Chapter 2

Production and Management of Sugarcane Biomass — Process Optimization

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Additional information is available at the end of the chapter

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1. Introduction

The worldwide search for alternative fuels for energy purposes has been growing for environmental and economic reasons. One of the renewable resources of considerable interest is biomass.

In countries where there is a vast area of fertile land, a tropical climate, and available water resources, the growing of sugarcane for subsequent use of its biomass is a viable alternative [35]. From the sugarcane, one may produce various types of sugar and alcohol as well as generate electricity. Even after processing its agricultural and industrial residues such as straws, bagasse, stalks, pulp, molasses, filter cake, and other products, it can be further exploited. The predominate products derived from the sugarcane as potential alternative energy sources are ethanol alcohol, bagasse, and residue of harvesting.

On the other hand, at present, there are significant logistical problems associated with producing biomass from sugarcane. The huge size of the agricultural area and the combined management of the economic, technical, political, social, and environmental factors cause the management of the the sugar–ethanol mills to become extremely complex. Thus, decision makers have sought help by resorting to mathematical and computational tools in an effort to optimize decision making in a safe, economic, and environmentally correct manner, thus making the use of this biomass more appealing.

Section 2 of this chapter addresses the major problems of the sugarcane crop, which may be solved by resorting to optimization techniques, while Section 3 discusses mathematical modeling and solution approaches to these problems.

Figure 1. Source: https://www.flickr.com

2. Improving the quality, production, and management of the sugarcane biomass

The sugarcane is a plant belonging to the genus *Saccharum* L, of which there are at least six species. The sugarcane planted today is a multispecific hybrid called *Saccharum spp*. It is a semiperennial crop since after planting it is cut several times before being replanted. The sugarcane species comes from South East Asia and today has become one of the leading world crops, grown in over 100 countries. About 80% of the planet's production is concentrated in ten countries, with Brazil and India accounting for over half the world's output. On average, its productive cycle ranges over 6 years with five harvests.

The productive cycle of sugarcane begins with preparation of the land and the subsequent choice of the variety to be planted. The cycle then involves development, ripening, and harvesting. The sugarcane resprouts and follows the cycle once more and can be cut up to five times. Then replanting takes place and the entire procedure repeats itself. However, whenever it is replanted, the sugarcane's quality suffers significantly in terms of biomass production, sucrose output, and fiber, in other words, in every measure that directly affects the end products: sugar, alcohol, and energy. Thus, considerable investment is required in the factors that improve cost, production, and quality of the cane without affecting environmental sustainability. Key factors include appropriate management, choice of the optimal variety to be planted, soil preparation, and the correct period for planting and harvesting.

The management of all these factors is extremely complex, and the farmers and factory managers have to resort to various tools to assist them. In this context, optimization techniques have proved to be fairly efficient, as they can contribute to optimized decision making, the achievement of optimum production goals, and the planning of environmentally sustainable processes.

The literature presents a vast amount of problems in which the solution can be assisted by using deterministic optimization methodologies. The application of these methodologies consists initially in studying the problem followed by its mathematical modeling, using the knowledge acquired on the issue concerned to identify parameters, variables, objectives, and constraints. Each optimization model has specific characteristics that depend on the problem that generated it. Functions defining objective function(s) and constraints may involve nonlinearities, convexities, and other particularities. Depending on these characteristics and the required solution technique, the model will be classified within an area of optimization. The next step is to validate the model by studying its performance and coherence of its mathematical results in relation to the reality being modeled. There then follows a discussion of the solution reached with specialists from the field.

Section 2.1 presents the main factors that characterize sugarcane biomass. Sections 2.2 to 2.5 discuss four problems which may be solved with the help of deterministic optimization techniques.

2.1. Sugarcane quality

The method of assessing the quality of the raw material should align with the needs of the producer in order to grow an economically viable crop while meeting the industry requirements. This implies that the choice of new varieties developed through genetic improvement should meet all these prerequisites.

According to Engelke [9], several measures may be used to assess the quality of sugarcane. These are the percentage of pol (sucrose) in juice and in cane, percentage of brix (total soluble solids) in juice and in cane, percentage of fiber in cane, commercial cane sugar (CCS), and purity. The process of determining sugarcane quality and calculation of each of the above measures is explained in detail by Engelke [9].

Among the measures detailed to ascertain the quality of the cane, the ones respecting the fiber and sugar contents should be emphasized. Fiber is a material that is insoluble in the water contained in the cane and constitutes a substance of great importance in the sugarcane agroindustry. From an agricultural standpoint, the varieties that are richest in fiber resist falling more easily, even when they are subject to straw removal and fire and are generally more resistant to the intrusion of pests in the stalk. From an industrial stance, the amount of fiber is important for the industry’s energy balance since the fibers (bagasse and pulp) can be used for burning in boilers, generating steam which is converted into electric energy for the mill itself. At the beginning of the harvest, it is of fundamental importance that the varieties have greater fiber content to ensure the provision of fuel for the boilers. Another significant measure of the sugarcane’s quality is the amount of sugars (pol percentage in cane) as it is mainly from sucrose (for sugar production), glucose, and fructose (for alcohol production) that the industrial output of sugar and alcohol stems. The level of sucrose is directly related to the point of sugarcane maturation since at this point the levels of sucrose are highest. Besides the content of sucrose, the point of sugarcane maturation is determined by the content of reducing sugars (glucose and fructose) and pulp humidity during the crop's cycle [2, 7, 27].

The period of time in which the variety displays appropriate technological conditions to be harvested is the useful period of industrialization, known as the period of industrial utilization (PIU). The PIU commences when the sugarcane reaches the content of sucrose (pol percentage in cane) above the accepted standard (in Brazil it is above 12.257%). From this point, it continues to increase and once it reaches its peak, the sugar content starts decreasing to a minimum permitted figure. This limit is imposed to avoid a significant loss in sugar content. In Brazil, the end of the PIU is determined when the sugar content falls to the minimum of 16%. Different varieties present different values of PIU, some shorter and others longer. Hence, the knowledge of the range of this period is extremely important when it comes to planning a variety's planting and harvesting. In this way, one can make the most of the quality of the sugarcane [7, 35]. Figure 2 illustrates the PIU values of varieties with different maturity curves.

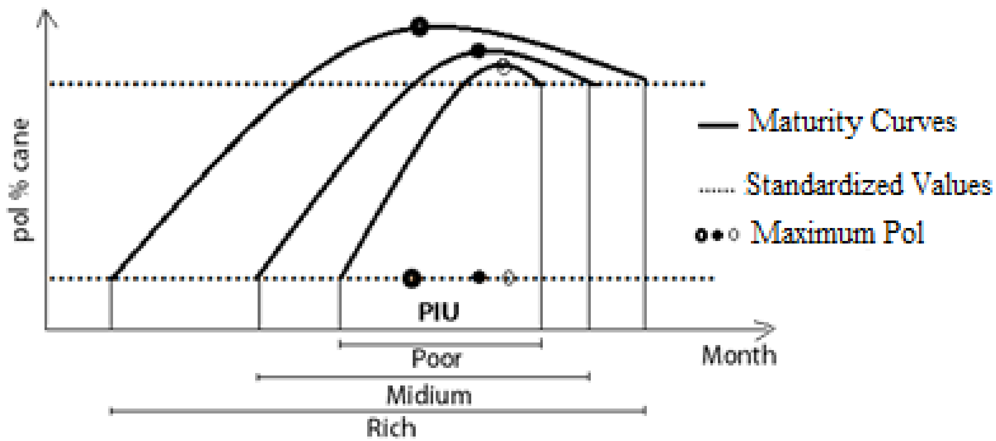

Figure 2. Maturity curves for poor (with a short PIU), medium (with a medium PIU), and rich (with a long PIU) cultivars [35].

In Brazil, the varieties regarded as poor display an appropriate period for harvesting of approximately 3 months. The varieties regarded as medium enjoy a period designed for a more flexible harvest, with a period of up to 4 months. The rich varieties can be gathered with maximum harvest flexibility, extending the period to up to 6 months, depending on the cultivar [35].

The fiber and pol contents are important means of measuring cane quality, but there are also other important factors to ensure the success of the sugar cane plantation in the production of quality biomass, such as preparation of the land for cane planting, choice of the right period for planting and harvesting, and the time the cut cane waits for milling [33].

On the basis of the quality factors discussed, mathematical optimization methodologies can help to determine the planning processes for sugarcane by striving to increase its quality and/ or quantity.

2.2. Preparing the land for planting

Preparing the land for planting has a direct influence on the production of sugarcane and hence assures economic, social, and environmental benefits for the sugar–alcohol sector. Because a favorable utilization of the area implies an increase in cane production, improvements in transport logistics, simplification of planting and harvesting, control of pests and weeds, and minimization of the number of maneuvers of the harvesters lead to reductions in the use of pollutants and fuel costs [16, 22].

Figure 3. Source: https://www.flickr.com

To profit more from the available area, a planning process is needed that considers the shape of the plots and the layout of the tracks, in keeping with the area's relief and soil. Thought should be given to the length and width of the plots in the light of the slope, as every terrace should have a track. The tracks should be rationalized, where the area used for the path system should range between 2.5% and 4.0%. It is recommended that secondary paths are made to adequately accommodate the use of machinery. Early road planning is important to define the road network and consequently the shape of the plots and position of the furrowing [4, 16, 22].

The best recommended plots are those that are rectangular in shape and as long as possible. These are compatible with highly efficient paths that avoid sharp bends and the need for the harvesters to make excessive maneuvers, leading to a loss in time and fuel consumption. One should choose an area devoid of trees, fences, stumps, and large stones, which may prevent the movement of machines. A general cleaning up should be made, removing all the irregularities such as furrows, gullies, and holes. The degree of compression of the soil and its depth should be detected, principally in areas of reform. Besides this, the plots should not have slopes greater than that which is permitted for the machinery available in the market [1].

Problem 1: Optimized partitioning of the land into plots.

Optimized planning of the partitioning of land into plots consists of dividing the area available for sugarcane planting into regular plots of adequate sizes, so as to increase the ease of turnover of the cane harvester and hence to minimize the fuel cost arising from the harvesters' maneuvers.

After preparing the soil and partitioning the land into plots, one should make the right choice of the variety to be planted in each plot, so as to enhance the production of the cane in terms of quality and quantity.

2.3. Selection of the sugarcane varieties

Among the sugarcane's production and quality factors, the choice of the variety to be planted constitutes the most important decision since it provides the basis of the other technologies of production and processing of raw materials, thus providing significant increases in industrial productivity without an increase in production costs [12].

Figure 4. Source: https://www.flickr.com

The varieties should display desirable features such as high yield, high sugar content, capacity to reshoot, no tendency to fall, and resistance to pests and diseases. The moment one chooses one variety to be planted, one must note its features and adaptation to the environment; otherwise, the productive and quality potentials may be compromised [29].

The right choice of sugarcane variety for cultivation is not an easy task, as it depends on a host of fundamental information related to agronomic and industrial factors, besides the interaction

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of biotic, abiotic, administrative, and economic factors. Many studies have been performed with a view to proposing mathematical optimization models to assist this choice.

Problem 2: Selection of sugarcane varieties to be planted.

The problem consists of determining which are the sugarcane varieties best adapted to local soil and climate such that they can be selected to be planted in the available plots, respecting constraints and optimizing the relevant objectives. The areas of the plots as well as the distances of the plots to the mill are generally known. The objectives include cost, profit, or production optimization and energy balance. Constraints ensure sugar and fiber demand is met as well as placing bounds on the planting areas, either in total or per variety.

2.4. Sugarcane cultivation and delivery

The sugarcane cultivation cycle extends from the preparation of the soil to delivery of the cane at the factory. Among the important stages of this cycle, planting and harvesting play a major role. In fact, planned planting and harvesting lead to a series of benefits throughout the cultivation cycle and in the industry. These are improved utilization of the area, increased cane output, improved transport logistics and better cane reception in the factory, administrative simplification of the industrial activities, enhanced response to the demands of the industry, improved utilization of labor, enhanced cost planning, and improved control of pests and weeds, among others.

Figure 5. Source: https://www.flickr.com

Setting up a sugarcane plantation involves a series of factors as it is semiperennial. To ensure that the harvest, mainly mechanized, is successful, attention must be paid to the planting process as the lifespan of the cane plantation depends on the interaction of the two operations detailed in previous sections. Regarding the first operation, many factors determine the quality of planting from its density, soil preparation, planting season, choice of variety, quality, and age of the plant and parallel alignment of the rows of plants. Quality planting directly influences not only the factors that determine if the crop will ensure a high yield following harvest, but also the reduction of crop production costs. The importance of the early operations calls for good planning and considerable technical know-how. In fact, the planting process involves high costs, and decision making in this phase will influence the entire plantation cycle [23, 32].

The harvest season is determined by considering certain factors, such as the amounts of sucrose and reducing sugars contained in the cane juice. For this reason, it is not recommended to begin harvesting until the canes have achieved the minimum technological standards for industrialization nor delay the harvesting season to avoid a fall in the average yield. The output environment may ensure the sugarcane crop is handled better, thus guaranteeing its maximum economic exploitation [23, 32].

The principal indicator in determining the moment to renew a cane plantation is related to the yield noted in the course of its ageing. The greater the number of cuts, the greater the chances of a fall in productivity and the greater the likelihood of the need for renewal. Sugarcane farming is more productive in the first cuts, with a strong tendency for the yields to decline as the years they remain standing in the plots [7, 23, 32, 35].

One problem encountered in high-yield sugarcane regions is that of ensuring that the cane harvests in all plots are performed as closely as possible to the date at which the cane has accumulated the highest PIU value (maximum point on the maturity curve, see Figure 1). Should this be possible, then one may make the most of the biomass to produce sugar and alcohol and to generate energy as well as avoid the need for chemical products. On the other hand, this is an extremely difficult task, as the factories have fixed transport and sugarcane milling capacities and have to meet demand in every period of the year. Often, out of necessity, the cane is cut outside the PIU due to factory demand, industrial limitations, or to avoid the cold periods in zones where the cane freezes, leading to high biomass loss [7]. To overcome this problem, one must undertake optimized planning of sugarcane planting and harvesting.

Problem 3: Planning the planting and harvesting of sugarcane.

Optimized planning of planting consists in deciding in which periods the cane should be planted in each plot so as to satisfy demand during every period of the subsequent 4 or 5 years. The planning of the harvest is linked to the planning of the planting, as planting in each plot should be performed in such a way that the cane harvest is undertaken close to the date of the maximum pol cane content while satisfying demand and respecting the mill's technical limitations. In this sense, mathematical optimization modeling can be of considerable assistance in producing the combining planting and harvesting plans.

2.5. Utilization of sugarcane residual biomass

Mechanized sugarcane harvesting generates large amounts of residue. This residue, known as harvesting residual biomass, is made up of stalks, straw, leaves, and fragments of cane stems. The purpose of this biomass has been widely studied, and various research papers demonstrate the feasibility of using stalks to produce energy in view of the high useful calorific value of this material. The calorific value varies according to the growing conditions and the type of variety [2, 3, 28, 30]. The process of handling the harvesting residual biomass is very costly, and the advantages of cropping, recovery, and utilization have mobilized university researchers, factory managers, and directors, all of whom are keen to find the most productive, economical, and effective way to conduct this operation. Biomass-related factors may provide another consideration in the choice of varieties. Optimized biomass allows for improved economic results and helps to implant the residue in the mill's energy production system. According to Sartori et al. [29], in an attempt to minimize the environmental impact and the influences affecting productivity, and hence the sugar–ethanol mill's profitability, researchers have persisted in choosing the sugarcane variety that produces stalks with a higher calorific value and a low harvesting cost without losing its yield features. Only in this manner will it be feasible to utilize this residue for energy co-generation.

Figure 6. Source: https://www.flickr.com

Problem 4: Utilization of residual biomass to generate energy.

The problem consists in the determination of the optimized process to collect residual biomass from the field (straw) and from the industrial process (bagasse) to be used for energy generation purposes.

Such processes may comply with the objectives of minimizing the cost of harvesting and transportation of the biomass to a processing center, or maximizing the energy and economic balance in the sugarcane processes, or other economic or environmental objectives.

3. Optimization processes

In the light of this biomass profile for the generation of energy, sugarcane has become one of the most important crops, and considerable attention has been devoted to its cultivation. It is therefore fundamental to assess its renewability and sustainability, aiming to improve the raw material intended for the sector. This includes the complete production system from soil preparation through to extraction of the raw material leading to its ultimate use. Due to its dimension and complexity, the productive sugarcane chain is faced with a range of different problems. Therefore, various tools that may help to solve these problems have been used, of which one of the most important is optimization modeling.

3.1. Mathematical programming models

Optimization is a process in which one strives to obtain the best combination of several factors (decision variables), given certain limitations (set of constraints) in keeping with one or more particular objectives (objective functions).

A general problem of single-objective optimization consists in minimizing or maximizing a function, where its domain, when dealing with mathematical programming, is represented by the set $\{ x \in R^n \ / \ g(x) \le 0\}$, which could also be expressed through the conditions $g(x) = 0$ or $g(x) \ge 0$:

$$\text{Minimize } f(x) \ (\text{or maximize}) \tag{1}$$

subject to

$$g(x) \le 0 \tag{2}$$

$$x \in R^n \tag{3}$$

where x is the vector of decision variables; function f: $R^n \to R$ is known as the objective function; a set of constraints is defined through functions g: $R^n \to R^p$. These define the feasible region, i.e., the set of feasible solutions, $n > 0$ and $p > 0$, are integer numbers associated, respectively, with the number of decision variables and constraints.

Depending on the nature of the optimization problem (Equations (1)–(3)), the objective function, constraints, and variables assume different characteristics, calling for different solution techniques. These different problems are classified according to the characteristics of the objective function, equations, or inequalities, which describe the restrictions and the decision variables:

- If f(x) and g(x) are linear functions, and x = $(x_1, x_2, \dots x_n)$, $x_i \in R$ for $i = 1, 2, \dots, n$, one has a linear programming problem (LP).
- If f(x) and g(x) are linear functions, and x = $(x_1, x_2, \dots x_n)$, x_i integer for $i = 1, 2, \dots, n$, one has an integer linear programming problem (ILP).
- If f(x) and g(x) are linear functions, and x = $(x_1, x_2, \dots x_n)$, x_i integer for some but not all $i \in \{1, 2, \dots, n\}$, one has a mixed integer linear programming problem (MILP).
- If f(x) and/or g(x) are nonlinear functions, and x = $(x_1, x_2, \dots x_n)$, x_i integer for $i = 1, 2, \dots, n$, one has an integer nonlinear programming problem (INLP).
- If f(x) and/or g(x) are nonlinear functions, and x = $(x_1, x_2, \dots x_n)$, $x_i \in R$ for $i = 1, 2, \dots, n$, one has a nonlinear programming problem (NLP).

The counterparts of these problems with binary (0 or 1) instead of integer variables have also been widely used. The corresponding acronyms are BLP, MBLP, and BNLP. If there exist q objectives $f_1(x)$, $f_2(x)$, ..., $f_q(x)$ to be maximized or minimized rather than a single objective, then one has a multiobjective programming problem (MOP). If the multiple objectives have target values to be achieved rather than being purely of the minimization or maximization type, then one has a goal programming problem (GP). Both multiobjective and goal programming models follow the same classification conventions with respect to integer variables and non-linear functions as the single objective case.

There are many other varieties of optimization problems, depending on the characteristics of the functions and variables involved [17, 18, 19]. For each class of problems, there are one or more exact or approximate specific solution methods [5, 8, 24, 36].

3.2. Approaches within sugarcane processes

The quality and quantity of biomass to be produced and the activities involving growing, harvesting, transportation, processing, and commercialization of the sugarcane are factors that may be optimized with the help of optimization techniques. Several studies dedicated to optimization models to resolve the above-mentioned Problems 1, 2, 3, and 4 have been published in recent years.

Problem 1: Optimized partitioning of the land into plots.

Consider an available area for planting sugarcane in a field. k is the number of possible plots that can be allocated to sugarcane in this area. Cherry et al. [6] defined the plot generation problem as follows. The planting area must be partitioned into rectangular plots with dimensions (l_j, w_j), where l_j is the length and w_j is the width of the plot j ($j=1,2,...,k$) in order to increase yield, reduce traffic, and minimize the maneuvers of the sugarcane harvesting machines while respecting all the constraints imposed by mill.

According to Cherry et al. [6], the planning begins with soil preparation and the partitioning of the planting area into sugarcane plots. The main feature of plots is that they must be rectangular to prevent excessive maneuvers by the harvesting machines. The cited authors propose a methodology using an NLP model for planning the division of the plantation area into plots in order to perform mechanized harvesting. As the plots are rectangular, the authors used a two-dimensional cutting theory based method to solve the problem. Computational experiments were performed regarding real cases, and the proposed methodology shows a reduction of over 40% in the number of maneuvers of the sugarcane harvesting machines, thus implying many economic and environmental advantages.

Problem 2: Selection of sugarcane varieties to be planted.

This problem consists in deciding which of the n varieties of sugarcane, adaptable to local climate and soil, should be planted in each of the k plots, with size L_j, and distance from the cane's processing center given by D_j ($j=1,2,...,k$), in such a way that it optimizes one or more objectives, whether it be to minimize costs and/or to maximize production, maximize profit, or others. The solution should meet the company's recommendations to maintain cane quality and the demand for sugar and alcohol. Examples of these constraints include the limitation of the average sucrose and cane fiber content and the utilization of the entire area set aside for the sugarcane plantation.

Sartori et al. [27] proposed two LP models for this problem. The first model involved the selection of varieties of sugarcane to be planted meeting the mill requirements to minimize the quantity of residue produced. The second model discussed the use of residue to produce energy. This is related to the selection of varieties and quantities to be planted in order to meet the requirements of the mill, to reduce the quantity of residue and to maximize the energy production. The models developed permit the optimization of the energy available in sugarcane residue and its quantity, with the purpose of selecting the best adapted varieties for the production of energy from the biomass or for the production of compost. With these models, it is also possible to determine the area to be planted per variety, the amount of pol to be produced, the amount of residue, and the amount of energy to be extracted.

Florentino and Sartori [13] linked the two problems proposed by Sartori et al. [29] with a BLP model to support variety selection and planting quantity of sugarcane in order to reduce crop residue, maximize energy generated by this residue, and satisfy the demand of the mill. They solved the conflict between these objectives by using nonzero-sum game theory. One player was associated with residue and another with energy. From the Nash equilibrium points supplied by the game, it was possible to choose a solution that satisfies the mill's interests, thus reducing the sugarcane crop residue and increasing the energy generated by this residue.

Sartori and Florentino [28] presented a BLP approach to a problem that is similar to the ones discussed by Sartori et al. [29]. The approach does not involve determination of the planting area per sugarcane variety but instead focuses on the decision about the variety to plant in each plot. The model of [28] is more realistic since in practice there is only one variety per plot.

Piewthongngam et al. [25] proposed an optimization model for planning cultivation of sugarcane by selecting the time and the varieties that each producer in the Northeast of Thailand should plant, avoiding the generation of excess supply during the peak of harvest. The planning takes place over a long time period and determines the cultivation period, the varieties to be planted, and the time windows of harvest for each farm so that the total sugar production is optimized. The proposed LP model allows decision makers to visualize the sugarcane production in each farm individually on different dates and with different varieties. The results presented by the authors using mathematical programming showed a potential increase of the 23% in sugar production when compared with the traditional planning method.

Florentino et al. [11] proposed a multiobjective ILP model to choose sugarcane varieties so as to minimize costs in the use of crop residue and simultaneously to maximize the energy balance. The model assists the selection of planting varieties by supplying the lowest costs for transferring residual biomass from the harvest in the field to the production center and the optimized residual energy balance. It thus provides the mean energy and fiber content of the varieties of sugarcane selected for planting, taking into account the mill's requirements. The above-mentioned authors encountered difficulty in solving this model using exact methods for large-sized instances. The two works mentioned below followed up [11] by trying to remedy these difficulties. Thus, Homem et al. [15] used a hybrid procedure involving the primal–dual interior point and the branch-and-bound method to solve the problem. The methodology presented a good computational performance and produced reliable practical solutions, but only for small size problems. Florentino and Pato [10] studied the computational complexity of the problem and showed that it is NP-hard. They proposed a solution methodology using a bi-objective genetic algorithm. A computational experiment undertaken with a set including real and semirandomly generated instances was reported, thus showing the practicality of the technique.

Problem 3: Planning the planting and harvesting of sugarcane.

The problem consists in determining the period of the year in which the cane should be planted and harvested in each plot over four consecutive years, so as to maximize the total cane production over the planning horizon. Constraints should be respected, such as imposing the guarantee that the cane be planted in all plots in the first year, a single variety be planted per plot, the guarantee of meeting the mill's pol and fiber demands every planning year and the guarantee that the factory's cane milling capacity be satisfied in all the harvest periods.

Milan et al. [21] presented an ILP model to minimize the cost of transportation of sugarcane from field to mill by integrating road and rail transport systems. The model presents constraints related to the continuous supply of sugarcane in the mill, time that the harvesters can work, type and capacities of vehicles for transportation, and the storage capacity of sugarcane and the availability of routes. According to the authors, the results showed that the model is useful for minimizing the cost of transportation and also for scheduling the transportation of sugarcane, even with the large number of variables and constraints that are present in the model.

The transportation logistics during the sugarcane harvest process is a difficult problem for mill managers to solve. Higgins [14] formulated and implemented an MILP model to assist in resolving operational problems and costs of transportation of sugarcane in Australia. The model improved the scheduling of vehicles and thereby reduced the number of vehicles needed as well as the queues and downtime of vehicles at the mill. Such transport scheduling facilitates the service of traffic agents at the mill during production. The Tabu Search and Variable Neighborhood Search metaheuristics were used to determine solutions to the model. These methodologies were able to find solutions with an average reduction of approximately 90% in vehicles' queue time, as compared with schedules produced manually by traffic agents of the mill. The solution showed also a potential savings of AU$240,000 per year compared to schedules produced manually by the traffic agent of the mill.

Mele et al. [20] formulated a multiobjective MILP model intended to optimize both the economic and the environmental performance of the production chain of cane sugar. The model is used as a quantitative tool to support decision making in the area of supply chain project planning for the combined production of sugar and ethanol, with sustainable strategic alternatives. An analysis of the model was made using a case study based on a real scenario. The authors conclude that this mathematical tool can help authorities in the analysis of strategic agroindustries and energy policies.

Silva et al. [31] proposed an integer GP model for the aggregate production planning of a Brazilian sugar and ethanol company. This model was based on conventional selection and processing techniques for the design of lots, representing the production system of sugar, ethanol, molasses, and derivatives. The work deals decisions on the agricultural and harvesting stages, sugarcane loading and transportation and energy cogeneration, selecting the production process. This approach allows decision makers to set multiple aspiration levels for their problems. An application of the proposed model for real problems in a Brazilian sugar and ethanol mill was conducted and discussed.

Ramos [26] presented a BNLP model to help solve Problem 3. The authors use strategies to calculate the model's parameters so that if the choice of harvesting dates lies outside the PUI, then the objective function suffers a penalty. This strategy also rewards harvesting dates close to the point of the cane's maximum maturing curve. Thus, the mathematical optimization model delivers an optimum plan with an estimated production figure 17.8% above production obtained by conventional means in the area in which it was applied.

Problem 4: Utilization of residual biomass to generate energy.

This problem consists in optimizing the processes involved in the exploitation of the sugarcane harvest's residual biomass for the purpose of energy generation.

Sartori et al. [29] developed a model to minimize the cost of the residual biomass transfer process, to evaluate the economics of using this material and to address sucrose production and planting area constraints, considering distances from the plots to the processing center. To solve this problem, multiobjective BLP techniques were used. The model enables one to determine an estimate of the total sucrose yield at a minimum cost and to demonstrate the economic viability of the use of the harvest's residual biomass to generate energy. Spadotto [34] proposed the application of optimization theory to improve a system designed to use the straw resulting from the mechanized harvest of sugarcane to generate energy. The goal is to maximize the volume of straw to be loaded onto the truck in the form of straw bales, thus minimizing transport costs to the processing center.

Sartori et al. [28] proposed the optimization of the sugarcane residual biomass energy balance by considering the difference between generated and consumed energy in the process of transferring this biomass from the field to the processing center. The corresponding model is a BLP model taking into account enterprise demand restrictions and cane planting area constraints. The authors concluded that using the residual biomass produced in sugarcane harvests is viable, thereby generating more energy and reducing biomass in the field. Therefore, the methodology can be applied to optimize the energy balance.

4. Conclusion

In recent years, sugarcane biomass has stood out as an alternative source of energy, both through its generation of alcohol and the cogeneration of energy through the cane's bagasse and the residue of harvesting. Thus, the growing of sugarcane has been the subject of many

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studies from planting to harvesting to removal to the mill. These studies have the purposes of providing a management procedure at a lower economic cost and improving the quality and quantity of the cane produced. These objectives can be attained through optimized cane cultivation planning because the planning brings about several benefits, principally enhanced quality, and yield, and thus an increase in the bio-energy to be generated. However, crop planning is a complex process that requires considerable care by sector managers as it involves social, economic, political, and environmental factors. These convert the decision-making processes into issues of a multiobjective nature with significant consequences. In this case, the need arises for mathematical and computational techniques, which may assist managers in setting up the planning process for cultivation and handling of the cane. This chapter has discussed the major problems of this area which may be overcome through optimization methodologies and points to literature discussing current models and their solution methodologies.

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