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Multi-objective programming to optimize the composition of pelleted feed for pigs in the fattening stage

Programación multiobjetivo para optimizar la composición de alimento peletizado de cerdos en etapa de engorde

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ABSTRACT

The production of balanced feed for pigs is a sector in the highly competitive industry that is characterized by establishing small margins between costs and benefits. A goal optimization model was applied to reduce the production cost and guarantee the amount of corn in the formulation. For this purpose, multiobjective programming was applied, with two defined goals and nine restrictions related to compliance with fat, fiber, moisture, and protein content. RStudio was used to find the most feasible formulation. With the establishment of goals and priorities, the optimal formulation is 24.3% corn, 11.60% calcium carbonate, 23.90% cane molasses, 19.30% monocalcium phosphate, 20.90% concentrated soybeans, and a negligible amount of palm oil. The results obtained in the deviation variables indicate compliance with the goal related to the minimum cost and noncompliance with the goal that guaranteed the minimum amount of corn in the formulation. The mathematical model developed may present variations if restrictions change, new variables are introduced, or changes in costs for the raw material used.

Keywords:costs; swine diet; multiobjective optimization; goal programming.

RESUMEN

La producción de alimento balanceado para cerdos es un sector de la industria altamente competitivo que se caracteriza por establecer pequeños márgenes entre costos y beneficios. Se aplicó un modelo de optimización de objetivos para reducir el costo de producción y garantizar la cantidad de maíz en la formulación. Para ello se aplicó una programación multiobjetivo, con dos metas definidas y nueve restricciones relacionadas con el cumplimiento del contenido de grasa, fibra, humedad y proteína. Se utilizó RStudio para encontrar la formulación más factible. Con el establecimiento de metas y prioridades, la formulación óptima es 24,3% maíz, 11,60% carbonato cálcico, 23,90% melaza de caña, 19,30% fosfato monocálcico, 20,90% soja concentrada y una cantidad insignificante de aceite de palma. Los resultados obtenidos en las variables de desviación indican cumplimiento de la meta relacionada con el costo mínimo e incumplimiento de la meta que garantizaba la cantidad mínima de maíz en la formulación.

Palabras clave: costos; dieta porcina; optimización multiobjetivo; programación por metas.

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Introduction

The optimization of processes is a tool used to identify existing deficiencies and based on this, find possible solutions that allow achieving the expected competitiveness [1, 2]. For this purpose, mathematical models are applied such as linear programming for an objective function and multiobjective programming for several functions whose objective is to find an efficient set of solutions [3].

Sometimes, multiobjective systems modeling can be totally or partially conflictive, given that the improvement of some objectives can lead to the worsening of others. This situation corresponds to multicriteria analysis problems since the objectives (or criteria) have different weights related to the planned goal. One of the techniques applicable when the objectives have fuzzy weights is goal programming, which is a methodology for solving multi-objective programming problems. The methods used for this purpose are weighted programming, programming by minimax goals, sequential linear algorithm, programming by lexicographic goals, commitment programming, and technique for order preference by similarity to ideal solution [4,5,6].

In goal programming, the deviation of the variable is weighted since the criteria are generally given in different units. One option to correct the errors caused by the different magnitudes is to weigh the deviations by dividing them by the aspiration level to obtain percentage deviations that do not have units.

Otherwise, each goal must be multiplied by weights to show the importance that each of these has [4].

Studies carried out in recent years address this type of problems through the application of linear programming since it allows including nutritional and technical details that must be met to formulate a nutritionally optimal diet for the pig [7].

Companies improve their processes by meeting their needs to reduce time and minimize costs. It has been demonstrated that not only improvements in machinery can mean productivity increases but also operational efficiency that allows the correct integration of production processes, materials management, good selection of personnel, and quality working conditions [8].

At a global level, this is the reality experienced in balanced food production areas. Feeds are products intended for animal consumption and are a source of economic income, which can be taken advantage of as a market opportunity [9].

In the case of pigs, there are two types of balanced feed: the first is composed of grains, a protein source, and additives; the second is made up of grains, agroindustrial byproducts, a protein source, and additives. Proper feeding of pigs is one of the most important aspects of the producer. It represents between 80 to 85% of the total production costs, affecting the productive performance of the animal and the profitability of the farm. Likewise, the correct use of these foods depends on a diet that covers nutritional requirements, with high-quality raw materials that provide the energy consumption required by the animal [10, 11].

There are situations, such as the determination of diets for animals, in which the modeling of real systems leads to the construction of multi-objective models (that is, with several objective functions), which can be totally or partially conflicting so that the improvement of some objectives usually leads to the worsening of others [12].

Pig farms and plants dedicated to the preparation of compound diets went from using food waste to acquiring rations from professional plants. Likewise, the tonnage of commercial balanced feed had a rebound, driven mainly by the growth and continuous modernization of the pork industry [13].

The production process of pelleted feed consists of a mixture of different ingredients with varied physical and chemical characteristics, which are necessary to guarantee the good performance of the pellet at the level of animal farms, where elements such as pressure, humidity, and temperature [14].

According to the FAO, mainly the pigs receive an unbalanced diet. However, its hardiness and survival instinct allow it to find a diet that ensures its reproduction and production, providing energy and proteins to the human diet. This food transformation capacity has allowed the pig, in an ancestral manner and new breeds, to integrate into industrial systems with great economic benefits as a consequence of the improvement in feed conversion rates [15].

By 2022, worldwide, the production of balanced feed for pigs decreased by around 3% as a result of African swine fever as well as the high prices of raw materials for diets. However, in countries such as Vietnam, China, South Africa, Brazil, and Mexico, there was an increase in the price of pork that allowed economic growth in the sector [16].

Pig production in Ecuador has not been fully developed [17].

A decade ago, inappropriate feeding techniques were used through the use of kitchen waste, affecting the health of animals as they become carriers of diseases, such as trichinosis and swine flu, without taking into consideration the nutritional needs of the pig [18].

Intensive farming systems are carried out by large companies in their feeding lines, affecting the costs of acquiring inputs for small producers, which sometimes forces them to opt for traditional feeding [19]. As a legal basis for quality in food products, for the operation of pelletized food production plants, food sovereignty in the production of animal food indicates that it constitutes a strategic objective and an obligation of the State to guarantee that the balanced products obtained are healthy, and appropriate for consumption [9].

Pork production is a highly competitive industry characterized by small margins between costs and benefits, which seeks to ensure longterm profitability. It is not enough for a diet to meet the nutritional needs of pigs; it is also a legal and professional requirement to know and apply, in the corresponding formulation, the official regulations of each country or area that govern the use and manufacture of food for the different stages of pigs [20].

In response to this statement, small industrial facilities are in charge of processing balanced feed for pigs. One of them is an agro industrial workshop located on the Ecuadorian coast, which has a pelletizing plant intended to obtain balanced feed for pigs. This workshop was created in 2007 and currently processes approximately 4 tons of balanced feed per week intended for feeding pig farms. This plant has a capacity of 1 Tn/hour. However, it is underutilized because the price of the final product is not competitive in the market.

For this reason, this study was carried out to propose a multi-objective programming model by goals, which allows establishing goals related to production costs and nutritional quality of the product to be obtained. Multi-objective optimization, applicable in the design of systems and processes, contributes to the improvement of more than one criterion simultaneously selecting the most convenient option in a situation as an effective alternative. With this, it is expected to have a better use of the raw material, reducing or conserving costs with the projection of making a new formulation for the pelletizing production process.

Methods

Information was collected in an agroindustrial workshop dedicated to the production of balanced food for animals located on the Ecuadorian coast of Ecuador. With this, the stages of the production process, the raw materials used, the unit costs, and the protein requirements of the food were known. From this, the decision variables objective functions and corresponding restrictions for the goal-based optimization model were known. The resolution of the problem described was carried out through the software RStudio version 4.3.1 following the model described for optimization by goals Grosskelwing Núñez.

Development of the mathematical model

The goal programming optimization method was used, which helps make decisions in the context of multiple objectives. In most cases, it will not be possible to meet all objectives good enough solutions will be sought instead of optimal solutions, which aim to simultaneously improve several objectives to a minimum level of satisfaction [19].

The preventive method of goal programming was used, which began by prioritizing the goals according to their order of importance. This model optimizes the goals according to the established priority order so that the highest priority solution is not degraded.

according to your decision maker. Given a situation of n goals, the complete mathematical model was described as:

Minimize G1 = r1 (Highest priority)

$\vdots$ either

Minimize Gn = rn (Minimum proportion)

Costs associated with packaging or production services were not considered. The steps that were followed are described below [20].

Establishment of goals and priorities

Two goals were established for the optimization model, according to their order of importance:

Goal 1. Priority 1: Minimize costs associated with the production.

Goal 2. Priority 2: Maximize amount of protein that corn represents in relation to the rest of the raw materials.

Definition of variables

The decision variables were established based on the raw materials used in the balanced feed production process. xi is the amount of the raw material i (table 1) used in the formulation of the balanced feed.

Table 1 - Identification of raw material (xi).

Raw material	$\mathbf{x_i}$
OM: Oatmeal	x_1
CO: Corn	x_2

CW: Common wheat	x_3
PO: Palm oil	x_4
CC: Calcium carbonate	x_5
CM: Cane molasses	x_6
MP: Calcium mono phosphate	x_7
RB: Rice bran	x_8
PSC: Palm stone cake	x_9
SF: Soy flour	x_{10}

Construction of the mathematical model

The model was built for the nutritional requirements of pigs in the fattening stage, which begins at 11 weeks of age. The costs of raw materials were taken from the local market, while the nutritional requirements were taken from the Spanish Foundation for the Development of Animal Nutrition [22].

Two goals were formulated, the first sought to reduce the cost of the product (1), and the second established the minimum amount of corn used as protein in the product (2). The goal programming technique was applied to optimize the multiple objectives, which proposes ordering all goals based on the preferences of the decision maker.

$$C_{OM}*x_1+ C_C*x_2+ C_{CW}*x_3+ C_{PO}*x_4+ C_{CC}*x_5+ C_{CM}*x_6+ C_{BMP}*x_7+ C_{RB}*x_8+ C_{PSC}*x_9+ C_{SF}*x_{10} \leq g_1 \quad (1)$$

$$x_2 \geq g_2*(x_1+ x_3+ x_4+x_5+x_6+x_7+ x_8+ x_9+ x_{10}) \quad (2)$$

Where Ci is the cost of each raw material. The average cost of the local market for balanced feed ranges between $0.40/kg and 0.60/kg. Considering being competitive in the market cost of $0.30/kg was established. Corn should represent at least 25% of the amount of protein in the fattening diet, published for Pooli, 2021.

To present each equation as a goal, it is necessary to add the corresponding deviation variables (si+ and si−), which will give flexibility to the goal, remaining as follows (3, 4). s_i^- and s_i^+ indicate the missing and excess amount to reach the proposed goal.

$$C_{OM}*x_1+ C_C*x_2+ C_{CW}*x_3+ C_{PO}*x_4+ C_{CC}*x_5+ C_{CM}*x_6+ C_{BMP}*x_7+ C_{RB}*x_8+ C_{PSC}*x_9+ C_{SF}*x_{10}+s_1^+-s_1^-= g_1 \quad (3)$$

$$x_2 \leq g_2*(x_1+ x_3+ x_4+x_5+x_6+x_7+ x_8+ x_9+ x_{10}) +s_2^+-s_2^-= 0 \quad (4)$$

Each of the inequalities represented a goal for the decision maker who will not be able to meet all the goals simultaneously, but rather the best that was found was a solution that manages to satisfy these proposed goals. The way in which goal programming determined this solution was to be able to convert each of the inequalities into flexible goals that can be violated if necessary.

To carry it out, each inequality was converted into an equality by adding two variables called deviation where:

s_n^- : missing deviation variable: calculates the missing amount to reach the proposed goal.

s_n^- : excess deviation variable: calculates the excess obtained over the proposed goal.

In this context, two goals were formulated in this case study, which were considered flexible. As a first goal, the amount of protein needed in the pelleted food is established. This flexibility is achieved by adding the two deviation variables and transforming the inequality into an equation:

s_1^-: calculate the missing quantity to reach the goal to reduce the cost.
s_1^+: calculates the excess obtained to achieve the goal to reduce the cost.

s_2^-: calculates the missing amount to reach the composition goal of 25% corn.
s_2^+ : calculates the excess obtained to reach the composition goal of 25% corn.

Definition of constraints

The commercial nutritional requirement percentages that guarantee good weight gain at the lowest cost were taken as a basis for establishing productive goals that ensure the most optimal daily performance. What was suggested by Villacrés et. al. (2018) (19), and the standard of the Spanish Foundation for the Development of Animal Nutrition (FEDNA) was taken to establish the minimum and maximum amounts of fat, fiber, moisture, and protein that must contain balanced feed for pigs (Table 2).

Table 2 - Nutritional requirement of the balanced.

Component	Minimum	Maximum
Fat, % (c_1)	1	10
Fiber, % (c_2)	1	4
Moisture, % (c_3)	8	13
Protein, % (c_4)	12	13

The restrictions of the model are defined based on the minimum and maximum amount of fat (F), fiber (B), moisture (M), and protein (P) that the balanced food must contain. The non-negativity of each variable in the model is also considered. The model equations are presented in (5, 6, 7, 8, 9, 10, 11, 12, 13).

$$Fx1 + Fx2 + Fx3 + Fx4 + Fx5 + Fx6 + Fx7 + Fx8 + Fx9 + Fx10 \geq c1\_min \quad [5]$$

$$Fx1 + Fx2 + Fx3 + Fx4 + Fx5 + Fx6 + Fx7 + Fx8 + Fx9 + Fx10 \leq c1\_max \quad [6]$$

$$Bx1 + Bx2 + Bx3 + Bx4 + Bx5 + Bx6 + Bx7 + Bx8 + Bx9 + Bx10 \geq c2\_min \quad [7]$$

$$Bx1 + Bx2 + Bx3 + Bx4 + Bx5 + Bx6 + Bx7 + Bx8 + Bx9 + Bx10 \leq c2\_max \quad [8]$$

$$Mx1 + Mx2 + Mx3 + Mx4 + Mx5 + Mx6 + Mx7 + Mx8 + Mx9 + Mx10 \geq c3\_min \quad [9]$$

$$Mx1 + Mx2 + Mx3 + Mx4 + Mx5 + Mx6 + Mx7 + Mx8 + Mx9 + Mx10 \leq c3\_max \quad [10]$$

$$Px1 + Px2 + Px3 + Px4 + Px5 + Px6 + Px7 + Px8 + Px9 + Px10 \geq c4\_min \quad [11]$$

$$Px1 + Px2 + Px3 + Px4 + Px5 + Px6 + Px7 + Px8 + Px9 + Px10 \leq c4\_max \quad [12]$$

$$xi \geq 0 \text{ for all } i \quad [13]$$

Table 3 - Composition of the raw material used in balancing for pig fattening.

Raw materials	OM	C	CW	PO	CC	CM	MP	RB	PSC	SF
Fat, %	4.4	3.0	1.0	99.0	0.0	0.0	0.0	14.7	6.8	1.3
Fiber, %	12.8	2.1	2.4	0.0	0.0	0.0	0.0	8.6	17.3	5.9
Moisture, %	9.5	13.6	11.5	0.0	2.0	27.4	2.0	10.2	8.4	12.1
Protein, %	9.9	7.3	10.2	0.0	0.0	4.3	0.0	13.6	15.6	44.0
Cost, $/kg	0.32	0.17	0.20	0.12	0.03	0.19	0.74	0.19	0.12	0.32

Where ci is the value of the restriction maximum (max) or minimum (min) of each variable considered in the nutritional composition of the pig feed.

Software used

To solve the proposed objective optimization problem RStudio version 4.1.2 was used, with the ROI and ompr libraries. The R Optimization Infrastructure (ROI) package provides an extensible infrastructure to model linear, quadratic, conic, and general nonlinear optimization problems in a consistent way [23]. The Model and Solve Mixed Integer Linear Programs (ompr) is solver independent and thus offers the possibility to solve a model with different solvers. It currently only supports linear constraints and objective functions [24].
The advantages of applying this software focus on the order of information presentation and the visualization of the processes that are carried out with R, all synchronously.

Sensitivity analysis

It is understood as the process by which changes are established that can result in the solution of a problem by varying some of its parameters or its structure [24]. Sensitivity analysis was applied to compensate for the deficit with the objective of satisfying the solution with the established priority structure and analyzing the values to investigate other solutions.

Results

Once the mathematical model was proposed for the optimization of the feed formulation for pigs, using the data described for this purpose (table 3), the objective function, goals, and restrictions are presented adding the variables s_i^+ and s_i^- as appropriate. These deviation variables are considered positive at all times, regardless of the sign of the goal.

Goals model

In the case of goal 1, which is to minimize, the variable s1− is added to the objective function (G). In the case of goal 2, it is expected to achieve that at least 25% of the protein is corn, the variables s2+ is added (14, 15).

$$\text{Min } G1 = s_1^{-} \qquad (14)$$

$$\text{Max } G2 = s_2^{+} \qquad (15)$$

Once the objective function is established (16, 17), the constraints that make up the model are described in equations (18, 19, 20, 21, 22, 23, 24, 25).

$$0.32x1 + 0.17x2 + 0.2x3 + 0.12x4 + 0.03x5 + 0.19x6 + 0.74x7 + 0.19x8 + 0.12x9 + 0.32x10 + s_1^{+} - s_1 = 0.25 \qquad (16)$$

$$x2 \leq 0.25*(x1 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10) + s_2^{+} - s_2^{-} = 0 \qquad (17)$$

$$0.044x1 + 0.03x2 + 0.01x3 + 0.99x4 + 0.147x8 + 0.068x9 + 0.013x10 \geq 0.01 \qquad (18)$$

$$0.044x1 + 0.03x2 + 0.01x3 + 0.99x4 + 0.147x8 + 0.068x9 + 0.013x10 \leq 0.1 \qquad (19)$$

$$0.128x1 + 0.021x2 + 0.024x3 + 0.086x8 + 0.173x9 + 0.059x10 \geq 0.01 \qquad (20)$$

$$0.128x1 + 0.021x2 + 0.024x3 + 0.086x8 + 0.173x9 + 0.059x10 \leq 0.04 \qquad (21)$$

$$0.095x1 + 0.136x2 + 0.115x3 + 0.02x5 + 0.274x6 + 0.02x7 + 0.102x8 + 0.084x9 + 0.121x10 \geq 0.08 \qquad (22)$$

$$0.095x1 + 0.136x2 + 0.115x3 + 0.02x5 + 0.274x6 + 0.02x7 + 0.102x8 + 0.084x9 + 0.121x10 \leq 0.13 \qquad (23)$$

$$0.099x1 + 0.073x2 + 0.102x3 + 0.043x6 + 0.136x8 + 0.156x9 + 0.44x10 \geq 0.12 \qquad (24)$$

$$0.099x1 + 0.073x2 + 0.102x3 + 0.043x6 + 0.136x8 + 0.156x9 + 0.44x10 \leq 0.13 \qquad (25)$$

Model solution

Once the proposed model was run, the optimal formulation of the balanced food was obtained to achieve the planned nutritional requirements and at the minimum cost (table 4).

Table 4 - Optimal formulation obtained

Variable	Value
x_1	0
x_2	0.243
x_3	0
x_4	8.67E-19

x_5	0.116
x_6	0.239
x_7	0.193
x_8	0
x_9	0
x_{10}	0.209
s_1^+	0
s_1^-	0
s_2^+	0.007
s_2^-	0

The following optimal formulation is obtained: corn (24.3%), calcium carbonate (11.60%), cane molasses (23.90%), monocalcium phosphate (19.3%), soybean concentrate (20.90%), and a negligible amount of oil palm.
The optimal solution of the mathematical model indicates that the variable s1−, entered into the mathematical model, is maximized, which poses a maximum food cost of $0.30/kg, and the sum of the variables xi results in 0.30$/kg. However, goal 2 is not met, where corn is expected to represent 25% of the protein formulation of the food.
It was observed that the deviations s1+ and s1− took a value of zero, which means that goal 1 exactly reached its aspiration level. In the case of s2+, it has a negative deviation of 0.007, which indicates that the percentage of corn established in the formulation was not reached.
The formulation obtained may be sensitive to changes in the event that variations are made in the limits of nutritional requirements, as well as in the prices of raw materials.

Sensitivity Analysis

Based on the fact that the corn content requirements are not met, a sensitivity analysis of the variation of the components was carried out, in order to determine if another mixture could be obtained that met the requirements.
The variation in the corn component [x2] was made by doubling its value, that is, going from 0.073 to 0.146. Table 5 analyzed how this change influenced the optimal solution.

Table 5 - Optimal formulation obtained.

Variable	Value
x_1	0
x_2	0.25
x_3	0
x_4	9.54E-5
x_5	0.272
x_6	0.484
x_7	0.244

x_8	0
x_9	0
x_{10}	0.185
s_1^+	0
s_1^-	0
s_2^+	0
s_2^-	0

With these values, we obtained: corn (25%), calcium carbonate (27.20%), cane molasses (48.4%), monocalcium phosphate (24.4%), soybean concentrate (18.5%) and a negligible amount of palm oil. In the optimal solution of the mathematical model, it was observed that the two resulting deviations of both s+ and s- for the established goals took a value of zero, which means that the goals exactly reached their aspiration level. The goal is also met if a lower protein limit equivalent to 11% is established.

Discussion

Cost is a relevant factor since some foods satisfy the nutritional demands of the pig without the need to invest significant amounts of money. In a related investigation, it was possible to formulate rations that allowed the pig to consume the necessary amount of food, significantly reducing the cost by 33%, equivalent to approximately $28.48 [26].

Within this context, Bernal et al. (2019) [15], consider that the use in the daily ration of sweet potato plus balanced feed constitutes an alternative in feeding pigs in the fattening and finishing stage due to the positive effect on weight increase and feed conversion, replacing 70% of the diet. However, its use is suggested in balanced conditions since there is little palatability for pork.

Most livestock producers look for optimal ways to feed their animals. Conventional algorithms are used for the optimal formulation of the feed at a minimum cost, satisfying the limitations related to the animal's nutritional requirements. This optimization process must be carried out every time nutritional requirements change. The availability of the entire set of solutions of an established mathematical model facilitates the understanding of the relationship between the different nutritional requirements and the corresponding cost [27].

The multiple objective programming model has been used in feed formulation to minimize nutrient variation and minimize ration cost. This model is more flexible than linear programming, providing a solution that handles multiple conflicting objectives simultaneously compared to the traditional linear programming approach, which can only handle one objective. The multiple objective programming model is an effective tool to assist decision making by solving a series of linear/nonlinear programs and interacting with decision makers [28].

In other cases, companies choose to carry out more in depth studies by taking samples at a certain time in order to obtain, in each portion of balanced food, the amount of each ingredient that the nutritionist considers necessary, based on the interpretation of variation coefficients [29].

Conclusions

1. The design, implementation, and construction of mathematical models consider aspects that allow finding an optimal solution to the problems that arise.

2. The goal programming model applied sought the fulfillment of two goals related to the reduction of costs and minimum quantity of one of the components used in the formulation of pork feed.
3. The equations developed sought to guarantee the adequate dosage of the raw materials used, to guarantee the nutritional requirements of pig fattening, and at the same time minimize feed costs. The result obtained indicates with s1+ and s1− equal to 0, the fulfillment of the goal related to cost reduction. The values obtained may vary if the restrictions or limits established in the formulation change.
4. Multi-objective programming can be applied to problems formulating financed pig diets to determine the planting of crops in areas that are required at the lowest cost and that at the same time cover nutritional needs.
5. It is proposed to apply the mathematical model to subsequent research, from a nutritional point of view, in order to determine the number of calories, proteins, carbohydrates, lysine, vitamins, liquids, among other nutritional elements of interest in animal feeding.

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