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Summary

Commercial feed formulation is typically based on linear programming (**LP**) algorithms that derive a least-cost solution for a blend of ingredients that meet specific nutrient criteria. This methodology has been effectively used for decades, but how we achieve our primary goal, which is sustainable poultry production, needs to be reconsidered in broader terms. Some of the issues that this paper will deal with are: not all parameters that we consider are linear and additive; we are still unsure of how to build the matrix required for feed formulation; dealing with the variability encountered in every batch of ingredient remains a challenge; the business model used for any poultry production system has a direct bearing on the formulation philosophy; the feed specification used for any formulation should be reconsidered as poultry genotypes evolve, or when commercial circumstances change; alternative ingredients and their impact on a system need to be evaluated, and last, as an industry, we will be obliged to formulate diets bearing sustainability in mind. This paper will outline how the formation system is central to successful broiler nutrition and offer suggestions on how to best deal with some of the shortcomings of LP.

Introduction

Feed formulation is how nutritionists apply their technical knowledge in practice. The realisation of how effectively linear programming (**LP**) can be used as a feed formulation tool is decades old (Fisher and Schruben,1953; Dent and Casey, 1967). Still, despite its practical importance, little on the topic has been published (Alhotan, 2021). To formulate poultry diets, some form of 'system' is required. These systems can be as simple as spreadsheet models, but formulations are typically executed using commercial feed formulation programs based on LP. Pesti and Alhotan (2014) believe that feed formulation advances follow nutrition advances. Instead, the advances in feed formulation systems have likely driven many of the advances in nutrition. This is because the exacting nature of the calculations required to formulate diets has been overcome, allowing for more complex solutions (more nutrients and variables) to be considered. The ease with which large databases can be managed and manipulated and the rapidity with which answers can be derived also allow for holistic modelling of feeding systems to be conducted. This has extended the formulation process from merely achieving nutritional adequacy to one which has become essential for the policies and strategies of poultry production businesses.

Typical feed formulation programs match the energy and nutrients in the available ingredients with a prescribed feed specification at the lowest cost. The selection of ingredients is based on ranking the cost-effectiveness of their nutrient and energy content, giving rise to what is known as the least-cost formulation. Thus, the cost and availability of feed ingredients and the determined energy and nutrient content play a central role in the ingredient content of any diet. A drawback of any formulation system is that each formulation represents a snapshot of the ingredient quality and pricing when the formulation was executed. Average or historical values are mainly used as the data source for feed formulation, a shortcoming that most nutritionists are acutely aware of.

Feed formulation software packages do only three things. They store and manage data, generally in a sequential database (**SQL**). Second, they carry out simple arithmetic based on the Simplex algorithm (Dantzig, 1951), which can be solved equally using pencil and paper (Dent and Casey, 1967). Last, they choose the cheapest possible blend of ingredients that meets the desired nutrient criteria. A feed formulation program is only a large calculator that can consider many variables simultaneously. Thus, any dietary solution produced is controlled entirely by the nutritionist, who decides which nutrients or energy system should be used and hence, what the dietary 'matrix' will look like. Nutritionists also decide on the limits of each ingredient's inclusion in the diet and take a view of the variability of the ingredients used. Further, a decision needs to be made about the diet's nutrient content (feed specifications), bearing in mind that the specifications used are circumstance unique.

There are several shortcomings in feed formulation methodologies. From a mathematical perspective, the data used in an LP system is assumed to be linear and additive, which is not true for many of the constraints we apply. Organisations must be profit-driven instead of cost-driven; a 'least-cost' system cannot achieve this goal. Formulation systems optimize a single variable (cost), but in the future, we will need to ensure that the diets formulated have the least environmental impact. Nutritionists must deal with the variability encountered in every batch of an ingredient, but an LP solution is based on a snapshot of a single moment in time. Lastly, formulation systems do not understand the impact of the diet on the end products (broiler carcass conformation, for example) being produced. The ethical aspects of animal feeding (feeding like to like) are not understood, nor is the commercial model used (integrated company or third-party miller).

One of the advantages of using feed formulation systems is that they are an excellent way to model a business, allowing for optimal ingredient purchasing decisions. These commercial aspects go beyond the remit of this paper, which will only deal with the more technical issues discussed above. However, the feed formulation system should lie at the heart of commercial decision-making. Many of the issues raised above overlap, and categorising the various aspects along rigid lines is often difficult. The reader is urged to consider each aspect discussed holistically.

Linearity and additivity

Mathematically, all the constraints used to formulate diets using LP are assumed to be linear and additive. Intuitively we know this not to be true. The measurement of feed density, for example, is not additive because small, dense particles can fit into the gaps between larger, less dense particles in a non-additive manner. Another well-known but mostly ignored example of non-linearity occurs when fat or oil is added to the diet. Low inclusion levels lead to the so-called 'extra-caloric effect', which describes the higher-than-expected energy yield from a small addition of fat. However, at higher levels of inclusion, the energy contribution of fat declines in a non-linear manner (Leeson and Summers, 2005; van der Klis et al., 2010). Another example of non-linearity that nutritionists confront is that the response to enzyme addition to a diet is not linear. The best-known example is phytase (Ravindran et al., 2000; Dersjant-Li et al., 2022).

The matrix

The feed formulation process begins with building a 'matrix' or table of energy and nutrient values for each feed ingredient. This is not straightforward. We are still unsure how best to describe and measure the energy component of the diet (or ingredient), as evidenced by the plethora of different energy systems in use. The metabolisable energy (**ME**) system is the most ubiquitous. Yet, despite the abundant research conducted on ME, the accuracy of determination is often questionable, and the methodology used in its determination is not well-defined (Mateos et al., 2019; Wu et al., 2020; Khalil et al., 2021). Table 1 shows how the comparative energy content of different ingredients varies depending on the energy system employed. Formulating diets using different energy systems leads to fundamentally different feeds, all purporting to provide the bird with the same amount of energy. The cost-effectiveness of the diets differs according to the energy system used and the relative ingredient prices, confirming that no single system offers any real advantage when formulating commercial diets (Kleyn and Ciacciariello, 2022). In an ideal world, the bird's energy requirements and the ingredients' energy content should be determined using the same energy system, but this may not occur in practice. For example, primary breeder standards are presented as AME, based on the WPSA system (Jansen, 1989), and these may not be applicable when using other energy systems. A further complication is that the energy content of a diet is a function of the bird consuming that diet rather than that of the diet itself. By illustration, a slow-growing broiler uses a larger proportion of consumed energy for maintenance purposes than a fast-growing broiler, resulting in a different dietary energy contribution.

Although the methods used to describe the diet's amino acid (**AA**) content and digestibility have been standardised (Ravindran et al., 2017), many nutritionists still formulate using crude protein as the basis of measurement for the protein quality of ingredients. Yet, we have known since the 1930s that true protein is a better measure (Jones, 1931; Alhotan and Pesti, 2016). Further, the manner in which we deal with minerals is confusing. Primarily P is described on an available or digestible basis (these measures are often used interchangeably in a bewildering manner), yet we steadfastly describe Ca in total terms. Considerable effort is being expended on the development of a usable digestible Ca system (David et al., 2021; Walk et al., 2021; Angel, 2022), and although the data being generated is less than perfect, we are now in a position to consider digestible Ca when formulating diets, allowing us to develop an understanding of the implications of the variability of Ca digestibility.

Table 1: Indexed energy values of ingredients relative to corn for each of five different energy systems used for formulating the diets of laying hens, together with the relative values of a typical diet (after Kleyn, 2023)

	Energy system				
Feed ingredient (g/kg)	**AME_n**	**INRAE**	**Brazil**	**CVB**	**NE**
Yellow corn 7.1%	100	100	100	100	100
Wheat middlings 15%	56	52	57	59	54
Soya bean meal 46%	72	73	73	66	58
Extruded fat soy 36%	104	108	102	107	104
Sunflower meal 35.5%	56	50	56	46	46
Soya oil	255	288	259	310	322
Value relative to AME_n	100	94	101	98	78

AMEn: Apparent metabolisable energy corrected for zero nitrogen retention; INRAE: Institut national de la recherche agronomique; Brazil: *Brazilian Tables for Poultry and Swine*; CVB: Centraal Veevoederbureau; NE: Net energy

Another downfall is that many nutritionists use the same values for their ingredients that they have always done (a fixed matrix). These values may have been developed within companies or could be average values from reference tables. Often, a matrix is sold as a part of a feed formulation program for demonstration purposes, and remarkably, these values are used to formulate diets implemented in practice. This static approach is not the best management practice as it ignores variability, source and ingredient evolution, as our ingredients change over time (Jones et al., 2010; Medic et al., 2014), and even simple issues such as the moisture content of each ingredient. There is a change in the available protein and energy with every change in an ingredient's nutrient profile; strictly speaking, levels should always be adjusted for these differences.

Dealing with variability

Variability is a significant issue in feed manufacture and can be defined as the opposite of uniformity. Ingredient variability accounts for 20 – 25 % of finished product variability. This increases to 80 – 85% when weighing, batch sizes and sampling/analytical errors are considered (Fawcett et al., 1992). Variability is multiplicative and not additive, meaning minor improvements in one area can make an enormous difference in overall variability. Although hard to measure, simple formulation and logistic errors should also be included as a source of possible variability.

Practically, the major constraint when formulating diets is that the nutritionist needs to know the energy and nutrient content and the expected variability of the ingredients entering the feed mill. Thus, there is a need for real-time determination of ingredients' energy and nutrient content before they are unloaded and used. Rapid methods for measuring the nutrient content of ingredients are of great value. Near-infrared spectroscopy (**NIR**) represents an exciting alternative to wet chemistry for the feed industry (Hughes et al., 2018; Alhotan, 2021). It provides a quick, non-destructive, and quantitative analysis of the organic constituents of plant and animal material. Near-infrared reflectance spectra depend on the number and type of C-H, N-H and O-H bonds in the material analysed. The accuracy of NIR depends on the quality of the NIR database used in the prediction. This depends on the number and diversity of the samples it includes (Soto et al., 2013). Predicting AA digestibility of disparate batches of ingredients remains a challenge, and whilst predictions are commercially available, the provenance of these measurements is not disclosed and is unlikely to arise from methodologically uniform experiments (Siegert, 2023). Regardless of the shortcomings of NIR analysis, the speed at which results can be obtained has made feed mill quality control programs more effective by several orders of magnitude. Unfortunately, most feed mills cannot retain the identity of disparate batches of ingredients or use them as such, as different ingredient deliveries are mostly stored in a single bin, bunker, or silo. This means that much of the careful variability monitoring is undone by the real world.

Using in-line NIR systems that can determine ingredients' nutrient and energy content as they enter the weigh hopper (FOSS, 2021), coupled with on-the-fly adjustments to feed formulations, offers a means of overcoming normal variability and the mill's inability to preserve ingredient identity (Siegert, 2023). The downside of automated feed formulation is that the feed specification remains static, and a nutritionist may not review formulae before they are implemented. Also, production costs may change hourly, which can create commercial difficulties. A more significant issue is that formulations change in what may appear to be a random manner, making inventory management and control very challenging. Indeed, emergency formulations in the face of stock outages probably introduce more variation from the bird's perceptive than moderate changes in the dietary protein do. For example, the sudden inclusion of an ingredient like sunflower (or its removal, for that matter) may result in feed refusal in breeder hens and broilers.

Understanding the business model

The goal of any commercial venture is to make a profit. Hence, it is essential that the profit of an operation, in this case, poultry feeding, is quantified. Within our industry, there are three clearly defined business models. Agribusiness is characterised by a high level of vertical control in what is broadly called 'integration', a strategy known to resist input and output price shocks (Kryger et al., 2010; Narrod et al., 2012). Most of the poultry meat sold is produced by integrators, whose goal is to produce products that maximise return over the entire supply chain. Here the nutritionist has to strive to maximize the margin over the fixed and variable costs. On the other hand, independent feed millers aim to maximize return per ton of feed sold. This requires a strict least-cost approach and a high degree of commercial awareness. A delicate balance between the selling price and margin needs to be maintained to remain competitive. Lastly, approximately 2.5 billion of the global population rely on small farms for their livelihood (FAO, 2013). These subsistence farmers mainly depend on local inputs for animal feed, fertiliser, and water (rainfall). In this instance, nutritional adequacy, rather than feed cost, tends to be the primary goal of the nutritionist.

Some independent feed millers enter into agreements with poultry producers and form what is known as a virtual integration, where all parties have access to the necessary information. In addition, many organisations may occupy all three of the spaces set out above. This may blur any distinctions between the business model used.

Feed formulation software is at the heart of all business models. Profit-maximising techniques may be more appropriate for integrators than the traditional LP formulations used by third-party feed millers (Kleyn and Gous, 1988; Guevara, 2004; Moss et al., 2021; Alhotan, 2021; EFG Software, 2023). Independent feed millers need to choose a nutrient density similar to that used by their competitors so that pricing can be competitive, and then use least-cost formulation to minimize costs while maintaining their sales margins. When formulating diets and feeding systems for smallholders, the nutritionist must be aware that ingredient quality can be variable, and a more conservative approach may be required.

The nutritionist must control and direct the best strategy in all business cases. The crucial decision revolves around determining the correct nutrient density and the correct assessment of ingredient quality. The data required to make these decisions may be limited in many cases.

Feed specifications

Many nutritionists consider the guidelines published in familiar tables (Aviagen, 2022; Cobb, 2022; Hy-Line, 2022) as 'ideal' requirements. While these data can be described as adequate, expecting any organisation to produce a single set of standardised recommendations for use in multiple management systems under many economic circumstances is unrealistic. The objective of commercial nutritionists is to decide upon a feed specification that fulfils the biological requirements of the bird, such that economic or commercial objectives are also achieved. To all intents and purposes, this entails selecting the optimal dietary protein and energy levels appropriate for each circumstance.

Modern broiler genotypes respond more strongly to balanced protein than energy (Aviagen, 2022). Although modern layer genotypes now produce more eggs in each laying cycle, they are somewhat lighter and produce smaller eggs than their historical counterparts. However, they still lay a single egg daily. Thus, their underlying daily nutrient requirements will have reduced slightly. Management systems have changed, impacting feed intake, which means that feed specifications may need to be revised depending on the management system employed.

The availability and relative cost of ingredients and the product's (meat or eggs) value are the essential drivers when determining diets' protein and energy content. These values can differ widely. For example, in some countries, little or no fat can be added to broiler diets. This makes it impossible to use diets with high energy levels and limits the 'space' in the diet for protein. As a result of this, low-density diets are the norm. In situations where broilers are sold live (wet markets), there is no incentive to produce broilers with large breast muscles, and in general, the balanced protein content of diets in such markets is lower.

More latitude exists when designing diets for laying hens because these birds can largely adjust feed intake to meet their energy and protein requirements (Kleyn, 2023). For example, if wheat bran is cheap and plentiful, it may be cost-effective to feed low-density diets, even if the hens consume more feed. The primary determinant of dietary protein in layer diets is the value of egg output. Egg size is determined to some extent by the intake of balanced protein, although modern genotypes tend to be less responsive to egg size manipulation by nutritional means (Hy-Line, 2018; Kleyn, 2023). Where ungraded eggs are sold, it makes little sense to feed high-protein diets. Using high-protein diets is sensible when a premium is paid for large eggs. This is reflected in the latest Hy-Line recommendations, which include diets for maximum output and economic output (Hy-Line, 2022).

To make the profit-maximising decisions described above, it is essential that nutritionists have response data available. Several factors complicate this. Rapid genetic progress within breeds means any response data will require periodic re-evaluation (Classen, 2013). As Kidd and Loar (2021) point out, the rate of change in our industry is such that it exceeds the science required from research to support emerging management practices. Environmental conditions, including temperature, ventilation rate, stocking density, litter quality, access to water, feeding systems, disease status and lighting programmes, all impact feed intake and immunological status and thus, the chickens' production level. These factors all impact the responses to energy and protein, limiting the usefulness of data determined in an experimental setting in commercial operations. For this reason, simulation modelling, which attempts to create response data from first principles, is becoming far more widely used (Alhotan, 2021; Moss et al., 2021; EFG Software, 2023).

Alternative ingredients

One of the benefits of using an LP feed formulation system is that it is possible to investigate the use of alternative ingredients in a structured manner. Linear programming ascribes a relative value to the ingredient being evaluated. The value of any ingredient is determined by several factors: the nutrient and energy content of the ingredient itself, the price and availability of the other ingredients to hand, and the diet in which the ingredient is to be used.

The business model plays a role in deciding which alternative ingredient should be purchased. For example, dried distillers' grains with solubles (**DDGS**) is a low-density ingredient. It is often attractive to independent feed millers as it can reduce the feed price. However, where high-density diets are in use, as with many integrators, DDGS may not be attractive unless the diet's nutrient density is reduced. Reducing nutrient density may harm performance and the margin over feed cost. Thus, the evaluation of ingredients should always be carried out bearing bird performance in mind, which cannot be achieved when a single feed specification is used. As discussed above, some form of response data or simulation modelling is always required for the meaningful evaluation of an ingredient.

It is worth pointing out that using alternative ingredients may be fraught with risk. Often the quantities available are limited, and these small parcels can vary in protein and energy content. Nutritionists cannot be sure how much of an ingredient can be included in the diet to preserve bird health and product quality. In addition, often, not enough analytical data of relevant to poultry nutritionists are available. For example, AME or digestible AA values are simply undetermined.

Sustainability

The overarching consideration for agriculture should be sustainability. The definition of sustainability is straightforward – *sustainable systems should meet the needs of the current generation without compromising the ability of future generations to meet their own needs* (Brundtland Commission, 1987). Sustainability is a concept with multiple facets, including environmental (demand for resources and potential for environmental pollution); ethical (welfare of man and his animals); economic robustness; and enactment or enforcement, which describes the legal and social frameworks required to achieve sustainable goals (FAO, 2012). Nutrition of farmed animals is central to all aspects of sustainability, and opportunities exist to improve sustainability through changes in feeding strategy.

As discussed above, deciding which protein and energy levels should be used in a diet is mostly economic. However, economic evaluation *per se* does not indicate whether a feeding system is sustainable. Research explicitly addressing the environmental impact of different feeding strategies on poultry production is still uncommon. However, there are two areas of concern: the use of nutrients, of which N and P are likely the most important, and emissions from poultry production (Lemme, 2023). The second area of concern is the environmental impact of using specific ingredients or sources of ingredients in feed formulation.

The ingredients used to manufacture poultry diets are a vital aspect of sustainability. The demand for resources is relevant to poultry production because nearly all feed offered to commercial chickens originates from commercial cropping. Modern farming has produced higher yields but demands higher inputs of land, water, fertilisers, pesticides, and fossil fuel, all of which place pressure on scarce resources and result in air, water, and soil pollution. The dilemma is that agriculture's extensive use of land and water harms the environment and biodiversity. Life-cycle analysis (LCA) has become the *de facto* standard to measure the impact of a system on sustainability. LCA uses a holistic approach that can aid in mitigating the adverse impacts of animal production (Benavides et al., 2020). Land-use change (**LUC**) describes the agricultural system from whence an ingredient is produced. Deforestation has an enormous impact, whereas the re-deployment of 'set aside' land minimises the carbon footprint (Cappelaere et al., 2021). Production methods such as precision farming and no-till conservation tillage play a role in reducing inputs (INRAE, 2023). The cultivars used in the production of feed crops affect both production efficiency and the size of the carbon footprint. Genetically modified crops facilitate conservation tillage practices that help to control soil erosion, conserve soil moisture, support carbon sequestration, decrease GHG emissions, reduce pesticide spraying, and increase yields by about 16% (Van Acker et al., 2017; Brooks and Barfoot, 2020).

A final consideration is an unwritten rule that *the more a product costs, the higher its carbon footprint will likely be*. It is logical that the price of an ingredient reflects the energy required to produce it. Both the GFLI (2022) database and the INRAE-CIRAD-AFZ (2023) feed tables carry data based on LCA, suitable for use in least-cost formulation systems. These data enable nutritionists to determine the environmental impact of diet formulation and animal production (Kleyn, 2023). However, to do this effectively, it is essential to know the source and origin of each parcel of ingredient. Both the distance from the source and the level of deforestation impact the carbon footprint (climate change potential). It is important to note that carbon footprint is only one of the six parameters evaluated. The others are phosphorus consumption, cumulative energy demand, acidification, eutrophication, and land competition (INRAE, 2023).

Different poultry production systems have different levels of sustainability because they have different carbon footprints and land use demands (Williams, 2009), with more extensive systems tending towards larger environmental impacts. In laying hens, diets low in energy and balanced protein resulted in the lowest footprint per gram of egg produced (Kleyn, 2023), yet most affluent consumers demand Extra-Large and Jumbo eggs. Not surprisingly, improved FCR in broiler production results in a lower carbon footprint (Chrystal et al., 2021).

The justification for reducing dietary protein levels is compelling (Greenhalgh et al., 2020). Reduced CP diets are fed to poultry by applying enhanced ideal AA profiles and employing an ever-widening range of free AA. Free AA has a high environmental footprint (Benavides et al., 2020; Siegert, 2023), so this approach ceases to be helpful at some point. Lower CP diets should yield similar technical performance, improved protein digestibility, reduced water intake, reduced manure nitrogen, and better bird welfare (Belloir et al., 2017; Chrystal et al., 2020; Lemme, 2023; Siegert, 2023). Lowering dietary CP by 1% reduces the carbon footprint of broiler production by 102 kg/ton of broiler produced (Martin, 2020). Selle et al. (2023) have calculated that if exogenous phytase were used correctly in all poultry diets, inorganic phosphate use would decrease by about 3 mil tons per annum. This is the equivalent of about 4.2 mil tons of CO_2 equivalent (INRAE, 2023).

New or alternative ingredients are a potential means of driving the environmental component of the sustainability of feeding poultry down. However, a complete LCA on each alternative ingredient will be required before claims in this regard are made. The use of alternative ingredients should not be at the expense of other aspects of sustainability, such as economic robustness. If locally produced ingredients replaced imported materials, a significant reduction in the carbon footprint of animal products can be realised, which is why smallholder farmers may well be able to produce poultry more sustainably than commercial agriculture.

Conclusion

Linear programming is a fast, simple, effective, and accurate means of calculating nutritionally adequate poultry diets. Despite its known shortcomings, it is a far better methodology than any system that preceded it. Although alternative profit-maximising algorithms for formulating feed exist, they are often cumbersome, so LP is unlikely to be replaced in the foreseeable future. At this stage, there is uncertainty about how artificial intelligence will impact decision-making in technical fields such as poultry nutrition. Still, it will likely become another decision-making tool in the nutritionist's arsenal.

Nutritionists need to be aware of the shortcomings of LP and place themselves at the centre of the decision-making process and not expect software to think for them. The mere use of a feed formulation system does not qualify one as a nutritionist, any more than the use of book-keeping software makes us accountants. A fair degree of modelling, post-formulation evaluation, and iterative formulation steps are required to achieve optimal diets.

Several decisions need to be made before the formulation process begins. These would include how the matrix is built and modified in accordance with ingredient variability. Feed specifications need to be set to meet the economic objectives of the company, only using the primary breeder specifications as an educated starting point. Lastly, we will need to be aware that the carbon footprint of the diets we formulate will come under scrutiny, and it is best to start thinking about these aspects sooner rather than later.

Sustainability is not a lofty goal. Instead, it should be seen as central to all agricultural endeavours. These authors believe that sustainability should be the principal objective of any poultry producer. Not only will a sustainable approach focus on maximising financial returns, but it will also have positive outcomes for the environment and ethical considerations.

The manner we produce and feed chickens will come under intense scrutiny. However, many of the current, perhaps less sustainable trends, are driven by consumer pressure. Thus, sustainability will only be achieved if all role players in the poultry supply chain (including the consumer) are mindful of the impact of their own decisions and choices.

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