Optimization in the Selection of Sugarcane Varieties in a Sucro Energy Plant Located in the State of São Paulo, Brazil

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Abstract: Sugarcane crops have undergone several changes with the intensification of agricultural machinery in Brazil in the last years. This occurs, mainly, due to the transfer of the semi-mechanized system to the mechanized one during harvest operations. Thus, studies are needed on the optimization of sugarcane production in relation to mechanized processes, since it is necessary to verify the adaptability of sugarcane varieties to the mechanization of the plantation. This study aimed to develop and apply a mathematical model of optimization to select sugarcane varieties that maximize production and meet the quality standards required by the industry for sugar and fiber contents. The data were collected in a sugarcane mill located in the interior of So Paulo state. The result obtained by the optimization process evinced an increase of 16.65% when compared to the productivity of the initial scenario.

Key words: Integer linear programming, mathematical model, mechanization, operational efficiency, sugarcane culture.

1. Introduction

Sugarcane is the main raw material for the production of sugar and ethanol in Brazil, besides being one of the most traditional and important agricultural crops in the country. The accumulated Brazilian production resulted in 651,841 thousand tons in 2016/2017 harvest [1].

The state of So Paulo is the largest producer in the country and responsible for about 60% of the production of its main derivatives: ethanol and sugar. Regarding sugarcane, the state's production equals 83% of the world's second largest producer, India. This represents a larger production than the other four major world producers combined, namely China, Thailand, Pakistan and Mexico [2].

The harvesting system used was semi-mechanized a short time ago, with the previous burning of

sugarcane, manual cutting and loading of the entire sugarcane by means of machines. However, the harvesting system has undergone many changes in recent years, with the transfer of the semi-mechanized system to the mechanized one. Self-propelled harvesters are used in the mechanized system, which are responsible for cutting, cleaning and transferring sugarcane to transshipment vehicles or directly to transportation vehicles, such as trucks.

This change has occurred for a number of factors, such as cost and supply of manual harvesting labor reduction, and especially the agri-environmental protocol proposed by the sugarcane industry association (Unio da Indstria de Cana-de-aar—UNICA), in partnership with the government of So Paulo, signed in 2007. The agreement aimed to anticipate, in lands with slope up to 12%, the deadline for eliminating sugarcane burning from 2021 to 2014. For lands with slope larger than 12%, considered to be non-mechanizable, the

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deadline has changed from 2031 to 2017. As a result, adherence to the cooperation protocol gives producers an Agri-environmental Compliance Certificate, which provides important advantages in the certification of their products for export [3].

However, the effects of traffic on agricultural areas are frequently reported [4], and they point out that the roots of the majority of plant species are unable to penetrate deeper in the profile when there is compaction in the topsoil. Both the use and the intensity of trafficking, as it causes the process of compaction, are the variables that should be taken into consideration [5].

The heavy traffic of the machines in areas that were not properly systematized causes the trampling of the sugarcane rows resulting in loss of vigor, failure, as well as in the lower development and population of the plants in the subsequent harvests, due to the damage caused to the sugarcane ratoon [6].

Technological advances play an important role in the development of sugarcane crop. The genetic improvement of the plant, associated with better management practices, is responsible for an increase in productivity of 0.43 t/ha per year [7].

Recent studies have been carried out to analyze the factors that affect the productivity of the sugarcane crop. Moraes *et al.* [8] observed the interference of different types of soil preparation and planting system on the agronomic characteristics and sugarcane productivity. Silva *et al.* [9] verified the productivity and technological quality of sugarcane in two agricultural crops, cane plant and cane ratoon, under the influence of organic and mineral fertilization sources.

There are many variables for the choice of varieties to be planted, such as adaptability to mechanized processes, maturation, root sprouting, productivity (t/ha and total recoverable sugar (TRS) kg/ha), technological characteristics required by industry as sucrose (percentage of oligosaccharides-POL) and fiber content, as well as its adaptation to the

production environment [10].

The standard sugarcane, in technological and economic conditions of industrial processing, should present sucrose content (sugarcane POL) of approximately 12.5%. Lavanholi [11] also describes that fiber levels of sugarcane stalks should be in the range of 8%-14%.

Varieties are considered very productive when sugarcane POL is higher than 14%, average production between 12.5% and 14%, and are considered little productive when POL is lower than 12.5% [12].

The mechanization of sugarcane plants in their agricultural activities demands mechanisms of data quantitative analysis for monitoring of crop productivity, since it is necessary to verify the adaptability of sugarcane varieties with mechanization.

This study aimed to propose and apply a mathematical optimization model to select sugarcane varieties that maximize production and meet the quality standards required by the industry regarding sugar and fiber contents.

2. Materials and Methods

The data used in this study were made available by a sugarcane mill located in São Paulo state, referring to a growing area located in the geographical coordinates of latitude 22°32'40.67" S and longitude 48°34'11.79" W. The climate of the region is Cfa type (Method of Köppen): hot temperate climate, mesothermic, humid and with average annual temperature of 21 °C [13]. Therefore, this work is characterized as a case study.

In 2011, this property presented a harvested area of 400.17 ha and in this site both the harvesting and the sugarcane loading without previous burning in 12 lots were performed through a mechanized system. At the site there were eight varieties of sugarcane arranged in 10 lots and two additional lots in which the varieties were planted in unspecified proportions.

An initial scenario was determined, in which data on the average productivity (t/ha), fiber (%) and POL (%) were used for the first four years of the analyzed lots from 2008 to 2011. With this information, the average production in the period was estimated.

There is a significant variation in the productivity and technological quality of sugarcane varieties in the first four years of harvest, which are directly influenced by the harvesting system used [14]. The sugarcane analyses of fiber (%) and POL (%) were carried out by the laboratory of the plant. Thus, documentary surveys were conducted in the company databases.

In order to solve the proposed mathematical model, the average of the productivity indicators (t/ha), fiber (%) and POL (%) of 25 sugarcane varieties from the first to the fourth harvest were used, which were also harvested under mechanized processes by the sugarcane mill in the period from 2008 to 2011. In this set of data, the eight varieties described in the initial scenario were also included.

These sugarcane varieties were the most used by the mill in its properties located around the plant, where the area studied is also located. This dataset was used so that the optimization process could be carried out with the use of real data, which portrays the daily agricultural activities of the analyzed plant.

Considering the practical importance of data evaluation of this nature and the exploratory nature of this study, the analytical procedures can be used, as long as the conclusions are restricted to the analyzed dataset.

The mathematical model used to maximize sugarcane production is now presented. Let n be the number of sugarcane varieties adaptable to the local environment and let k be the number of lots available for planting. It is desired to determine the variety i , $i = 1, \dots, n$, to be planted in lot j , $j = 1, \dots, k$, in order to maximize the sugarcane total production, respecting the limits of fiber and POL established by

the plant.

The mathematical model is:

$$\text{Maximize } \sum_{i=1}^n \sum_{j=1}^k S_i L_j X_{ij} \quad (1)$$

$$\text{Subject to } \sum_{i=1}^n \sum_{j=1}^k A_i L_j X_{ij} \geq \bar{A} \sum_{j=1}^k L_j \quad (2)$$

$$\bar{F}_l \sum_{j=1}^k L_j \leq \sum_{i=1}^n \sum_{j=1}^k F_i L_j X_{ij} \leq \bar{F}_s \sum_{j=1}^k L_j \quad (3)$$

$$\sum_{j=1}^k L_j X_{ij} \leq \bar{L} \sum_{j=1}^k L_j \quad i = 1, \dots, n \quad (4)$$

$$\sum_{i=1}^n X_{ij} = 1 \quad j = 1, \dots, k \quad (5)$$

$$X_{ij} \in \{0,1\} \quad i = 1, \dots, n, \quad j = 1, \dots, k \quad (6)$$

The decision variables X_{ij} are binary: $X_{ij} = 1$ indicates that variety i will be planted in lot j , and $X_{ij} = 0$ indicates otherwise. The coefficients of the objective function (1) are the products $S_i L_j$, where S_i is the sugarcane productivity of the variety i , in t/ha, and L_j is the area of lot j , in ha.

In restriction (2), A_i is the POL of the variety i . This restriction ensures that the average amount of POL produced is greater than or equal to a predetermined quantity $\bar{A}$, here established at 12.5% [11].

In restriction (3), F_i is the fiber percentage of variety i , and the restriction ensures that the total percentage of the harvest is between a lower limit $\bar{F}_l$, and a higher limit $\bar{F}_s$, set at 8% and 14%, respectively. According to Lavanholi [11], sugarcane is considered mature in this range of percentage, according to its chemical composition.

Constraints (4) limit the percentage $\bar{L}$ of the total area that can be planted with only one sugarcane variety. In this study, $\bar{L} = 15\%$ was used, according to MAPA [15], to minimize the risks of disease infestations in the sugarcane crop.

Constraints (5) impose that exactly one variety of

sugarcane should be planted in each lot and restriction (6) defines the domain of the variables.

The proposed mathematical model was solved using Gurobi 7.0.1 software on a computer with Intel i5 CPU 2.67 GHz and 4 GB RAM.

3. Results and Discussion

An initial scenario was designed for the analyzed area where the averages from the 1st to 4th harvest of the technological indicators analyzed were considered. Thus, an average production of 38,930.69 t of sugarcane was determined in an area of 400.17 ha, with a total productivity of 97.3 t/ha, as shown in Table 1. At this site, eight varieties of sugarcane distributed in twelve lots were planted. In lots 11 and 12, several varieties of sugarcane were planted in unspecified proportions.

Table 2 shows the averages of the analyzed variables. The number of samples (y) corresponds to the number of lots where the varieties were planted in owned and leased areas of the studied company.

For the selection of the most productive varieties, the ones harvested in the area analyzed in the 2011 crop were also included. However, the

“miscellaneous” option, described in the initial scenario, was not considered because there is no way to reproduce exactly the same planting in the next crops, since several varieties were planted in unspecified proportions in these lots.

For the optimized scenario (Table 3), it is proposed to plant sugarcane varieties that were more productive in the lots described in the initial scenario. It should be noted that, for the data used in this study, fiber (%) and POL (%) restrictions did not influence the results of the optimization model, since all varieties of the dataset already met the required percentage ranges. However, as the model was developed for a day-to-day situation of agricultural operations, this technological information, fiber (%) and POL (%), on sugarcane varieties may change over the planting and harvesting cycles, and thus can be selected in light of the constraints mentioned.

In the optimized scenario, the average productivity of the crop is estimated at 113.5 t/ha, which represents an increase of 16.65% when compared to the productivity of the initial scenario of 97.3 t/ha.

In view of the optimized scenario presented, the varieties SP 813250 and RB 835486 were selected,

Table 1 Technological information on analyzed varieties harvested in 2011.

Lot	Variety	Average productivity (t/ha) from the 1st to 4th term	Harvested area (ha)	Quantity harvested (t)	Average fiber (%) from the 1st to 4th harvest	POL (%) average from the 1st to 4th harvest
1	SP 813250	109.15	53.18	5,804.60	11.7	14.07
2	SP 813250	109.15	49.64	5,418.21	11.7	14.07
3	SP 813250	109.15	41.06	4,481.70	11.7	14.07
4	SP 803280	89.46	50.36	4,505.21	12.68	14.96
5	PO 8862	97.07	17.76	1,723.96	12.48	13.73
6	PO 8862	97.07	31.65	3,072.27	12.48	13.73
7	SP 891115	104.39	25.55	2,667.16	12.02	13.58
8	RB 855453	99.7	26.36	2,628.09	12.42	14.26
9	RB 835486	108.71	1.69	183.72	12.6	15.19
10	RB 855536	91	28.32	2,577.12	12.52	14.09
11	Miscellaneous	78.41	51.93	4,071.83	11.87	14.46
12	Miscellaneous	79.26	22.67	1,796.82	11.42	14.29
Total			400.17	38,930.69		

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Table 2 Productivity, fiber (%) and percentage of oligosaccharides (POL) (%) contents of sugarcane varieties (averages from the 1st to 4th harvest).

Variety	Productivity (t/ha)	Fiber (%)	POL (%)	y
CTC 15	110.12	11.50	13.26	120
CTC 16	102.87	12.19	13.91	10
CTC 2	92.39	12.42	14.85	155
CTC 5	96.37	11.93	14.43	10
CTC 6	121.64	11.31	14.18	58
CTC 9	118.20	11.54	13.74	39
IACSP93-3046	101.44	12.03	15.50	59
IACSP95-5000	110.61	11.34	12.63	38
PO 8862*	97.07	12.48	13.73	626
RB 835486*	108.71	12.60	15.19	13
RB 855156	96.70	11.75	13.75	374
RB 855453*	99.70	12.42	14.26	287
RB 855536*	91.00	12.52	14.09	241
RB 867515	92.35	12.48	14.13	5,520
RB 925211	105.70	11.94	13.05	1,085
RB 935744	93.81	12.57	13.59	559
RB 946903	110.21	11.35	13.14	50
RB 965902	107.31	12.12	13.33	54
RB 965917	114.65	11.40	13.24	36
SP 791011	99.34	13.61	14.54	80
SP 801816	99.68	12.23	13.48	55
SP 801842	94.45	12.50	14.26	1,134
SP 803280*	89.46	12.68	14.96	160
SP 813250*	109.15	11.70	14.07	650
SP 891115*	104.39	12.02	13.58	256

* Varieties harvested in 2011.

Table 3 Proposal of variety planting in an optimized scenario.

Lot	Variety	Productivity (t/ha) average from the 1st to 4th harvest	Area (ha)	Amount to be harvested (t)	Fiber (%) average from the 1st to 4th harvest	POL (%) average from the 1st to 4th harvest
1	RB 965917	114.65	53.18	6,096.85	11.40	13.24
2	SP 813250*	109.15	49.64	5,418.43	11.70	14.07
3	CTC 9	118.20	41.06	4,853.09	11.54	13.74
4	CTC 15	110.12	50.36	5,545.79	11.50	13.26
5	CTC 9	118.20	17.76	2,099.15	11.54	13.74
6	CTC 6	121.64	31.65	3,849.99	11.31	14.18
7	RB 946903	110.21	25.55	2,815.85	11.35	13.14
8	RB 946903	110.21	26.36	2,905.12	11.35	13.14
9	RB 965917	114.65	1.69	193.75	11.40	13.24
10	CTC 6	121.64	28.32	3,444.92	11.31	14.18
11	IACSP95-5000	110.61	51.93	5,744.15	11.34	12.63
12	RB 835486*	108.71	22.67	2,464.42	12.60	15.19
Total			400.17	45,431.52		

* Varieties harvested in 2011.

which were already planted in 2012. However, the variety RB 835486 was changed from lot 9 to lot 12 and SP 813250 variety was maintained in lot 2. The two most productive varieties, CTC 6 and CTC 9, are suggested for planting in lots 6 and 10 (CTC 6) and 3 and 5 (CTC 9), and they correspond to 31.36% of the estimated total production.

Several studies on mathematical modeling have been developed with the purpose of assisting agricultural operations in the sugar-alcohol sector, which are described below. Lemos *et al.* [16] used the Data Envelopment Analysis (DEA) technique, which is based on non-parametric mathematical models, to analyze the efficiency of sugar-alcohol plants in the periods from 2005/2006 to 2014/2015.

Borodin *et al.* [17] presented an overview of the use of recent operational research methodologies to deal with uncertainties in the management of the agricultural supply chain. Jena and Poggi [18] provided mathematical models using mixed integer programming for the tactical and operational planning of sugarcane harvesting. Oliveira Florentino and Pato [19] developed bi-objective optimization models for the selection of sugarcane varieties that meet environmental and economic requirements.

Colin [20] used a quadratic programming model to develop sugarcane crop planning. Higgins and Davies [21] applied computational simulation to plan the capacity of the sugarcane transport system. Salassi *et al.* [22] presented a proposal that assists in the choice of the sugarcane harvesting system, through the application of a mixed integer programming model.

4. Conclusions

Optimization models using linear programming can help the agents of the sugar-alcohol industry in the selection of sugarcane varieties to make year-to-year combinations, considering the historical data of sugarcane harvesting areas.

This optimization process also contributes to selecting the varieties that are adaptable to soil and

local environment and which present higher productivity with the adoption of mechanized harvesting and loading operations.

The collection and storage of data, the use of analysis tools and the subsequent monitoring of information on processes involving sugarcane cultivation, from planting to harvesting, are important for monitoring the effects of intensive use of mechanization in the exploitation of the culture.

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