305® (DC305; cow management software) and Feed Comp (feed management software). Specific information about the data collected from each software are detailed in Table 1. These 2 data streams were merged using the merging function and cleaned using str_replace_all function in R studio. Pen ID (Pen) and file date (Fdate) were used as reference variables to merge the datasets (Table 1). This simulation study included all healthy, lactating cows at the farm (N=2,374±185 animals). The entire group of lactating cows are currently grouped in 14 pens according to their parity (primiparous and multiparous) and stage of lactation (postpartum, early, peak, and late lactation) for which 9 diets are provided. They use the nutritional dynamic systems (NDS) diet formulation software for diet formulation and diet costs (Table 2). The farm diets are reformulated a few times a year and nutritional requirements are not used as criteria to allocate cows across pens. Cows are regrouped every week on Tuesdays during the night shift. The decision of which cows are moved in each group is made by the farm manager. A report with a list of cows, pen number, stage of lactation, and parity is printed from DC305, and based on this information the farm manager make the decision of what cow to move. The weekly regrouping process is made by sorting cows using electronic automatic gates and cow's RFID but require employee supervision and correction.

Following farm practice, the model was run every week to allocate cows to groups, first, by parity and DIM, and then, by NE_L, MP, and milk yield. Cows were allocated in the 14 pens and for each one of them, a diet was reformulated. The optimum MP and NE_L requirements to formulate the NG diet were calculated using the 83rd percentile of milk yield method (McGilliard et al., 1983). Also, consistent with farm practice, the average of the weekly diets per pen was used for all the 9 weeks of simulation analysis. Hence, diet in each pen remained constant for both FG and NG during the study period. Diets for all groups and for FG and NG were formulated based on the optimum MP (as main constraint) and NE_L (as secondary constraint) requirements calculated by the model using the same software of the farm, NDS.

2.3. Results and Discussion

2.3.1. Grouping cows

Different than FG practice, our NG model uses predicted MP and NE_L requirements and milk yield as grouping criteria, in addition to parity and stage of lactation categories. As depicted in Table 3, same lactation, DIM, and stage categories are further classified in different milk yield and diet-requirements pens. For example, in peak multiparous groups, pen 8 has the least, pen 9 has medium, and pen 10 has the highest milk yield (Table 3), which results in low, medium, and high MP and NE_L predicted requirements, respectively. Different nutrient allocation for 3 nutritional groups are consistent with results previously reported by Kalantari et al. (2016) and Wu et al. (2019).

Our NG model kept the desired number of cows per simulated pen fixed over time, which removed the potential risk of over or under-stocking cows in the simulated pens (Table 4). The number of simulated nutritional groups per parity and stage of lactation category is consistent with the number of nutritional groups recommended by several researches (Cabrera et al., 2012, St-Pierre and Weiss, 2015, Kalantari et al., 2016). However, these depend on the farm facility design and farmer goals.

In the simulation study, as expected, the NG model showed better allocation of cows by parity (primiparous and multiparous) and stage of lactation (postpartum, early, peak, and late lactation). As observed in Figure 1, FG management shows parity and DIM misclassifications (Figure 1.A and 1.B) of cows in the stages of: postpartum (pen 6 for multiparous and pen 1 for primiparous), early (pen 2 for primiparous and 7 for multiparous), peak (pen 8, 9, and 10 for multiparous, and pen 3, 4, and 5 for primiparous cows), and late lactation (pen 11, 12, 13, and 14 for multiparous and primiparous cows).

Number of cows moved across pens is an important factor to consider when implementing NG management. As expected, the model calculated greater movements occurred for NG in simulated pens that had the opportunity of applying nutritional groups (pens 3, 4, 5, 8, 9, 10, 11, 12, 13, and 14) (Table 4). This is due to the natural changes in the predicted nutritional requirements and milk yield of the cows throughout lactation. One of the dairy farmers concerns about the increase of moving cows across groups is the potential drop of milk yield after moving happens. Nevertheless, Zwald and Shaver (2012) reported that increasing the number of cows' movements among groups does not decrease significantly milk yield, if the groups sizes are larger than 100 cows (Albright, 1978, Zwald and Shaver, 2012).

2.3.2. Nutritional accuracy

The simulation study evidenced improvements in the theoretical nutritional accuracy of the diet due to better allocation of nutrients among simulated pens with the NG management. As observed in Table 5, the 14 groups of lactating cows currently in the farm are fed with 9 different diets. The peak and the late lactation groups (primiparous and multiparous) are each fed with a single diet. However, each one of these has its own diet with NG. The use of NG management facilitates the allocation of nutrients through the formulation of diets with greater nutritional accuracy (Cabrera and Kalantari, 2016). This fact is proven by the lower NG DAIMP and DAINE reported in Table 5 and their fewer variable distributions (Figure 2). High variability of predicted requirements was expected and seen with FG since there is not nutritional allocation, which constrains the possibility of improving the nutritional accuracy of the offered diets. Even though simulated pens for peak and late lactation cows are aggregated based on their predicted nutritional requirements, some simulated pens still show large variability because of the presence of cows with extreme low or high predicted nutritional requirements due to the imposed farm grouping criteria and the constraint of maintaining pen size constant. Because diets for the simulation study were formulated using predicted MP as the main requirements constraint and predicted NE_L as secondary requirement constraint, greater improvement on theoretical DAIMP than DAINE was expected and found (Table 5).

In addition, DAIMP and DAINE can be improved by increasing the frequency of formulate diets as suggested by White and Capper (2014). Once the NG model is adopted by the farm management, pen diets could be adjusted weekly according to ever-changing cow requirements assigned to pens for even greater accuracy.

2.3.3. Environmental benefits of NG management

Better theoretical nutritional accuracy of the diets using NG management results in less nutrient losses of predicted N supplied by the diets, in benefit of the environment (White and Capper, 2014). The predicted N supplied from diets with NG strategy (711.21±99.23) was hypothetically 15.14 g/cow per d lower than in FG management (726.35±65.94) (Table 6). The total decrease of annual predicted N supplied by the diets was 13.12 tons for the average lactating herd size of 2,374 cows. As observed in Table 6, groups of cows for NG strategy with low and medium predicted nutritional requirements (pens 3, 4, 8, 9, 11, 12, and 13 in Table 3) have diets that supply lower predicted N, while groups of cows with high nutritional requirements (pens 5, 10, and 14) have diets that supply greater predicted N than the diets for FG management.

2.3.4. Economics of NG management

The improvement of dietary nutrition accuracy may generate economic benefits from potential increase on milk yield (Kalscheur et al., 1999, Maltz et al., 2013, Kalantari et al., 2016) and savings from a decrease in diet costs (Cabrera and Kalantari, 2016, Kalantari et al., 2016, Wu et al., 2019). In this research, we did not predict potential milk yield improvement from the NG strategy. Thus, the economic benefits related to the potential increase of milk yield was not considered in the economic analysis. Hypothetical economic benefits reported here are only due to savings from decreased diet costs. With exception of pens 2, 5, 6, 7, 10, and 14, all other diets showed lower diet costs (Table 7). The most significant increase on diet cost for NG was in pens for postpartum and early lactation multiparous cows (pen 6 and 7). This is related to the effect of grouping cows by parity and stage of lactation following farm protocol. Simulated pens 6 and 7 show increase in the predicted MP density of the diets for NG in comparison with FG management (Table 5). Simulated pens 5, 10 and 14 show greater cost of diets because of the NG management effect. These pens house the cows that have the highest milk yield and predicted nutritional requirements. Thus, the adjustment in the diets to a greater predicted MP and NE_L supply increased the cost of the diets in comparison with the diets of FG management. Most of the increase on diet cost was related to the predicted CP which is the most expensive nutrient of a diet (St-Pierre and Thraen, 1999). But, overall, the potential average cost of the diets across all the simulated pens was $31/cow per yr less for NG strategy than for current FG management. This savings from decrease on diet costs are mostly due to the simulated nutritional groups (pens 3, 4, 5, 8, 9, 10, 11, 12, 13, and 14). Our results are consistent with other studies. Kalantari et al. (2016) found that NG management increased the IOFC by $39±6 for 3 nutritional groups and $46±7 for 4 nutritional groups. They reported that the main drivers for increasing IOFC were the increase in milk yield and lower feed cost. The decrease on feed cost was mainly related to the decrease on predicted MP concentration in the diet. Also, Wu et al. (2019) and St-Pierre and Thraen (1999) reported an average IOFC increase of $71 and $76.65/cow per yr, respectively, when using 3 diets instead of only 1 diet.

2.3.5. Implications NG management implementation

The nutritional grouping strategy is an application designed to systematize the implementation of NG management in dairy farms. It allows a dairy farmer or farm manager to 1) integrate data streams from feeding and cow's profile recording systems; 2) group cows according to nutritional requirements in addition to pre-defined farm criteria such as parity and/or stage of lactation; 3) calculate the optimum nutritional requirements per group; and 4) formulate group diets accordingly. The systematization of grouping cows could help the dairy farmers to decrease the time and errors in the decision-making process of grouping cows. Less time and errors could decrease the labor time and costs, over-stocking cows in pens, and misplaced cows. Importantly, implementing NG management creates more homogeneous groups of cows in terms of nutritional requirements. These groups would facilitate a better allocation of nutrients in diets and therefore would improve herd's nutritional accuracy. Although not implemented and tested in this study, improved nutritional accuracy through NG may result in greater milk yield (not included in this study), less over-conditioned cows (not included in this study), lower negative environmental impacts due to decreased nutrient losses, increased milk income (not included in this study), and decreased diet costs.

2.3.6. Limitations of the model and the study

The analysis did not account for any potential increase on milk yield when performing NG strategy. The model does not predict cow's production performance in response to formulated diets due to the lack of parameterization data. On-farm field trials of NG strategies are required to measure the quantitative effect of NG management in milk yield.

Even though the NG model is flexible enough to be implemented in commercial dairy farms, it still requires farm-specific adjustments to accommodate each farm's specific data and software recording systems. Also, the application still requires a user-friendly interface to facilitate its use and application.

The economic analysis did not consider the additional cost for NG management related to increasing the number of diets. Extra labor time, equipment, and machinery required for additional diets are factors that need to be measured and considered in the economic analysis. Further on-farm validation study can provide the information required to account for the extra costs. Nonetheless, based on previous studies, we speculate that the additional costs will be small compared with the benefits and would not diminish the value of applying a NG strategy on dairy farms (Kalantari et al., 2016).

2.4. Conclusions

The simulation study demonstrated the theoretical advantages of implementing NG strategies on dairy farms. Application of our model could decrease the errors on misplacing cows or missing cow movements to a different group. The NG model decreased to time required to create a list of cows to be allocated to pens and reduced the risk of under- and overcrowding pens. In addition, the NG model showed better allocation of cows to simulated pens according to predicted nutritional requirements. Importantly, our nutritional grouping management improved diet accuracy. This improvement resulted in lower predicted N supply in benefit of the environment. Average predicted N supply with the simulated nutritional grouping management was 15.14 g/cow per d lower. Our proposed NG management resulted in potential economic benefits from diet cost savings. The simulation study suggests that implementing NG management may results in theoretical $31/cow per yr greater IOFC due to potential diet costs' savings. In addition, the economic benefits of NG management could be greater if the potential increase of milk productivity when applying NG management are accounted for. A future research goal is to measure the impact of NG management in milk productivity using on-farm trials.

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Table 1. Data variables required by the nutritional grouping model for the simulation study

Data source*	Variable	Definition	Unit	Variable objective
DC305 and Feed Comp	PenID	Pen identification number	-	Reference values for merging data
DC305 and Feed Comp	Fdate	Observation date	Date (yyyy-mm-dd)	
DC305	CowID	Cow identification number	-	Values for calculating nutritional requirement parameters
DC305	DIM	Days in milk	d	
DC305	Parity	Parity number	Number	
DC305	BW	Body weight	kg	
Feed Comp	ActualDMIkg	Actual dry matter intake per pen	kg/cow per d	
DC305	MY	Milk yield	kg/cow per d	
DC305	PCTS	Milk protein	%	
DC305	PCTF	Milk fat	%	

*Dairy Comp 305® (DC305) and Feed Comp ® (Feed Comp)

Table 2. Summary of the Total Mixed Ration (TMR) ingredients, nutrients content, predicted DMI, and price by pen of farm grouping management

Feeds	Feed price ($/ton)	TMR ingredient quantity (kg DM/cow per d)							
		Pen 1	Pens 2, 3, 4, and 5	Pen 6	Pen 7	Pens 8, 9, and 10	Pen 11	Pens 12 and 13	Pen 14
Whey	$25.77	0.63	0.77	0.97	1.16	1.16	1.35	1.16	1.37
Molasses	$188.50	0.41	0.68	0.67	0.88	0.88			0.54
Corn gluten	$142.20	1.12	2.85	1.83	1.22	1.22	2.03	3.25	3.66
Soybean meal 47.5 solvent	$395.73	1.64	1.71	0.58	1.03	0.632	1.32	1.44	1.09
Corn grain	$137.39	1.20	1.20	0.96	2.56	2.57	2.5	3.00	4.50
Low mineral mix	$546.69						1.11	1.11	1.11
Protein mix	$393.48				9.08	9.11			
Medium protein mix	$450.18		6.31						
Fresh protein mix	$400.36	7.00		9.04					
Corn silage	$137.79	5.00	5.35	7.46	6.71	6.73	6.38	7.26	7.01
Haylage	$137.79	4.50	5.26	5.58	7.38	7.40	5.44	6.35	4.24
Total MP (g/kg of DM)		130.37	126.21	127.27	120.95	118.48	107.59	110.43	110.10
Total NE_L (Mcal/kg of DM)		1.75	1.74	1.74	1.78	1.77	1.56	1.60	1.63
Predicted DMI (kg/cow per d)		21.49	24.13	27.09	30.03	29.71	20.14	23.57	23.52
Total diet cost ($/cow per d)		**$8.27**	**$8.91**	**$9.71**	**$10.47**	**$10.32**	**$6.88**	**$7.86**	**$7.47**
Total diet cost ($/cow per yr)		**$3,018.55**	**$3,252.15**	**$3,544.15**	**$3,821.55**	**$3,766.8**	**$2,511.2**	**$2,868.9**	**$2,726.55**

Table 3. Milk yield and days in milk (DIM) of cows allocated to pens on farm grouping (FG) and nutritional grouping (NG) management

Parity	Stage of lactation	Pen	DIM		Milk yield (kg/cow per d)	
			FG	NG	FG	NG
Primiparous	Postpartum	1	22 ± 12	28 ± 13	32.7 ± 8.04	34.06 ± 8.24
	Early	2	69 ± 35	75 ± 15	39.8 ± 5.86	39.65 ± 6.01
	Peak	3	166 ± 56	194 ± 42	39.54 ± 6.95	33.65 ± 7.34
		4	170 ± 51	181 ± 45	39.28 ± 7.09	39.03 ± 4.68
		5	177 ± 44	164 ± 47	38.64 ± 6.79	43.09 ± 4.9
Multiparous	Postpartum	6	16 ± 15	17 ± 8	45.48 ± 11.21	45.84 ± 11.29
	Early	7	46 ± 15	47 ± 12	54.78 ± 7.88	54.79 ± 7.86
	Peak	8	139 ± 53	159 ± 36	50.74 ± 7.79	41.55 ± 9.4
		9	143 ± 61	134 ± 37	51.48 ± 8.19	50.96 ± 5.64
		10	148 ± 65	110 ± 38	51.44 ± 7.83	56.34 ± 6.48
Multiparous & Primiparous	Late	11	353 ± 96	367 ± 101	23.39 ± 5.73	22.23 ± 5.81
		12	296 ± 76	318 ± 69	29.8 ± 5.09	29.86 ± 5.02
		13	253 ± 57	299 ± 62	35.37 ± 4.91	35.31 ± 5.2
		14	316 ± 71	273 ± 49	35.25 ± 5.76	42.21 ± 6.71

Table 4. Group profiles and cow movements across pens for farm grouping (FG) and nutritional grouping (NG) management.

			Number of Cows		DIM		PARITY		*MOVE (n-cows/week)		
Parity	Stage	Pen	FG	NG	FG	NG	FG	NG	FG	NG	Difference (%) **
Primiparous	Postpartum	1	116 ± 8	148 ± 0	22 ± 12	28 ± 13	1.00 ± 0.04	1 ± 0.01	23 ± 8	23 ± 8	0.00
	Early	2	150 ± 3	148 ± 0	69 ± 35	75 ± 15	1.00 ± 0.03	1 ± 0.00	21 ± 6	22 ± 7	4.55
	Peak	3	149 ± 7	147 ± 0	166 ± 56	194 ± 42	1.00 ± 0.00	1 ± 0.00	15 ± 10	44 ± 19	65.91
		4	149 ± 6	148 ± 0	170 ± 51	181 ± 45	1.01 ± 0.10	1 ± 0.00	8 ± 9	70 ± 16	88.57
		5	149 ± 7	149 ± 0	177 ± 44	164 ± 47	1.00 ± 0.00	1 ± 0.00	13 ± 10	49 ± 11	73.47
Multiparous	Postpartum	6	135 ± 12	148 ± 0	16 ± 15	17 ± 8	2.80 ± 1.02	2.8 ± 1.02	44 ± 10	43 ± 8	-2.33
	Early	7	140 ± 7	148 ± 0	46 ± 15	47 ± 12	2.69 ± 1.00	2.74 ± 1.02	47 ± 8	46 ± 10	-2.17
	Peak	8	149 ± 2	147 ± 0	139 ± 53	159 ± 36	2.77 ± 0.96	2.86 ± 1.04	20 ± 10	61 ± 14	67.21
		9	148 ± 3	148 ± 0	143 ± 61	134 ± 37	2.85 ± 0.99	2.79 ± 0.97	20 ± 10	75 ± 13	73.33
		10	150 ± 2	149 ± 0	148 ± 65	110 ± 38	2.94 ± 1.14	2.87 ± 1.03	18 ± 8	68 ± 22	73.53
Multiparous & Primiparous	Late	11	153 ± 10	157 ± 8	353 ± 96	367 ± 101	2.16 ± 1.10	2.15 ± 1.19	86 ± 42	88 ± 36	2.27
		12	151 ± 5	158 ± 7	296 ± 76	318 ± 69	2.26 ± 1.09	2.09 ± 1.14	55 ± 20	92 ± 22	40.22
		13	144 ± 1	157 ± 7	253 ± 57	299 ± 62	2.79 ± 1.05	2.08 ± 1.14	27 ± 9	82 ± 21	67.07
		14	150 ± 8	159 ± 8	316 ± 71	273 ± 49	1.00 ± 0.00	2.08 ± 1.16	27 ± 6	58 ± 13	53.45

*MOVE = number of cows moved in and out of each pen every week.

**Difference (%) in MOVE variable = increase of number of cows moved by NG strategy in percent units $Difference\ (\%) = \left(\frac{NG}{NG-FG}\right) \times 100$

Table 5. Nutrients supplied per diet and diet accuracy index for metabolizable protein (DAIMP) and net energy (DAINE) for farm grouping (FG) and nutritional grouping (NG) management

			MP (g/kg of DM)		NE_L (Mcal/kg of DM)		*F:C		†DMI Adjustment factor		Predicted DMI (kg/cow per d)		DAIMP		DAINE	
Parity	Stage of lactation	Pen	FG	NG	FG	NG	FG	NG	FG	NG	FG	NG	FG	NG	FG	NG
Primiparous	Postpartum	1	130.37	129.88	1.75	1.75	44:56	44:56	1.3	1.26	19.21 ± 5.73	19.67 ± 5.41	0.46 ± 0.31	0.4 ± 0.32	0.46 ± 0.28	0.40 ± 0.29
	Early	2	127.6	126.35	1.74	1.74	45:55	44:56	1.04	1.02	24.78 ± 3.08	24.95 ± 2.7	0.14 ± 0.12	0.12 ± 0.09	0.20 ± 0.12	0.19 ± 0.11
	Peak	3	125.51	118.98	1.73	1.7	45:55	48:52	0.94	0.94	24.95 ± 2.52	23.59 ± 2.88	0.13 ± 0.09	0.14 ± 0.11	0.18 ± 0.1	0.20 ± 0.13
		4		123.05		1.73	45:55	45:55	0.92	0.93	24.54 ± 2.45	24.74 ± 2.15	0.12 ± 0.09	0.10 ± 0.06	0.16 ± 0.1	0.17 ± 0.08
		5		126.08		1.75	45:55	42:58	0.94	0.92	24.63 ± 2.42	25.17 ± 2.31	0.14 ± 0.09	0.08 ± 0.08	0.20 ± 0.1	0.15 ± 0.11
Multiparous	Postpartum	6	127.28	128.33	1.74	1.74	48:52	47:53	1.36	1.34	23.28 ± 7.19	22.69 ± 6.73	0.69 ± 0.41	0.7 ± 0.42	0.53 ± 0.3	0.53 ± 0.29
	Early	7	120.95	122.48	1.78	1.78	47:53	45:55	0.99	1.02	28.23 ± 4.95	28.74 ± 4.89	0.16 ± 0.23	0.17 ± 0.24	0.19 ± 0.18	0.19 ± 0.2
	Peak	8	118.48	115.58	1.77	1.75	48:52	52:48	0.96	0.95	30.07 ± 4.16	27.62 ± 4.26	0.15 ± 0.31	0.13 ± 0.1	0.27 ± 0.42	0.25 ± 0.11
		9		117.09		1.76	48:52	49:51	0.95	0.96	29.72 ± 3.22	30.23 ± 3.06	0.10 ± 0.08	0.09 ± 0.07	0.19 ± 0.1	0.19 ± 0.08
		10		120.49		1.78	48:52	47:53	0.97	0.95	30.34 ± 3.19	30.27 ± 3.92	0.11 ± 0.08	0.12 ± 0.29	0.21 ± 0.09	0.21 ± 0.4
Multiparous & Primiparous	Late	11	107.59	101.76	1.56	1.52	59:41	62:38	0.91	0.92	20.89 ± 2.38	20.52 ± 2.53	0.20 ± 0.12	0.18 ± 0.13	0.17 ± 0.09	0.16 ± 0.1
		12	110.43	105.71	1.60	1.56	58:42	61:39	0.92	0.91	22.79 ± 2.15	22.62 ± 2.25	0.13 ± 0.09	0.1 ± 0.08	0.14 ± 0.08	0.11 ± 0.1
		13		106.98		1.6	58:42	57:43	0.91	0.9	24.48 ± 2.47	24.03 ± 2.87	0.09 ± 0.08	0.07 ± 0.1	0.11 ± 0.1	0.10 ± 0.15
		14	110.1	120.54	1.63	1.7	48:52	41:59	0.85	0.91	22.43 ± 2.62	26.42 ± 4.08	0.11 ± 0.17	0.14 ± 0.15	0.11 ± 0.24	0.16 ± 0.22

*F:C = Forage: concentrate ration of the diets

†DMI Adjustment factor = correction factor for predicted DMI = actual DMI (kg/cow per d) average per pen divided by the predicted DMI (kg/cow per d) average per pen.

Table 6. Total nitrogen supplied per diet (N) for farm grouping (FG) and nutritional grouping (NG) management

Parity	Stage of lactation	Pen	N (g/cow per d) FG	NG	Difference (FG-NG)
Primiparous	Postpartum	1	672.62	664.71	7.91
	Early	2	742.53	736.94	5.59
	Peak	3	720.51	609.18	111.33
		4		684.37	36.14
		5		754.8	-34.29
Multiparous	Postpartum	6	770.99	805.75	-34.76
	Early	7	819.57	863.8	-44.23
	Peak	8	788.64	699.93	88.71
		9		749.13	39.51
		10		826.29	-37.65
Multiparous & Primiparous	Late	11	578.04	491.53	86.51
		12	693.94	600.53	93.41
		13		655.66	38.28
		14	625.13	819.9	-194.77

Table 7. Comparative economic analysis between farm grouping (FG) and nutritional grouping (NG) management

Parity	Stage of lactation	Pen	Number of Cows FG	Number of Cows NG	Diet Cost ($/cow per d) FG	Diet Cost ($/cow per d) NG	Diet Cost ($/cow per d) Difference (FG-NG)
Primiparous	Postpartum	1	116 ± 8	148 ± 0	$8.27	$8.23	$0.04
	Early	2	150 ± 3	148 ± 0	$8.85	$8.89	-$0.04
	Peak	3	149 ± 7	147 ± 0		$8.19	$0.61
		4	149 ± 6	148 ± 0	$8.79	$8.63	$0.17
		5	149 ± 7	149 ± 0		$9.10	-$0.30
Multiparous	Postpartum	6	135 ± 12	148 ± 0	$9.71	$9.86	-$0.16
	Early	7	140 ± 7	148 ± 0	$10.47	$10.62	-$0.15
	Peak	8	149 ± 2	147 ± 0		$9.72	$0.60
		9	148 ± 3	148 ± 0	$10.32	$10.04	$0.28
		10	150 ± 2	149 ± 0		$10.52	-$0.20
Multiparous & Primiparous	Late	11	153 ± 10	157 ± 8	$6.88	$6.42	$0.46
		12	151 ± 5	158 ± 7	$7.86	$7.11	$0.76
		13	144 ± 1	157 ± 7		$7.79	$0.08
		14	150 ± 8	159 ± 8	$7.47	$8.70	-$1.23

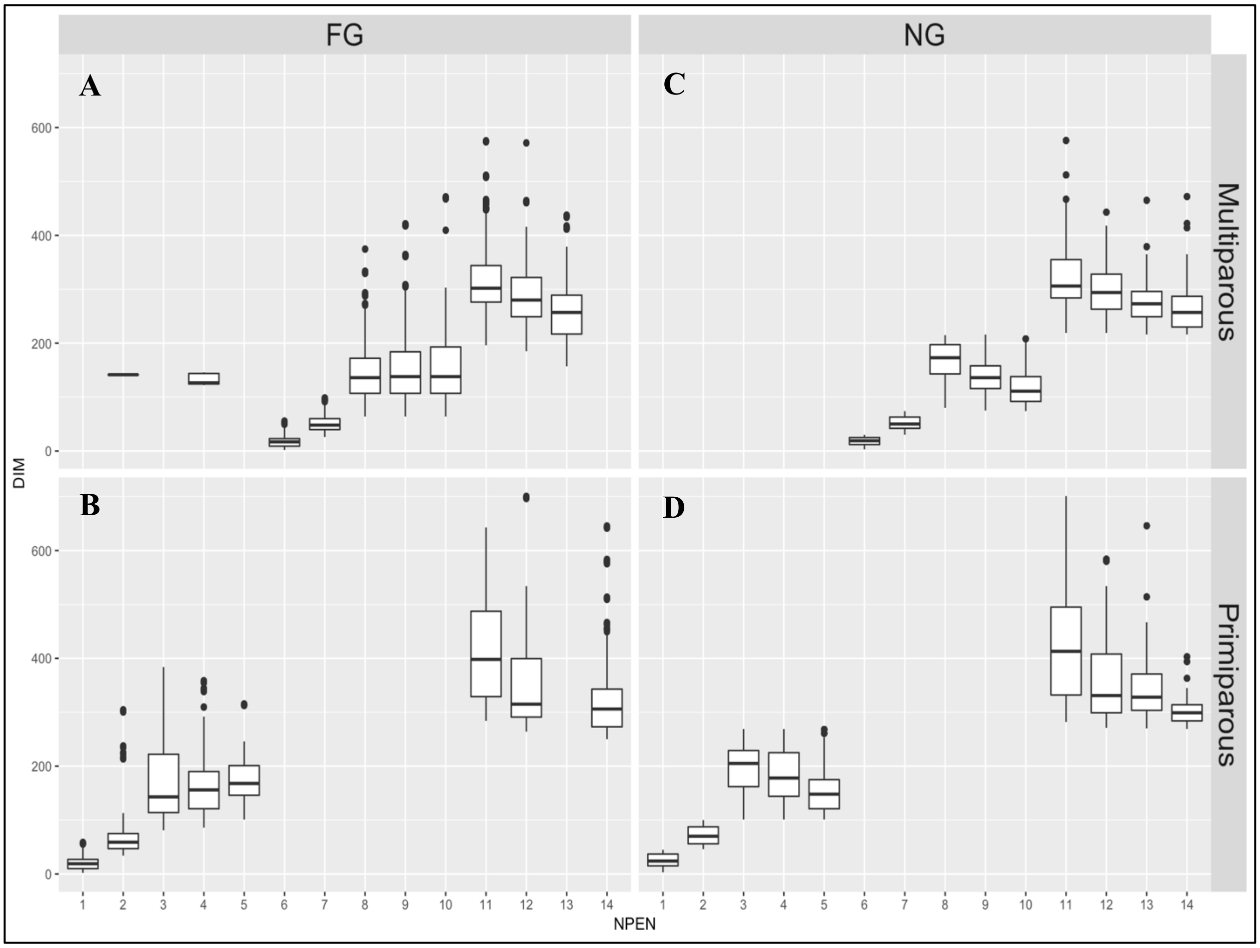

Figure 1. Boxplot for the DIM of cows in different pens, for multiparous cows in farm grouping (FG) (A), primiparous cows in farm grouping (FG) (B), for multiparous cows in nutritional grouping (NG) (C), and primiparous cows in nutritional grouping (NG) (D).

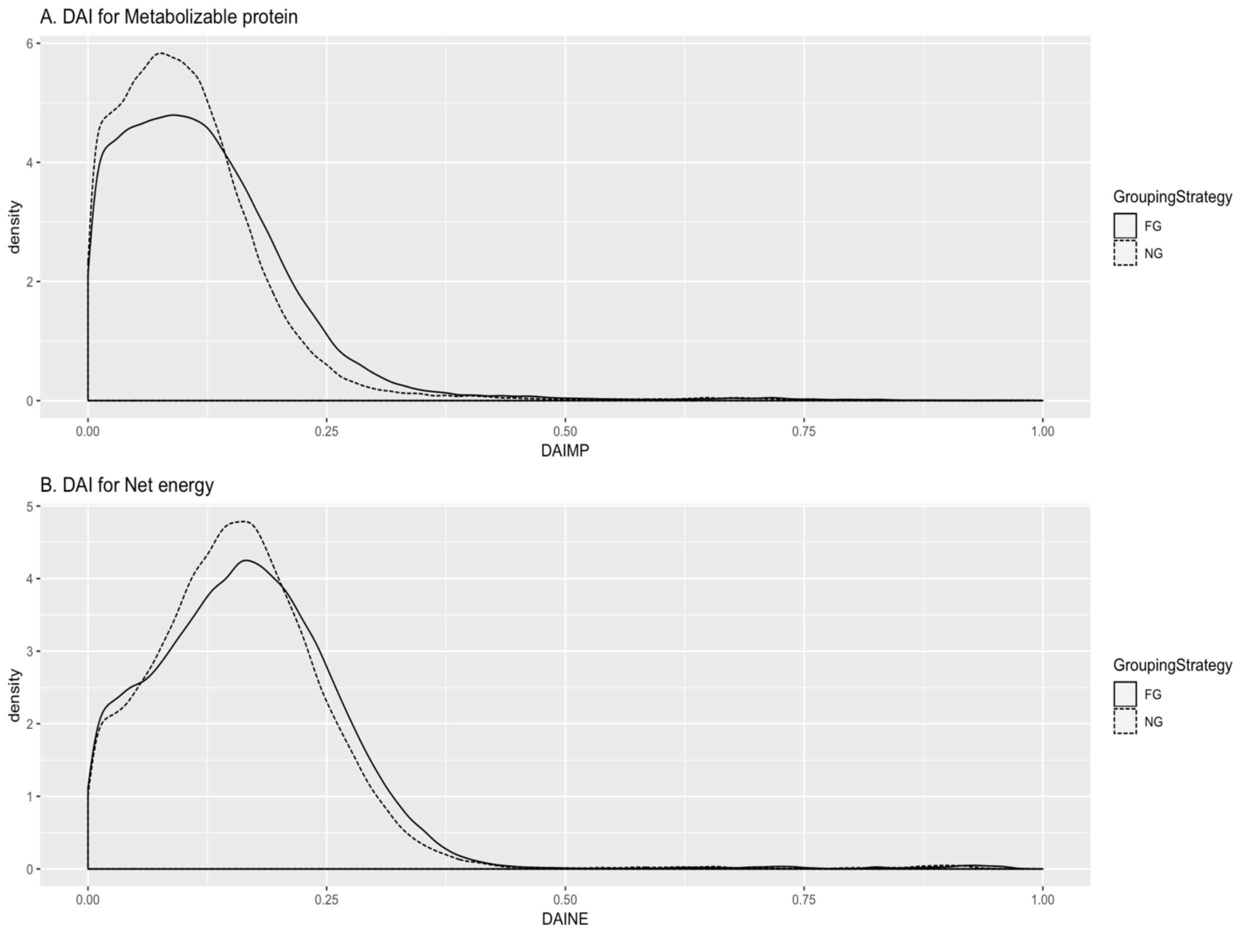

Figure 2. Statistical distribution of diet accuracy index for metabolizable protein (DAIMP) and diet accuracy index for net energy (DAINE) for farm grouping (FG) and nutritional grouping (NG) management