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Resource allocation in pastoral dairy production systems: Evaluating exact and genetic algorithms approaches

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ABSTRACT

The problem of food resources allocation to a heterogeneous dairy herd was studied in this paper. We focused on how to allocate available resources by grouping cows and their subsequent distribution in the field (pasture and/or feeding area). The main goal of this paper was to maximize either milk production or the margin over feeding cost for the entire dairy herd. The input of energy from different feed resources and the animal requirements of energy were considered. A mathematical model and a Genetic Algorithm (GA) were programmed. An experimental evaluation was performed in order to analyze the quality solution of the GA and to study how the resource allocation should be performed by interpreting the solutions' structure for both methods. The diversity of the solutions provided by the GA was also studied. The experimental evaluation showed that the gap values (milk production difference) between the GA and the Exact Method (EM) solutions were smaller than 2%. Also, when food resources were scarce, there was a great difference (almost a 50% difference for a herd of 1500 cows) between the GA and the EM solutions' structure. The results showed that values obtained by the GA were very close to the values obtained by the exact method, but generating different assignment structures, presenting a good diversity and a wider exploration of the solutions' space.

1. Introduction

The agricultural industry is one of the most important sectors of the Uruguayan economy. In particular, the dairy industry represents 9.3% of the gross value of agricultural production, ranking third after beef and rice (Yavuz et al., 2010).

The Uruguayan area dedicated to dairy production is estimated in 857,000 ha (Uruguay, 2012). The dairy production exceeds 1800 million liters per year (Freiría and Hernández, 2010; Yavuz et al., 2010), being Uruguay the largest milk producer per capita in Latin America with about 550 l, and having one of the highest consumption rates in the world exceeding 250 l/person (Freiría and Martin, 2014). The export ratio is about 61.2% of total production, and is exposed to the volatility of the international market for dairy products (Freiría and Hernández, 2010).

Because of the importance of the dairy industry for the Uruguayan economy, the complexity of the dairy management systems and the increase of the intensification process (Chilibroste, 2011), it is of highly interest to study problems related to dairy systems using an operational research focus to enrich traditional agronomy approaches. Particularly, in this paper we address the problem of food resources allocation in pastoral based dairy systems.

The dairy production system in Uruguay is defined as a pastoral system with supplementation (Chilibroste et al., 2012). The feed supply structure is defined by pasture directly grazed by cows, conserved forage and concentrates. Concentrates are resources that can be easily purchased in the market. Food demands at a given time are defined by the number of milking cows and their characteristics, particularly their potential for milk production, based on their body weight, days in milk, and potential food consumption. In Uruguay, cows are milked twice a day which implies animals round movement from the feeding area to the milking parlor. The feeding area can be a grazing plot or a feeding place, where cows receive the available supplements that will be described later. The feeding places are located close to the milking parlor.

The food resource allocation to a dairy herd consists in determining how to distribute the available resources in order to maximize dairy production or the economic benefit (we refer to economic benefit as the margin over feeding cost for the entire system). Those resources are different food types located in field areas and associated with a certain availability of dry matter (DM)[1] and energy, that must be allocated to different types of cows, therefore we need to determine how to

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[1] The dry matter is the remaining part of a material after removing all the water possible.

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distribute each cow (for feeding purposes) considering their characteristics. In other words, we need to group the cows and distribute them into different feeding areas. The solution to the problem involves having as many groups of cows as existing feeding areas. Many combinations can be done to assign those cows to existing resources, but some solutions are better than others. This allocation process is usually based on the experience, intuition (and even traditions) of the producers, following some management rules considering parity, days in milk, actual milk production, among others. However, this problem is difficult to solve when the problem size increases and/or when resources are scarce.

The application of Operational Research (OR) in agriculture has been extensive and varied (Weintraub and Romero, 2006). However the literature review performed has shown that this study is original, specially considering how the problem have been addressed. One of the first successful mathematical programming applications in agriculture was proposed by (Waugh, 1951), who used linear programming models to determine the minimum cost of the livestock ration. The nutritional requirements were fulfilled. Since then (early 1950s), many farmers have relied on linear programming for an optimal design of cattle diets (Weintraub and Romero, 2006). Years later, a model considering the ingredients prices was studied in order to find the optimal mixing food. To address this problem various multiple criteria models have been formulated (e.g. (Czyzak and Slowinski, 1990; Neal et al., 1986; Rehman and Romero, 1984; Zhang and Roush, 2002)). These models involve different types of food to feed cows, including grass species that can be grazed directly, but also species that must be harvested mechanically, which adds an additional cost. (Neal et al., 2007) addressed the problem of determining the most cost-effective combination of forage species by developing a linear programming model. All these previous works focused on optimizing different aspects of dairy systems, but the main difference with our work is that they developed models to find solutions without considering differences for food allocation or animal groups. This is the significant contribution of this research (in addition to the methods evaluated).

In another line of work, (Anderson and Ridler, 2010) presented a model that incorporates the economic relationships of production factors on a 100 ha pastoral system. Linear programming was used in order to optimize the economic benefit, considering some limitations such as average milk production, the herd replacement rate, cows' death rate and the maximum number of lactations per cow. Total and individual milk production is also an area where operational research techniques have been used. (Dean et al., 1972) analyzed the possibilities of increasing the efficiency and profitability of milk production per cow. In their work, production functions and linear programming models were combined to develop a computer system capable of providing feeding programs that optimize feeding dairy cattle. (Ridler et al., 2001) used a linear programming model to integrate individual components of a pasture based system, with the objective of implementing a unique economic model to maximize farm profitability. The papers mentioned above include different aspects of the dairy systems, but an important difference with our proposal (apart from how the herd is handled) is the definition of the model. Some previous work define the milk production as a constant and then determine the livestock ration in order to maximize the economic benefit. We maximized the economic benefit by allocating the available resources to then obtain the total milk production as an output.

A different problem that includes optimization models in dairy systems is the study of the optimal replacement for dairy cows. Considering that milk production depends on several factors that vary over time, the objective of this problem was to determine the optimum replacement policy for dairy herds keeping total milk production relatively constant. (Kalantari et al., 2010) tackled this problem using dynamic programming. Later, (Doole et al., 2012, 2013) introduced a nonlinear programming model that incorporates several important processes in pastoral dairy production system. Finally, (Doole and Romera, 2013) incorporated major biophysical processes to their management model for pastoral systems that uses a nonlinear optimization model. Through an empirical application, advantages and disadvantages obtained by the use of a high stocking were discussed. There is a great difference between the models reviewed and our proposal. In some cases because they perform an optimization in an annual basis and they considered a fixed-size cattle with predetermined characteristics.

In general, the problems mentioned above did not consider the animal grouping and did not differentiate how cows of different types were fed.

The main goal of this work was to determine how to allocate the available resources (by considering the entire herd and distributing the cows into the different food types) in order to maximize dairy production or the economic benefit. The problem of food resources allocation to a heterogeneous dairy herd was studied and modeled as a combinatorial optimization problem. Because of the inherent difficulty, large-scale combinatorial optimization problems usually cannot be solved with traditional exact approaches. In this context, several metaheuristics have been applied to obtain good quality approximate solutions in a reasonable execution time. Genetic Algorithms (GA) (Goldberg, 1989; Talbi, 2009), which belong to the Evolutionary Algorithm family (Bäck, 1996), have proven to be flexible and robust methods for effectively solve complex optimization problems. For these reasons, a GA tailored for the food allocation problem was also developed and included in the experimental study. Once the resource allocation results were obtained, we studied the allocation by interpreting the solutions' structure. We also analyzed the quality of the solutions obtained by the GA and studied the diversity of these solutions.

2. Materials and methods

The problem was presented in terms of supply and demand. The supply structure was defined by the availability of food resources, while the demand structure was defined by the energy required by the herd (based on the nutrient requirements of dairy cattle as published by the NRC (National Research Council, 2001)). The resource allocation model allows to group animals and move the cattle to a set of known field areas (pastures and/or feeding places). Considering each pasture activity or food type available for each feeding place, and depending on the different conditions presented by each animal to produce milk, the goal was to find a resource allocation by grouping cows and distributing these groups to the feeding areas, that maximizes the total milk production or the economic benefit.

2.1. Milk production model

The most important food supply of Uruguayan dairy production systems are pastures, which are located in different zones and are differentiated by the distance to the milking parlor and the herbage characteristics like mass (measured in kilograms of dry matter per hectare, kg DM/ha), energy density (measured like the net energy megacalories per lactation per kilogram of dry matter, Mcal ENL/kg DM[2]) and cost (measured in United States dollars per ton of dry matter, US dollars/ton DM). In this work, the available pastures were considered as a finite resource, and could only be used once. Returning to the same pasture was not considered an option and therefore, the rate of regrowth was not contemplated. We also considered different types of conserved forage and concentrates that differ in their energy density, availability and costs.

Food demand was determined by the specific features of each cow. Let i correspond to an arbitrary identification assigned to each cow, where $i = 1, \ldots, M$ (M is the considered number of cows). The specific features of each cow have the following attributes: body weight (*bw*,

[2] One calorie is equal to 4.184 joules.