Automatic feed formulation method based on Differential Evolution algorithm for precision feeding of dairy cows

Peng Guo*, Longhao Zhang
College of Computer and Information Engineering, Tianjin Agricultural University, Tianjin, China

*Corresponding author e-mail: super_guopeng@163.com

Abstract. To improve the efficiency of feed utilization and reduce the feeding cost, we proposed a feed formulation method based on Differential Evolution algorithm. Individuals were constructed according to the content of each raw material in the feed formulation and the lowest feed formulation cost was taken as the objective. The feed formulation was solved by Differential Evolution algorithm. Using NRC (2001) prediction model of main nutrient requirement of dairy cows and the data of common feed of dairy cows in China Feed Database, we carried out the experiment of feed formulation for lactating dairy cows. Compared the feed formulation result of our method with those of Linear Programming method, our method performed better.

1. Introduction
In the livestock industry, feed cost is an important part of the total cost, generally accounting for 70% ~ 80% [1], which has a crucial impact on the profits of breeders. The aim of feed formulation is to find appropriate ingredients and right quantities based on animal’s nutritional requirement and cost. It is essential to provide the best diet at the least possible cost [2]. Researchers have proposed various methods for feed formulation using linear and nonlinear programming [3]. Due to the linear/nonlinear constraints, the feed formulation optimization problem is often complex and difficult to solve. The development of population-based algorithms such as Genetic Algorithm [4], Particle Swarm Optimization Algorithm [5], Evolutionary Algorithm [6] provide more effective choices for the research on feed formulation. Compared with the above mentioned algorithms, Differential Evolution used real numbers in individual encoding, which had the advantages of short running time, strong robustness, and simple implementation. Uyeh Daniel Dooyum proposed interactive livestock feed ration optimization using Differential Evolution algorithms, the data of nutritional requirements were obtained from the authority of Korea [2]. In fact, the nutritional requirement depend on the purpose, age, quality of product desired [7], the estimation of the requirement should depend on measured data of the animals. In order to make full use of the inherent nutritional effect of diet and realize the precise feeding for animals, we proposed an automatic feed formulation method based on Differential Evolution algorithm in accordance with the nutritional requirements estimated with models in NRC 2001[8]. By analyzing the nutrient content of feed ingredients and constructing the diet based on nutritional requirement, our method can fully utilize the intrinsic nutritional potential of feed and realize the precise nutritional formula design of each animal to reduce the feed cost and improve the breeding profits.
2. Feed formulation based on Differential Evolution

2.1. Nutritional requirement estimation

The models used for nutritional requirement estimation were from NRC2001 [8]:

(1) Dry Matter Intake predictions of Lactating cows (kg)

\[
DMILact = ((BW^{0.75}) \times 0.0968 + 0.372 \times FCM - 0.293) \times (1 - e^{-1 \times 0.192 \times (WOL + 3.67)})
\]

Where, BW was body weight (kg), FCM was 4% fat corrected milk production (kg/day), WOL was week of lactation, \(e = 2.718\), which was natural constant.

(2) Maintenance Energy requirement (Mcal/d)

\[
NEmaint = (BW - CW)^{0.75} \times 0.08 + NEmact
\]

Here, CW was conceptus weight, if not pregnant, \(CW = 0\). Nemact was the energy requirement for activity.

\[
NEmact = (\text{Distance/1000} \times \text{Trips}) \times (0.00045 \times BW) + 0.0012 \times BW
\]

Where, Distance was the distance from the pasture to the milking parlor (km). Trips was the number of times that animals went to and from the milking parlor daily. If the topography of the trips was hilly, additional energy should be considered:

\[
NEmact = NEmact + 0.006 \times BW
\]

In this study, the energy requirement without grazing was studied.

(3) Maintenance Protein Requirement (g/day)

\[
MPMaint = 0.3 \times (BW - CW)^{0.6} + 4.1 \times (BW - CW)^{0.5} \times \text{TotalDMFed} \times 1000 \times 0.03 - 0.5 \times (MPBact / 0.8 - MPBact) + MPEndoReq
\]

Where, Scurf Requirement = 0.3 \times (BW - CW)^{0.6},
Urine Requirement = 4.1 \times (BW - CW)^{0.5},
Fecal Requirement = \text{TotalDMFed} \times 1000 \times 0.03 - 0.5 \times (MPBact / 0.8 - MPBact),
MPEndoReq = Endogenous requirement,
MPBact = microbial protein supply.

(4) Lactation Energy Requirement

If lactose content of milk was not available, Energy content of milk (Mcal NEI/kg)

\[
\text{MilkEn} = 0.0929 \times \text{MilkFat} + 0.0547 \times \text{MilkTrueProtein} / 0.93 + 0.192,
\]

Otherwise,

\[
\text{MilkEn} = 0.0929 \times \text{MilkFat} + 0.0547 \times \text{MilkTrueProtein} / 0.93 + 0.0395 \times \text{Lactose}.
\]

Daily energy secretion in milk (Mcal NEI/day):

\[
\text{YEn} = \text{NELact} = \text{MilkEn} \times \text{MilkProd}.
\]

(5) Lactation Protein Requirement

Daily milk protein yield (kg/day):

\[
\text{YProtn} = \text{MilkProd} \times (\text{MilkTrueProtein} / 100)
\]

Protein quality for lactation:

\[
\text{MPLact} = (\text{Yprotn} / 0.67) \times 1000
\]

Where MilkFat was the milk fat (%) and MilkProd was the daily milk production (kg). Models for estimation of mineral requirements referred to model evaluation and prediction equation in NRC2001[8].
2.2. Feed Formulation
The purpose of feed formulation was to reduce the cost of feed composition as much as possible and improve the economic profits on the premise of satisfying the nutritional requirements of the animal, its essence was to optimize the feed formulation. The model [9] used was,

\[
\begin{align*}
    f(x_1, \ldots, x_n) &= \text{Min}(\sum_{j=1}^{n} C_j x_j), \\
    \sum_{j=1}^{n} a_{ij} x_j &\geq b_i, \quad (i = 1 \ldots m) \\
    \sum_{j=1}^{n} d_j x_j &\geq \text{DMI} \\
    \text{LB}_j &\leq x_j \leq \text{UB}_j \quad (j = 1 \ldots n)
\end{align*}
\]

Where, \( f(x_1, \ldots, x_n) \) was the total cost of the feed formulation, \( \text{Min}() \) was used to calculate the minimum value, \( n \) was the number of ingredients in the feed formulation, \( C_j \) was the unit price of the \( j \)-th raw material, \( x_j \) was the amount of the \( j \)-th raw material, \( m \) was the number of nutrients, \( a_{ij} \) was the single content of the \( i \)-th nutrient of the \( j \)-th raw material, \( b_i \) was the requirement of the \( i \)-th nutrient. \( d_j \) referred to the unit content of dry matter in the \( j \)-th raw material, \( \text{LB}_j \) was the lower limit of the \( j \)-th raw material, \( \text{UB}_j \) was the upper limit of the \( j \)-th raw material, and \( \text{LB}_j > 0, \text{UB}_j > 0 \). \( \text{DMI} \) was the mass of dry matter to be taken in.

2.3. Differential Evolution for feed formulation
Differential Evolution started from a randomly generated initial population, generated a new individual by linear operation between differences of any two individuals and the third individual in the population, and then compared the new individual with the corresponding individual, if the fitness of the new individual was better than that of the old one, the new individual would replace the old one in the next generation, otherwise, the old would not be changed.

2.3.1 Fitness calculation. The fitness function calculated the fitness value of individuals which determined whether the individual being replaced or not. In this paper, we selected the equation (6) as the fitness function.

2.3.2 Individual encoding. Each real number in the individual corresponded to the quantity of feed ingredient. Assuming that the maximal value of the \( k \)-th raw material in the feed formulation was \( \text{UB}_k \) and the minimal value was \( \text{LB}_k \), the initial value of the \( k \)-th ingredient of the \( i \)-th individual was \( \tau_{ik} = (\text{UB}_k - \text{LB}_k) \times \theta + \text{LB}_k \), and \( \theta \) was a random value between 0 and 1, the \( i \)-th individual in the population was as

\[
T_i = (\tau_{i1}, \tau_{i2}, \ldots, \tau_{in})
\]

Where, \( n \) was the number of feed ingredients.

In the experiment, the population size was set to 200, and the number of ingredient was 7.

2.3.3 Stopping criterion The maximum iteration was set to 5000.

2.3.4 Evolution operation Nutritional data of concentrated feed and roughage were read from the data file. The algorithm we used was DE/rand/1/bin, just as followed:
(1) Mutation operation
For each target vector \( \tau_{iG} \), the variation vector was generated by the following formula

\[
\delta_{L,G+1} = \tau_{r_1,G} + F(\tau_{r_2,G} - \tau_{r_3,G}), \quad r_1 \neq r_2 \neq r_3 \neq i
\]
here, \( r_1, r_2, r_3 \in [1, NP] \) were randomly selected subscripts, \( G \) was number of generation, \( f \) was scale factor, and \( NP \) was population size.

(2) Crossover operation

The generated generation vector was

\[
u_{i,G+1} = (u_{1,i,G+1}, u_{2,i,G+1}, ..., u_{D,i,G+1})
\]

(9)

here, \( u_{j,i,G+1} = \begin{cases} 
\delta_{j,i,G+1}, & \text{if } \text{randdb}(j) \le CR \\
\tau_{j,i,G}, & \text{otherwise}
\end{cases} \]

\( j = 1,2,\ldots,D \)

here, \( D \) was the number of feed ingredient, \( \text{randdb}(j) \in (0,1) \) was the \( j \)th evaluation of a uniform random number. \( CR \in (0,1) \) was the crossover rate.

(3) Selection operation

In the selection stage, a greedy selection scheme was used,

\[
\tau_{i,G+1} = \begin{cases} 
\frac{u_{i,G+1}}{f(u_{i,G+1})} & \text{if } f(u_{i,G+1}) < f(x_{i,G}) \\
\tau_{i,G} & \text{otherwise}
\end{cases}
\]

(10)

For \( j = 1,2,\ldots,D \), if the fitness function value of the generated vector \( U_{i,G+1} \) was better than that of \( x_{i,G} \), then \( x_{i,G+1} \) was set to \( u_{i,G+1} \); otherwise, the old value \( x_{i,G} \) remained unchanged.

(4) Algorithm procedure

Step 1: calculating nutritional requirements including dry matter, protein, energy according equations (1)-(5), calculating mineral requirements in according with models in NRC2001.

Step 2: reading in the data of feed nutrients.

Step 3: setting crossover rate \( CR \), scale factor \( F \), population size \( NP \), iteration variable \( t=0 \) and stop criterion \( T_{max} = 5000 \).

Step 4: generating initial population using equation (7).

Step 5: performing mutation as equation (8).

Step 6: performing crossover as equation (9).

Step 7: computing fitness values as equation (6).

Step 8: performing selection as equation (10).

Step 9: \( t = t + 1 \), if \( T < T_{max} \), go to step 5, else output the result.

3. Experiments

We verified our method using the mixed feed formulation of lactating cow. The nutritional requirement of lactating cows included energy requirement and protein requirement for maintenance, energy requirement and protein requirement for lactation, and mineral requirement. According to NRC2001[8], the nutritional requirements of cow consisted of 20 items, such as dry matter, energy and protein, calcium, phosphorus, potassium, magnesium, chlorine, sodium and sulfur in minerals and cobalt, copper, iodine, iron, manganese, selenium, zinc, vitamin A, vitamin D and vitamin E. In this study, we selected dry matter, energy, protein, calcium, phosphorus, potassium, chlorine and zinc to test our method.

We compared results of our method with the Linear Programming method (LP) [9][10], which was the most popular feed formulation method. The calculation of LP for feed formulation was implemented using linear programming with Excel solver. In experiments, we selected three cows with different ages and lactation, they were
(1) Cow 1
39 months old, weight 580kg, no pregnancy, milkdays 90, milkprod 25kg/day, fat 3.5%, lactose 4.8%, MilkTrueProtein 2.5%, no grazing, no heat stress and cold stress.

(2) Cow 2
50 months old, weight 645kg, no pregnancy, milkdays 60, milkprod 25kg/day, fat 3.5%, lactose 4.8%, MilkTrueProtein 2.5%, no grazing, no heat stress and cold stress.

(3) Cow 3
60 months old, weight 678kg, no pregnancy, milkdays 120, milkprod 30kg/day, fat 3.1%, lactose 4.0%, MilkTrueProtein 2.3%, no grazing, no heat stress and cold stress.

Following estimation model in section 2.1, requirement of dry matter, energy, protein and minerals of each cow were calculated and listed in Table 1.

| Table 1. Nutritional requirements of dairy cows |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | DM              | Energy          | Protein         | Ca              | P               | K               | Cl              | Zn              |
| Cow1             | 21.9            | 117.62          | 1596.82         | 48.94           | 38.55           | 150.37          | 41.8            | 126.1           |
| Cow2             | 22.38           | 121.71          | 1615.21         | 51.01           | 39.01           | 154.83          | 43.26           | 129.02          |
| Cow3             | 25.44           | 131.38          | 1792.46         | 58.16           | 45.85           | 176.28          | 49.76           | 150.51          |

DM: dry matter, Ca: calcium, P: phosphorus, K: potassium Cl: chlorine, Zn: zinc.

The experiments were carried out using the nutritional composition data from the Chinese feed database (http://www.chinafeeddata.org.cn). Table 2 shows the results of the content of each ingredient. The total cost was the sum of each material multiplied by its unit price. From Table 2, we could find that the amount of concentrated feed (corn, wheat bran, soybean meal, soybean oil) from LP of the three cows were same, and there were differences in roughage (alfalfa stem, corn silage and straw), but the differences were small, while there were obvious differences in concentrated feed and roughage in the feed formula based on Differential Evolution (DE). In terms of the total cost, the results of DE for three cows were lower than those of LP.

| Table 2. Feed formulation result, ingredient (kg), unit price (RMB/kg), total cost (RMB) |
|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| Method          | Price | Corn | WB   | SM   | FM   | SBO  | AFS  | CS   | straw | TotalCost   |
| Cow1            | LP    | 8    | 4    | 3    | 0.3  | 0.2  | 2    | 2    | 6.5   | 39.03       |
|                 | DE    | 5.52 | 3.97 | 2.55 | 0.18 | 0.09 | 5.42 | 5.2  | 5.62  | 35.75       |
| Cow2            | LP    | 8    | 4    | 3    | 0.3  | 0.2  | 2    | 2    | 7     | 39.35       |
|                 | DE    | 6.56 | 3.96 | 2.82 | 0.27 | 0.06 | 5.62 | 5.86 | 4.23  | 38.86       |
| Cow3            | LP    | 8    | 4    | 3    | 0.3  | 0.2  | 7    | 2    | 7     | 41.70       |
|                 | DE    | 7.77 | 3.58 | 2.6  | 0.18 | 0.14 | 5.73 | 8.12 | 6.84  | 39.71       |

WB: Wheat Bran, SM: Soybean Meal, FM: Fish Meal, SBO: Soya Bean Oil, AFS: Alfalfa Stem, CS: Corn Silage.

Compared with the total cost, the content of nutrients in the formulation were more important. Dry matter was an important indicator to measure nutrients. As shown in Table 3, values of dry matter in feed formulation were the same or slightly higher than the requirement, while the energy, protein and mineral element content in the feed were generally higher than requirement, while the chlorine content was lower than the nutritional requirement.
Table 3. Analysis of nutritional assessment

| Nutrient | Method  | DM (kg/day) | Energy (Mcal/day) | Protein (g/day) | Ca (g/day) | P (g/day) | K (g/day) | Cl (mg/day) | Zn (mg/day) |
|----------|---------|-------------|-------------------|-----------------|-----------|----------|----------|------------|------------|
| Cow 1    | Requirement | 21.9       | 117.62            | 1596.82         | 48.94     | 38.55    | 150.37   | 41.8       | 126.1      |
|          | LP      | 21.9       | 136.07            | 1610.41         | 53.46     | 41.29    | 162.36   | 9.03       | 125.31     |
|          | DE      | 22.12      | 141.52            | 1680.22         | 56.5      | 53.41    | 158.52   | 19.75      | 127.08     |
| Cow 2    | Requirement | 22.38      | 121.71            | 1615.21         | 51.01     | 39.01    | 154.83   | 43.26      | 129.02     |
|          | LP      | 22.38      | 132.01            | 1633.31         | 54.94     | 41.74    | 158.51   | 9.03       | 135.31     |
|          | DE      | 22.40      | 124.11            | 1655.21         | 56.57     | 42.71    | 164.01   | 21.81      | 140.16     |
| Cow 3    | Requirement | 25.44      | 131.38            | 1792.42         | 58.16     | 45.85    | 176.28   | 49.76      | 150.51     |
|          | LP      | 26.81      | 134.21            | 1820.61         | 63.72     | 46.72    | 182.91   | 9.03       | 155.31     |
|          | DE      | 26.01      | 132.64            | 1836.54         | 64.33     | 67.45    | 187.21   | 20.75      | 152.65     |

DM: Dry Matter, Ca: Calcium, P: Phosphorus, K: Potassium, Cl: Chlorine, Zn: Zinc.

In this study, the unit of measurement of each feed ingredient was kg, which was different from the unit of measurement of feed material in some existing feed formulation using ratio of the total feed. Obviously, these reasons led to the results of LP and DE were slightly higher than those of requirement. However, the content of chlorine in the feed material obtained from the Chinese feed database platform was very low, which made the content of chlorine in the feed formula unable to meet the requirements. It was necessary to increase the composition of sodium chloride or other additives in the formulation.

4. Conclusion

Essentially, feed formulation was an optimization problem. As an important branch of population-based algorithm, Differential Evolution had excellent performance in the fields such as numerical optimization, image processing and data analysis. In this paper, we proposed the automatic feed formulation approach using Differential Evolution algorithm. Compared with Linear Programming, feed formulation based on Differential Evolution was more flexible and the total cost of feed was less. Differential Evolution belongs to stochastic optimization algorithm, and the results of multiple runs might be inconsistent. With the improvement of Differential Evolution and the analysis of feed nutrition composition and animal nutrition models, feed formulation based on Differential Evolution could further improve the feed utilization efficiency and economic efficiency of the breeding industry.

5. Acknowledgments

This work was financially supported by Tianjin Natural Science fund (Project No. 19JCYBJC24800), China and Innovation and entrepreneurship training program for college students of Tianjin Agricultural University (Project No. 201810061152), China.

References

[1] A. J. F. Webster, Understanding the Dairy Cow, 2nd edition., Blackwell Scientific Publications, New Jersey, NJ, USA, 1993.
[2] U. D. Dooyum, R. Mallipeddi, T. Pamulapati, T. Park, J. Kim, S. Woo, Y. Ha. Interactive livestock feed ration optimization using evolutionary algorithms. Computers and Electronics in Agriculture. 155 (2018) 1–11.
[3] P. Saxena, M. Chandra, Animal diet formulation models: a review (1950–2010). Animal Sci. 2011. Rev. 189–197.
[4] V. N. Wijayaningrum, W. F. Mahmudy, M. H. Natsir. Optimization of Poultry Feed Composition Using Hybrid Adaptive Genetic Algorithm and Simulated Annealing. Journal of Telecommunication, Electronic and Computer Engineering, 9(2017) 183-187.
[5] A. A. Altun, M. A. Sahman. Cost optimization of mixed feeds with the particle swarm optimization method. Neural Comput & Applic. 22 (2013) 383–390.
[6] R. A. Rahman, G. Kendall, R. Ramli, Z. Jamari, and K. R. Ku-Mahamud, Shrimp Feed Formulation via Evolutionary Algorithm with Power Heuristics for Handling Constraints. Complexity. 2017 (2017) 1-12.
[7] M. E. Van Elswyk, S. H. McNeill. Impact of grass/forage feeding versus grain finishing on beef nutrients and sensory quality: The U.S. experience. Meat Science. 96 (2014) 535-540
[8] National Research Council. Nutrient Requirements of Dairy Cattle. Seventh Revised Edition. Washington, DC: The National Academies Press, 2001
[9] B. Xiong, Q. Luo, Z. Pang, L. Yang, L. Yang. Precise Calculation System of Total Mixed Ration for Lactating Cow. Scientia Agricultura Sinica. 2012,45(14):2948-2958.(in Chinese)
[10] V. Radhika, S. B. N., Rao. Formulation of low cost balanced ration for livestock using Microsoft Excel, Wayamba Journal of Animal Science. (2010) 38-41.