Another Feed Formulation Method for Livestock and Poultry: Multi-Formula Parallel Design Postprint

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Abstract

Multi-formulation parallel design represents another approach for compounding livestock and poultry diets. This study aimed to apply this method to animal feed formulation. Employing various combinations of multi-formulation parallel design, diets for growing pigs across seven distinct developmental stages were formulated simultaneously, with comparative analysis conducted on diet unit price, ingredient usage, and nutrient content. The nutrient contents—including energy, calcium, phosphorus, crude protein, amino acids, total nitrogen, and minerals—in the 49 growing pig diet formulations generated through this design approach all met or exceeded the recommended requirements for swine nutrition proposed by the National Research Council (2012), while also satisfying minimum cost criteria. Case examples demonstrate that multi-formulation parallel design can simultaneously formulate multiple livestock and poultry diets and identify superior formulations within a broad spectrum, indicating its practical feasibility for application in animal feed formulation design.

Full Text

A Parallel Design with Multiple-Formulas: Another Approach to Diet Formulation for Livestock and Poultry

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Abstract: Parallel design with multiple-formulas represents another approach to diet formulation for livestock and poultry. This study aimed to apply this method to animal feed formulation. Using different combinations of parallel design with multiple-formulas, diets for seven distinct growth stages of pigs were formulated simultaneously, with comparisons and analyses made of diet unit price, ingredient usage, and nutrient content. The nutrient contents of energy, calcium, phosphorus, crude protein, amino acids, total nitrogen, and minerals in all 49 growing pig diet formulas generated through this design method met or exceeded the recommendations for swine nutrient requirements proposed by the National Research Council (2012), while also satisfying minimum cost requirements. The case study demonstrates that parallel design with multiple-formulas can formulate multiple livestock and poultry diets simultaneously and select superior formulas across a broad range, indicating practical feasibility for application in animal feed formulation design.

Key words: parallel design with multiple-formulas; feed formulation; nutrient content; cost; growing pigs

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The development of livestock and poultry feed represents a systematic engineering process, with formulation design serving as its core technology. To date, feed industries and livestock farms have utilized various mathematical programming approaches—typically linear programming—with different objective functions, constraints, or numerical algorithms for computer-aided formulation design of diets for diverse animal species and production purposes [1-18]. Such feed formulation designs aim to minimize cost while meeting all nutrient requirements for animal survival, growth, and production. The conventional process involves sequentially designing individual formulas one at a time. This sequential approach is simple, practical, and effective, making it widely adopted in both production and research settings. However, when multiple formulas require design, sequential methods present significant limitations: while each individual formula may achieve optimal results, these optima are not necessarily optimal from a holistic perspective. Moreover, sequential design offers a narrow selection range for optimal formulas and wastes human resources while increasing computational costs [19].

Therefore, this paper proposes parallel design with multiple-formulas for livestock and poultry diet formulation. In stark contrast to traditional sequential methods, parallel design and its algorithms can execute target operations simultaneously across different processing units, merging results to obtain correct outcomes. Originating in computer science, this approach has gradually expanded into broad domains of information technology and numerical computation [19-20]. Evidently, for feed processing enterprises or livestock operations requiring multiple formula designs with various opportunities to obtain better least-cost feed formulas, parallel design with multiple-formulas becomes essential. This study applies computer-based parallel design with multiple-formulas to explore the feasibility and application prospects of selecting superior optimal livestock feed formulas through multiple opportunities.

1.1 Mathematical Model for Parallel Design with Multiple-Formulas

Livestock and poultry feed formulation design is a typical combinatorial optimization problem that applies linear programming to combine various raw materials in specific proportions to create formulas meeting particular nutritional requirements at minimum cost. Based on this concept, the mathematical model for parallel design with multiple-formulas for livestock and poultry feed is constructed using the following mathematical symbols and formulas.

Let n be the number of formulas, m be the number of feed ingredients, be the amount of ingredient j in formula i, and be the unit price of . The problem under investigation uses linear programming mathematical optimization methods to minimize total feed cost , yielding the following minimization formula:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij}$$

Simultaneously, Formula   holds under the conditions satisfying the following formulas:

where: n is a positive integer, n$ $2; t is the number of feed nutrients, t=1,···,p; is the unit content of nutrient t in ingredient j for formula i; b__t is the minimum or maximum requirement for nutrient t.

1.2 Feed Ingredients

The feed ingredients used included corn, barley, wheat middlings, wheat bran, soybean meal, fish meal (63% crude protein), soybean oil, glucose, anhydrous dicalcium phosphate, limestone, salt, DL-methionine (Met), L-lysine (Lys), multivitamin, zinc sulfate monohydrate, sodium selenite, and anhydrous copper sulfate. Nutrient composition and content data for feed ingredients were obtained from the *Chinese Feed Composition and Nutritive Value Table (2014 25th Edition)* [21-22]. Feed price data were primarily provided by Hunan Jiahe Agriculture and Husbandry Inc., with remaining prices referenced from Alibaba online transaction prices [23]. Table 1 lists the nutrient contents and prices of main ingredients.

1.3 Formulation Design

The parallel design with multiple-formulas for pig feed proposed in this study refers to simultaneously formulating several formulas that meet specific nutritional requirements and achieve minimum cost using the same optimization method within a single mathematical model. From a mathematical perspective, the objective of optimal formulation design is to find the optimal solution for a set of non-negative variables, i.e., minimizing the cost function of the independent variable vector x = (x_1, x_2, ···, x). That is:

$$\hat{x} = \arg\min f(x)$$

where: is the solution or estimated value of the independent variable (arg)x that minimizes the cost function .

This concept can be readily extended to problems with n ($ $2) formula designs, which can be divided into several subsections (k segments) according to the actual growth and production conditions of livestock populations, where k = 1, ⋯ , n. Specifically, when k = 1, all formulas are optimized simultaneously; when k = n, formulation optimization proceeds at n single-point segments. Consequently, n formula problems can be addressed through three distinct optimization schemes of parallel design with multiple-formulas: full-section, subsection, and point-section approaches. The full-section includes all formulas, subsections contain at least 2 formulas, and point-sections contain only one formula.

This study employs growing pig feed formulation as an example for parallel design with multiple-formulas. The full-section formulation includes all seven diets for different growth stages. Subsection formulations consist of four types: creep feed, starter feed, grower feed, and finisher feed, containing 2, 2, 2, and 1 diet(s), respectively. Point-section formulations represent one diet per segment, totaling seven diets corresponding to the NRC (2012) recommended diets for growing pigs at body weight ranges of 5-7, 7-11, 11-25, 25-50, 50-75, 75-100, and 100-135 kg. These are designated as pre-starter, starter, early grower, late grower, early finisher, late finisher, and finisher feeds, denoted by symbols Gw05, Gw07, Gw11, Gw25, Gw50, Gw75, and Gw100, respectively.

It follows that if optimal solutions exist for growing pig diet formulation, there would be only one full-section formulation, seven point-section formulations, and more than six subsection formulations, with the exact number determined through combinatorial theory-based pairing among formulas.

In this specific case, the seven growing pig diets are first represented by seven distinct numbers (1, 2, 3, 4, 5, 6, 7). Subsection design then proceeds. To form a subsection, at least two different diets are required, consistent with the subsection definition provided above. Therefore, selecting two from the seven formulas or seven distinct numbers yields 21 different combinations or subsections through pairwise matching. These are subsequently divided into seven groups designated as Groups I, II, III, IV, V, VI, and VII. Finally, the six formulas in each group are combined with the remaining single point-section formula to complete the parallel design with multiple-formulas, with results presented in Table 2 . This demonstrates that each of the seven growing pig diets can have seven formulas and their optimal solutions, yielding a total of 49 optimal formula solutions worthy of further investigation.

1.4 Nutritional Standards

Nutritional standards represent the nutrient requirements of different pig populations and serve as the criteria for feed formulation design. Based on the nutrient requirements proposed in the latest 11th edition of *Nutrient Requirements of Swine* by the NRC Committee on Swine Nutrition [24-25], the nutritional standards for this parallel design with multiple-formulas were established. The feed nutrient components, constraints, requirements, and units for the seven formulas are listed in Table 3 . The listed nutrient requirements for pig diets, which constitute the formulation design standards, total 27 items. Notably, the new edition includes two important new nutritional standard indicators: standardized total tract digestible phosphorus (STTDP) and total nitrogen (TN). The calculation formulas are as follows:

STTDP = standardized total tract digestibility of phosphorus (STTD) × total phosphorus (TP) Formula ;

where: STTD values are referenced from [24].

1.5 Numerical Calculation Software

Numerical calculations for the parallel design with multiple-formulas for pig diets were performed using GAMS 23.5 software [26]. GAMS, an acronym for General Algebraic Modeling System, is an internationally renowned advanced modeling system for mathematical programming and optimization developed in the United States. A standard GAMS program consists of sets, parameters, variables and equations, model and solve statements, and display output. Following the language and syntax rules of GAMS and adhering to the aforementioned program structure, GAMS programs for the three types of parallel design with multiple-formulas for pig diets (full-section, subsection, and point-section) were developed using feed ingredient prices, nutrient values, and dietary feeding standards. Execution of these programs yielded results for minimum cost and satisfaction of nutritional requirements for different growing pig populations across all formulas.

1.6 Quantitative Comparison Method

To quantitatively analyze the fitting degree of nutrients in diet formulas, the mean deviation of calculated nutrient values from their standard values was defined. The calculation formula is as follows:

$$m(i) = \frac{1}{p}\sum_{t=1}^{p}(d_{nrit} - d_{nrit}^{s})$$

where: p is the number of nutrients in the diet or formula; t is nutrient t in diet i; r is growth stage; is the calculated content value of nutrient t in diet i at stage r; is the standard content value of nutrient t in diet i at stage r; m(i) is the mean deviation between calculated and standard values of nutrient t in diet i at stage r.

If an optimal solution exists for a diet formula, a feasible solution must also exist. This implies that the mean deviation can only be greater than or equal to 0. When this mean deviation equals 0, it indicates that the formulated nutrient value equals the standard value, meaning the nutrient meets the nutritional standard. When greater than 0, it indicates the formulated nutrient value meets or exceeds the standard value. Larger values indicate greater overall disparity between formulated diet nutrient content and standard values, while smaller values indicate less disparity. Abnormally large values may indicate extreme nutrient values in the formula. Therefore, this mean deviation can objectively evaluate the suitability of nutrient formulation values in parallel design with multiple-formulas.

2 Results and Analysis

2.1 Comparison and Analysis of Ingredient Usage

The ingredient usage for seven diets for different growth stages of pigs formulated through parallel design with multiple-formulas—pre-starter, starter, early grower, late grower, early finisher, late finisher, and finisher—is presented in Table 4 . Due to the adoption of grouped subsection parallel design with multiple-formulas, each diet has seven formulas, totaling 49 formulas, among which 28 formulas are identical within groups and 21 differ within groups. Among the 16 feed ingredients formulated, copper sulfate did not enter diet formulation (usage was 0 in all formulas and thus not listed in the table). Glucose usage was limited to 5% only in pre-starter diets for suckling pigs due to formulation constraints. Table 4 shows that the seven pre-starter diets for pigs weighing 5-7 kg had identical ingredient types and amounts; the seven starter diets for pigs weighing 7-11 kg had identical ingredient types but not identical amounts, differing only in sodium selenite usage; ingredient amounts differed among the seven early grower diets for pigs weighing 11-25 kg, the seven late grower diets for 25-50 kg, the seven early finisher diets for 50-75 kg, the seven late finisher diets for 75-100 kg, and the seven finisher diets for 100-135 kg. High-energy feed ingredients, including corn, barley, wheat middlings, wheat bran, soybean meal, fish meal, and soybean oil, showed average usage of 91.9%, 94.1%, 91.3%, 90.2%, 88.9%, 79.2%, and 83.9% across the seven diets, respectively. High-protein feed ingredients, including soybean meal and fish meal, showed average usage of 40.9%, 34.1%, 34.5%, 25.2%, 23.5%, 14.2%, and 18.9% across the seven diets, respectively.

2.2 Comparison and Analysis of Diet Costs

Overall, the costs of the seven diet formulas decreased progressively from pre-starter to finisher diets, with average costs of 4.153, 4.059, 3.837, 3.795, 3.622, 3.598, and 3.597 yuan/kg, respectively. Examining ingredient usage in relation to formulation costs reveals that formulas with identical prices within the same diet category had identical ingredient usage (same price, same quantity within diets), while formulas with identical prices across different diet categories had different ingredient usage (same price, different quantity across diets). Furthermore, the usage of high-energy and high-protein feed ingredients generally decreased as diet cost decreased.

2.3 Comparison and Analysis of Nutrient Contents

The nutrient contents of seven diets for different growth stages of growing pigs formulated through parallel design with multiple-formulas—pre-starter, starter, early grower, late grower, early finisher, late finisher, and finisher—are presented in Table 5 . Compared with nutritional standards (Table 3), nutrients in these diet formulas—including digestible energy (DE), metabolizable energy (ME), calcium (Ca), total phosphorus (TP), STTDP, arginine (Arg), histidine (His), isoleucine (Ile), leucine (Leu), lysine (Lys), methionine (Met), Met + cysteine (Cys), phenylalanine (Phe), Phe + tyrosine (Tyr), threonine (Thr), tryptophan (Trp), valine (Val), TN, sodium (Na), chlorine (Cl), magnesium (Mg), potassium (K), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and selenium (Se)—all met or exceeded standard nutrient requirements [NRC (2012)]. Although all nutrient contents in these diet formulas satisfied the standards for growing pig nutrient requirements, the degree of compliance varied.

Table 6 presents the mean deviations of nutrient contents from standard values (i.e., minimum requirements) for 49 diet formulas across seven groups, with each group containing seven diet formulas: pre-starter, starter, early grower, late grower, early finisher, late finisher, and finisher. The ranges (maximum, minimum) of mean nutrient content deviations for Groups I, II, III, IV, V, VI, and VII, as shown in Table 6 , are (1.69, 1.69), (3.71, 1.42), (10.19, 1.65), (11.96, 2.58), (20.38, 2.53), (12.74, 3.00), and (12.24, 3.05), respectively, corresponding to ranges of 0, 2.29, 8.54, 9.38, 17.84, 9.74, and 9.19. Larger mean deviations indicate greater distance from standard values, while larger ranges of mean deviations indicate broader variation scopes.

Comprehensive comparison revealed the following descending order of mean nutrient content deviations and their ranges: Group V > Group VI > Group IV > Group VII > Group III > Group II > Group I. Large mean deviations and ranges likely resulted from extreme nutrient values within formulas. Based on information provided by mean deviations, examination revealed that Group I had no excessively large selenium values, while Groups II, III, IV, V, VI, and VII contained large selenium values. Notably, copper sulfate, an ingredient included in formulation design, was not utilized and showed no nutrient content values, indicating it was unnecessary for diet formulation and that copper requirements could be satisfied using organic biological feed sources.

3 Discussion

3.1 About Diet Formulation Design Methods

Parallel design is a concurrent processing design and algorithm that handles several different objects simultaneously [19-20]. Using growing pig diet formulation as an example, this study proposes a parallel design with multiple-formulas and its algorithm for livestock and poultry. This approach has three key characteristics: First, multi-formula capability. It enables multiple formulas to participate in design and can find optimal solutions for these formulas, provided they all have feasible solutions. Subsection design serves as a pathway to obtain multiple formulas for a given diet. On one hand, multi-formula combinations are identified through professional segmentation (e.g., growth stages); on the other hand, combinations of several formulas are obtained through mutual pairing of diets based on mathematical combinatorial theory. Second, parallelism. Parallelism means these multiple formulas undergo optimization simultaneously. The optimal solution for any particular formula is not determined by itself but rather through mutual determination among all formulas. However, this depends on the formulation design method. If these formulas are divided into several segments, formulas within segments influence each other, while formulas across segments do not, as segmentation aims to prevent certain formulas from being affected by others. If formulas are divided such that each segment contains only one formula, they become mutually independent and unaffected by each other. The point-section formulation design method proposed in this paper can essentially obtain results identical to sequential methods due to this inter-formula independence. In other words, while studying parallel design with multiple-formulas, conventional independent formulation methods can also be compared simultaneously. Third, global optimality. If parallel design with multiple-formulas is employed to examine multiple formulas concurrently, the optimal solution obtained on the basis of feasible solutions becomes their common solution—a globally optimal solution satisfying all formulas.

3.2 About Dietary Mineral Formulation

Dietary minerals include macro and trace elements. Trace elements, in particular, often fail to meet minimum dietary requirements due to low contents in organic biological feeds, necessitating supplementation with mineral feed sources. This study selected three mineral feedstuffs—sodium selenite, zinc sulfate, and copper sulfate—for formulation design. The aforementioned mineral comparisons and analyses indicated that all dietary zinc nutrients and some selenium nutrients failed to meet dietary requirements, with varying deficiency amounts across different formulas. Sodium selenite and zinc sulfate were supplemented according to specific conditions (Table 4) rather than using a uniform premix addition. It should be noted that sodium selenite supplementation resulted in extreme nutrient values in certain formulas. These extreme values, which deviate substantially from nutritional standards and exceed requirements considerably, arise from the high concentrations of selenium and zinc in their compounds combined with very small addition amounts in formulas. However, they can be corrected to required or slightly above-required levels through manual or automated methods. This analysis is provided to inform practitioners. Ferket et al. [27] noted that many producers feed diets with zinc and copper additions far exceeding NRC (2012) recommendations—up to 10 times higher—with the direct consequences of increased environmental burden and suboptimal animal growth improvement. Powers et al. [28] also proposed that livestock nutrition strategies must address environmental challenges.

3.3 About Diet Formulation Methods

Currently, livestock and poultry feed formulation design employs sequential methods, formulating one least-cost diet at a time to meet dietary energy, calcium, phosphorus, and crude protein requirements, sometimes with added amino acid constraints. The growing pig diets formulated using the parallel design with multiple-formulas in this study not only met or exceeded nutritional standard requirements for nutrients including energy, calcium, phosphorus, crude protein, amino acids, and minerals, but also achieved minimum cost prices. Four points warrant mention: First, feed ingredient selection. The 16 feedstuffs selected for this formulation design were primarily based on those used in pig production at Hunan Jiahe Agriculture and Husbandry Inc. (Table 1). Second, nutrient item selection. All 27 nutrient items listed in the 11th edition of NRC' s *Nutrient Requirements of Swine* (2012) [24-25], including energy, calcium, phosphorus, crude protein, amino acids, and minerals, were incorporated into this formulation design. Two nutrients—STTDP and TN—introduced for the first time in this publication were also included as constraints in the mathematical model. Third, premix selection. Premixes primarily supplement trace minerals, vitamins, Met, and Lys. Since minerals, Met, and Lys were added as nutrient constraint items in the formulation model, no premix was configured in the design; instead, a multivitamin was used. Fourth, dietary vitamin formulation. Although NRC' s *Nutrient Requirements of Swine* 11th edition (2012) [24-25] lists vitamin requirements for different growing pig stages, this study' s parallel design with multiple-formulas did not consider vitamins as constraint items in the mathematical model. This omission resulted from numerous missing data entries for vitamin contents in current feed composition and nutritive value tables, making feasible solutions unattainable. Through multiple dietary trial formulations, the types and quantities of vitamins not meeting requirements have been identified and can be supplemented to diets as vitamin additives to achieve compliance with dietary vitamin needs.

3.4 About Diet Formula Selection Methods

First, diet formula selection must have scientific basis and consider diet affordability, adequacy, balance, and safety. Animal production is a highly competitive industry with relatively small profit margins. Under such conditions, economic efficiency becomes the key factor ensuring long-term profitability, making economic concerns the fundamental basis among numerous issues [2]. Therefore, livestock and poultry diet formulation adopts minimum cost as the objective function and uses NRC (2012) recommended nutrient requirements for growing pigs as nutrient constraints, providing scientific theoretical foundation and broad practical context for diet formula affordability, adequacy, balance, and safety. This study employed growing pig feed formulation as an example for parallel design with multiple-formulas. Through combinations of 16 feed ingredients and seven different growth stage formulas, 49 least-cost formulas were obtained, with energy, calcium, phosphorus, crude protein, amino acids, TN, and mineral contents meeting or exceeding nutritional needs for survival and growth. Appropriate reduction of selenium addition in certain formulas enhanced diet safety while reducing costs.

Second, diet formulation methods capable of generating multiple formulas are essential. The parallel design with multiple-formulas proposed in this paper represents a novel pathway for selecting optimal formulas, offering an extensive selection range. For example, this study involved seven diets in parallel design with multiple-formulas, with one design each for full-section and point-section approaches, each generating seven diets. Subsection design yields numerous iterations and diet formulas. For instance, the seven growing pig diets in this study generated 49 diet formulas through subsection design combinations—seven times more than traditional sequential design. Thus, parallel design with multiple-formulas provides an excellent approach for selecting diet formulas that satisfy nutrient adequacy, balance, safety, and affordability from numerous least-cost options.

Conclusions

The parallel design with multiple-formulas for livestock and poultry diets proposed in this study represents another formulation design approach that simultaneously generates multiple distinct diet formulas through different multi-formula combinations. This not only improves formulation design efficiency but, more importantly, increases opportunities for selecting superior diet formulas, providing a new pathway for obtaining rational and balanced diets for livestock and poultry. Numerous case studies have verified the practical feasibility of applying parallel design with multiple-formulas to animal feed formulation design.

Through combination of two different parallel design schemes—subsection and point-section—seven groups totaling 49 growing pig diet formulas were obtained. Following comparison and analysis of ingredient usage, unit price, and nutrient content, these formulas all met or exceeded NRC (2012) recommended nutrient requirements for growing pigs for dietary energy, calcium, phosphorus, crude protein, amino acids, TN, and minerals, while also satisfying minimum cost requirements. This study merely proposes the use of parallel design and combinatorial theory for livestock and poultry diet formulation and explores its feasibility. Further research should involve in-depth investigation of these methods and theories, along with application of the parallel design with multiple-formulas for livestock and poultry diets in production settings at farming enterprises and feed processing plants.

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