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Mathematical Optimization Models in the Sugarcane Harvesting Process

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Abstract

Over the past few decades, due to environmental and economic factors, the sugarcane has been considered a versatile and important plant to the several countries. The energy-sugar-ethanol agro-industries are seeking to take advantage of all its material, with the main products produced being renewable energy, sugar and ethanol. In this chapter, we propose to present a review of the important works that use mathematical and computational tools, aiming to optimize the sugarcane harvesting, in the past 30 years.

Keywords: economy, mathematical models, optimization, sugarcane, mechanized harvesting

1. Introduction

A number of environmental and economic benefits are claimed for sugarcane. Currently, the ethanol is the most widely used biofuel for transportation worldwide. Production of ethanol from sugarcane is one way to reduce consumptions of both crude oil and environmental pollution. In addition to ethanol, sugar and renewable energy can also be produced from sugarcane. In this way, sugarcane is considered one of the most important industrial cash crops of the world.

On the other hand, there is a great concern about some factors related to the sugarcane production, for example, to increase the processing capacity of the large volume of sugarcane; control the pollution; improve the sugar content and quality of the harvested cane crop; reduce the losses and to increase the volume of the load in the transshipments and trucks. In this context, much research has been carried out in an attempt to improve the

production process in this sector, especially with regard to the sugarcane harvesting [1]. Many studies have been performed in the sugar-energy sector using mathematical and computational modeling techniques in the mechanized harvesting planning. These studies present methodologies to optimize the sugarcane harvesting planning aiming to maximize sugarcane production; minimize costs related to harvesting; minimize the number of maneuvers of the harvester machine; optimize routes for the transport of machines and trucks and many others. The mathematical tools use continuous, discrete and heuristic optimization techniques [2–7].

According to Sethanan and Neungmatcha [2], one of the important aspects to increasing sugarcane mechanized harvesting efficiency is the optimal planning of the harvesting. These authors noted that minimizing the distance traveled during the harvesting and maximizing the sugarcane production, many economic and environmental gains are achieved. However, these are difficult task to implement because there are conflicting objectives that need to be considered simultaneously. Most of these and many other aspects of the sugarcane industry make their management very complex. In addition to the intrinsic knowledge on the part of the managers, the agro-energy industries have sought partnerships with researchers from universities and research centers to assist them in the development of an optimized crop management. In this way, the development of scientific methodologies such as mathematical modeling and operational research (OR) techniques to aid in decision-making has been very important in this area [7, 9].

Based on the above discussions, we propose in this chapter to present a review of the important works that use mathematical and computational tools, aiming to optimize the management of sugarcane, in the past 30 years.

This chapter is structured as follows. Section 2 describes the evolution of mechanized harvesting in the world since the 1940s. Section 3 presents the world scenario for sugarcane production and harvesting. Section 4 describes the types of harvesting in several countries, as well as their advantages and disadvantages. Section 5 presents the relevance of the mathematical optimization models applied to the sugarcane harvesting process.

2. Evolution of the mechanized harvesting of sugarcane

There are reports on the use of mechanization in sugarcane harvesting since the 1940s; however, due to the great loss of raw material caused by the first harvester machines, mechanization did not gain importance in this period, predominating manual harvesting until the 1950s [10–12].

From the 1960s to the 1980s, there was a great increase in the use of mechanization in the sugarcane harvesting. In the 1960s, some countries, such as Australia, used the mechanized system in about 80% of the sugarcane harvesting [10, 11]. At the end of the 1970s, the sugarcane harvesting in Australia reached 100% of mechanization [13]. In some other countries, the mechanized system was introduced only in the late 1980s, due to labor shortages, economic and environmental problems [14]. Mechanization requires large initial capital

investments, however, increases production and significantly diminishes labor requirements and costs.

The fuel crisis (the search for alternative fuel sources, for example, ethanol) and environmental (reduction of burning in sugarcane plantations), social (labor issues) and economic issues led other countries to join the mechanized harvesting system from the 1990s. In this way, the mechanized harvesting was introduced in the scenario of the sugarcane industry. After that, many and great improvements have been observed, such as the increasing volume of the sugarcane harvested, the industry became able to meet the demands, studies have been made aiming the performance improvement of the machinery and equipment, and the pollution generated by the pre-harvest burning of sugarcane has been reduced. Therefore, the mechanized harvesting grew in synchrony with the technological evolution, forced by the demand of the consumer market and the environmental impositions [15–17].

3. Sugarcane in the world

Sugarcane is a semi-perennial crop and is produced in several regions in the world. According to Kim and Dale [18], in the past, the main uses of sugarcane in the world were basically for food manufacturing and seed extraction. Over the years, the sugarcane started to be looked as an energy feedstock rather than a food and this fact made its production grow significantly. The global evolution of the area planted with sugarcane and the amount harvested for mechanized and manual harvesting are presented in **Figure 1**.

Brazil has remained the world’s largest producer of sugarcane since 1970, followed by India, China and other countries (**Figure 2**).

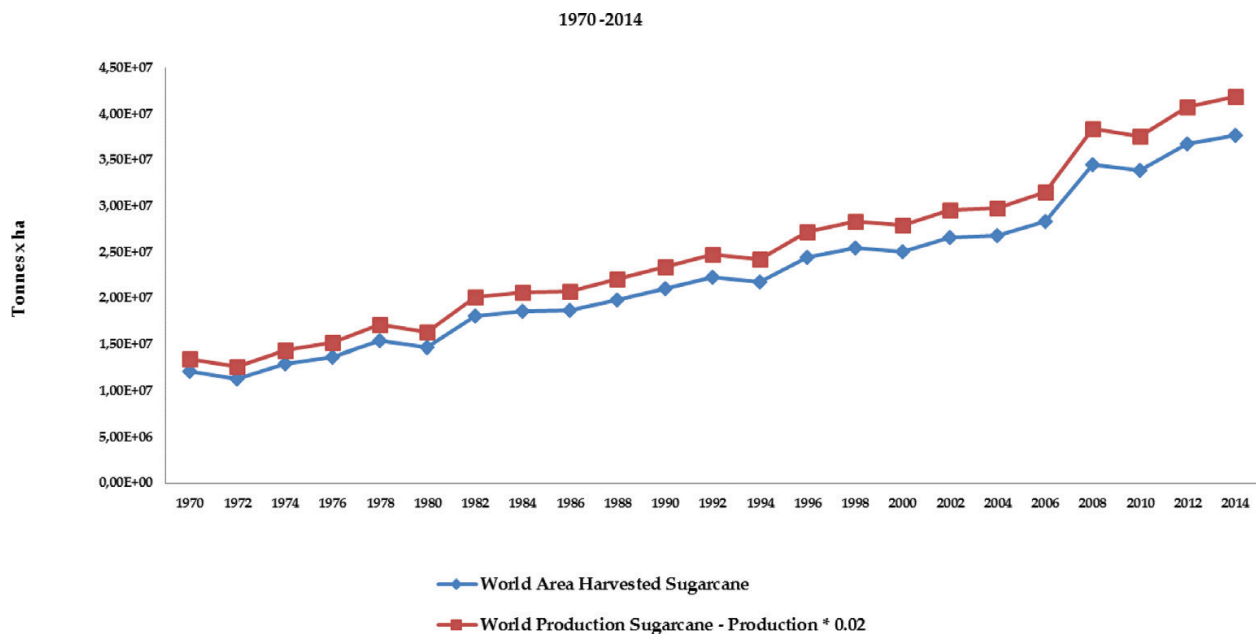


Figure 1. Sugarcane production in the world [19].

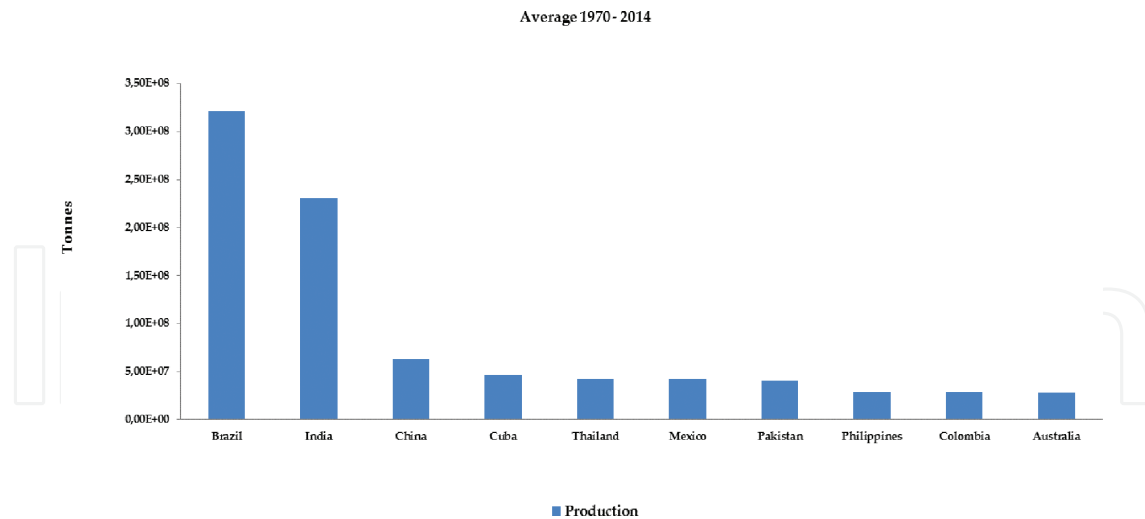


Figure 2. Top 10 producers of sugarcane [19].

Therefore, it is evident the importance of sugarcane for the economy and sustainability of several countries in the world.

4. Sugarcane harvesting

Sugarcane cultivation has been strengthened in some regions of the world, such as North America, Central America, South America, Asia and Oceania, due to the climate, temperature, humidity, relief, topography and soil type. In these countries, planting and harvesting of sugarcane were first carried out in a rudimentary way, manually, as shown in **Figure 3**.

Even with the evolution of sugarcane harvesting technology, there is still manual harvesting practice. In countries, such as United States (Louisiana, Hawaii, Texas and Florida) and Australia (Queensland), the sugarcane has been mechanically harvested since the mechanization of the sugarcane became feasible; however, in others countries, such as Brazil, Argentina, Colombia, Indonesia, among others, the mechanized harvesting was slowly developed and the manual harvesting is present in part of the cane fields until now. In these countries, the transition from manual to mechanized harvesting has been required to improve productivity and to meet labor and environmental issues [20–22].

The sugarcane harvesting can be done with the raw cane or burned cane. In general, a pre-burning of the straw is performed prior to manual cutting of the sugarcane. This practice is used to clean the cane, making it easier and safer for manual laborers to work. Some countries also use mechanized harvesting with the burned cane. The burning of the sugarcane is a common practice; however, it is very widely criticized due to environmental and productive factors. Therefore, mechanized harvesting of raw cane (**Figure 4**) is more commonly used nowadays, and is a focus of research worldwide. Researchers search for a new approach to the sugarcane mechanized harvesting that could make it more economically and environmentally attractive [23–26, 27].



Figure 3. Hand sugarcane harvesting. Credit: Luiz Carlos Dalben.



Figure 4. Sugarcane mechanized harvesting. Credit: Luiz Carlos Dalben.

The authors [14, 28] describe the operation of the sugarcane harvester, which can be categorized into whole stalk harvesters and chopper harvesters. The sugarcane harvester machines perform the basal cutting, promote the cleaning of sugarcane and chop the stalks into 15–40 cm billets, unloading them onto a transshipment (Figure 5). Additionally, the sugarcane is delivered to a train or a truck and transported to the processing center.

The mechanized harvesting of the sugarcane is carried out annually and each machine cuts approximately 80 tons per hour. Depending on the number of hours worked, it can cut annually between 50,000 and 150,000 tons per harvester [20].

Thailand is the second largest exporter and the fifth largest sugarcane producer in the world. However, most sugarcane farming is family business, hence sugarcane is cultivated in a small area, which makes mechanized harvesting unfeasible and promotes low productivity [28, 29]. According to Pongpat et al. [23], despite the great importance of sugarcane to Thailand's economy, the population has been aging and it has been difficult to meet the significant market demand using only manual harvesting. It is necessary to review the concepts and apply new investments in the mechanization of harvesting in this country.

In Cuba, sugarcane is considered the second largest source of economy, has hundreds of mills and produces millions of tons of sugar per year; however for this, the integrated harvesting, transshipment and loading system work efficiently [30].

Sugarcane has a great economic importance in Australia. According to Higgins and Davies [31], in this country, the sugarcane is mostly concentrated in the northeast, and the cut begins in the winter and goes until the end of spring, when the highest percentage of sucrose is concentrated.



Figure 5. Transshipment to aid the transport of sugarcane from the plot to the truck or train. Credit: Luiz Carlos Dalben.

According to Braunack et al. [33], the traffic of machinery in the sugarcane plantation is very intense and requires a good planning of the harvesting process to avoid problems of harvest delay, loss of sucrose, soil compaction, delayed delivery of harvested sugarcane and many others. In [34], the quality of sugarcane harvested manually and mechanically is compared. They conclude that in both cases that after the cut, the sugarcane must be quickly taken for processing because after 24 hours the loss of quality begins. The logistic integration of harvesting, transshipment and transportation must be in constant harmony, aiming to optimize the time between cut and milling in the mill, i.e., there must be an efficient communication network and a good harvesting planning. Therefore, researchers in various parts of the world investigate effective and economical ways to manage the process of harvesting sugarcane. Many of these researchers make use of mathematical and computational methodologies to optimize this process.

5. Optimization process

Investments in technology have grown considerably in developed and developing countries, mainly investments in technologies aimed at agricultural machinery, including sugarcane harvesting machine. Due to these investments, the machines have become more agile and productive, promoting a considerable increase harvesting yields, and consequently forcing managers to make faster decisions during the process of mill management. Therefore, many studies were directed towards the development of optimization mathematical models as a way to assist managers in decision-making.

5.1. Mathematical models

Since the 1970s, many mathematical models have been developed aiming to optimize the mechanical harvesting process of sugarcane

In 1977, Gentil and Ripoli [35] analyzed and simulated the mechanized harvesting system, transport and additionally, the reception of sugarcane in the mills. The logistics of transportation and harvesting of the sugarcane were optimized aiming to reduce the time involved in the harvesting process and the number of vehicles (harvesters and trucks). Despite the computational limitations, promising results were obtained, considering the dimensions of the problems of this time.

In 1982, Singh and Abeygoonawardana [36] developed an optimization model for the harvesting and transport of sugarcane, aiming to optimize the number of trucks for the transportation of harvested sugarcane in mills in Thailand.

In 1994, Singh and Pathak [37] presented an optimization model-based decision support system and simulation of the harvesting operation, aiming to minimize harvesting costs and aid the optimal management decision-making for the mechanized harvesting of sugarcane.

In 1995, Semenzato [38] used a heuristic to simulate the sugarcane harvesting, aiming to assist the decision maker to optimize cutting, loading, transport and discharge time. The results achieved helped in making optimized decisions aiming at the organization and use of scarce resources.

In 1999, Askita et al. [39] developed a scheduling algorithm called SFSW (Stochastic Farm Work Scheduling Algorithm based on Short Range Weather Variation) to assist Japan's sugarcane industry in determining the optimal daily amount of sugarcane to be harvested and deciding which fields to perform the operation of harvest. This algorithm was considered quite promising when was compared to real practices.

In 2000, Díaz and Perez [30] considered that to optimize the harvesting and transportation of sugarcane, involving the cutting and loading of the truck is a complex task. Therefore, these authors proposed a computational simulation aimed at the optimization of sugarcane harvesting and transportation. The results found contributed to the development of optimal planning of sugarcane processes.

In 2001, Arjona et al. [40] observed some problems in Mexican sugar-energy sector related to the underutilized machines and difficulties presented by farmers to plan the sugarcane harvesting. These authors developed a computational simulation of the harvesting, transportation and sugarcane processing systems, aiming to aid managers to plan and evaluate actions with a computational tool. The results of this research allowed the correction of the problems underutilization of machinery and the minimization of costs, fuels and processing time of sugarcane.

In 2002, Higgins [41] proposed an integer linear programming model to optimize the number of harvesters to be used at five Australian mills. The author describes the great importance and benefits that mathematical modeling can promote to power mills. Higgins and Muchow [42], in 2003, also explored operational research techniques to increase productivity and profit in sugarcane production and harvesting.

In 2005, Higgins and Davies [43] emphasized the complexity of mechanized harvesting and transportation in the sugar-energy sector. They proposed a stochastic model to evaluate scenarios of cost reduction in mechanized harvesting and transportation. The results allowed to obtain a more efficient transportation service and with greater benefit to the harvest. Jiao et al. [44] proposed a linear programming model to improve crop planning in order to optimize the amount of cane to be cut per farm and the sugar content. As a result, a software called SugarMax was introduced with the purpose of assisting in decision-making.

In 2006, Higgins [4] proposed a mixed integer linear programming model with the objective of reducing the queuing time of the trucks and optimizing the harvesting process. The computational tests were performed using the GAMS software, OSL and heuristic techniques. Milan et al. [45] studied the transport of sugarcane, involving numerous variables and constraints, such as decisions of the continuous milling, harvesting machining, number of vehicles used to transport sugarcane and available routes. The model was designed to minimize transport cost and harvest limitation.

In 2007, Grunow et al. [32] investigated the safety stock of sugarcane to be used as raw material for sugar production. The problems of cultivating farms, harvesting, dispatching and harvesting equipment were analyzed. A mixed integer linear programming (MILP) model was proposed for the mechanized harvest planning, optimizing the weekly milling of sugarcane and the amount of sucrose and allowing a more detailed harvest schedule with small sucrose losses.

In 2008, Salassi and Barker [46] developed a study aiming to reduce costs and minimize harvesting time. In this way, a mathematical programming model was developed, which provided the ideal harvest time under different waiting times.

In 2009, Jena and Aragão [47] proposed an integer linear programming model to optimize harvesting. In order to facilitate the resolution of the problem, heuristic initial solutions were obtained and exact methods were applied with the use of CPLEX and other software, obtaining an improvement of almost 25% in the total average of cane production. The authors recommended the use of mathematical techniques for this type of problem.

In 2010, Scarpari and Beauclair [9] also used linear programming and the General Algebraic Modeling System (GAMS) software to maximize profit and harvesting time for sugarcane.

In 2012, Stray et al. [48] formulated a model of optimization based on traveling salesman problem aiming to determine an optimal planning of the sugarcane harvesting involving large number of fields and extensive areas of planting. The researchers concluded that the decision support system provides practical support for sugarcane harvesting; however, even then, numerous researches are needed in this area.

In 2013, Silva et al. [49] developed and applied a Multi-Choice Mixed Integer Goal Programming Model (MCMIGP) for a real problem of production planning in a sugarcane mill, extending to mechanized harvesting. The authors argue that mathematical techniques are good tools to assist power plant managers in making decisions. Sethanan et al. [50] presented an optimization model applied to sugarcane harvesting aiming to maximize sugar production in the harvest period. The authors presented a heuristic to schedule the sugarcane harvesting and a Tabu Search algorithm to optimize production. The results showed an improvement average of 16.38% in sugar production. Jena and Poggi [8] presented an optimization model for tactical and operational planning such that the total sugar content in the harvested sugarcane is maximized. The model was solved using heuristic techniques and approached Lagrangian relaxation or Benders decomposition.

In 2014, Florentino and Pato [5] presented a bi-objective binary linear programming model for sugarcane variety selection and harvesting residual biomass utilization. The computational experiment showed a high quality of the proposed multiobjective Genetic Algorithm and a low computational time. The authors concluded that the mathematical techniques could aid the managers of mills in the strategic planning process of productive activities of the sugarcane. Silva and Marins [51] proposed a Fuzzy Goal Programming (FGP) model to optimize storage and transport logistics of sugarcane involving uncertainties in the agricultural process of sugar and ethanol production. The results indicated that the presented methodology could assist the managers in the decision making, mainly to the processes related to the harvesting, transshipment and transportation of the sugarcane.

In 2015, Silva et al. [52] proposed a Revised Multi-Choice Goal Programming (RMCGP-LHS) model to address uncertainty in sugarcane harvesting planning, production planning and energy cogeneration for a sugarcane mill. The model addresses the agricultural and industrial stages, allowing the decisions to be taken within a weekly planning horizon, including the process of variety selecting of the sugarcane to be planted, the design of the cutting front and the agricultural logistics, as well as the choice of the production process of sugar and ethanol.

The objectives of this model are to obtain information to harvest the sugarcane in the period closest to the maximum sucrose content; minimize agro-industrial costs and maximize the production of sugar and ethanol and the sale of energy. Neungmatcha and Sethanan [53] carried out studies on optimum planning of the mechanized harvesting route in order to improve transportation. These authors proposed a mixed integer model aiming to increase profits and reduce costs through the better supply of sugarcane and more efficient mechanized harvesting and transportation. Kittilertpaisan and Pathumnakul [54] studied problems related to the mechanized harvesting of sugarcane in Thailand. A mathematical model related to the problem of routing of vehicle was formulated. Harvest sequences, routes, harvesting period and harvesting time were successfully determined.

In 2016, Ramos et al. [3] proposed a methodology to determine an optimum planning for planting and harvesting of the sugarcane for 5 years. The main decisions approached in this methodology are related to the determination of the planting date, selection of the varieties to be planted and determination of the harvest date for each plot, aiming to optimize the global production. A binary nonlinear optimization model was proposed and solved using computational and mathematical strategies, ensuring that the date of harvest is always in the maximum maturation period of sugarcane and considering all operational constraints of the mill. An optimal planning was determined, obtaining a potential improvement production of sugarcane 17.8% above the production obtained by conventional means.

In 2017, Junqueira and Morabito [55] proposed an optimization approach to support decisions from the scheduling and sequencing of harvesting fronts using the General Lot Sizing and Scheduling Problem (GLSPPL). Santoro et al. [56] proposed a mathematical model to solve the route planning problem of the sugarcane harvester, which aimed to optimize the time of maneuver of the harvesters in comparison to the maneuvers that were being commonly used. Based on the presented results, a 32% time reduction was observed compared with the traditional harvest process for the same area when the route of the harvest machine was not planned. Florentino et al. [57] proposed a methodology to aid the planning of the sugarcane harvesting aiming to improve the sucrose production and the raw material quality, considering the constraints imposed by the mill as well as the sugarcane demand per period. In this way, an extended goal programming model was proposed to optimize sugarcane harvest planning, so that the harvesting is done as close as possible to the sugarcane maturity peak. A genetic algorithm (GA) was developed in order to solve large-size problems with an appropriate computational time. A comparative analysis between GA and an exact method for small instances was given to validate the performance of the model and the methods developed. The computational results show that crop planning for small farms can be generated by the exact method, and for medium and large farms, a metaheuristic is required for this planning.

6. Conclusion

The sugarcane contributes significantly to the economies of many countries. However, there are still great challenges for sugarcane culture such as increase sugarcane productivity. Several studies have been developed aiming to obtain improvement of the genetic base of sugarcane

varieties; increase production of first and second generation ethanol; obtain improvement of the environmental integrated production and recycling management; develop new technologies applied to the sugarcane culture; obtain more efficient machines to planting and harvesting of sugarcane; improve vehicles and improve job qualification and many others. Other researchers from universities have established partnership with private companies in the sugar, ethanol and energy sector, aiming to solve the logistical problems, mainly focused on harvesting logistics.

The transition from manual harvesting to mechanized harvesting promoted many productive gains and reduced losses; on the other hand, the harvesting system demanded a more complex planning, necessitating the development and application of mathematical and computational techniques, aiming to assist managers to make more assertive decisions during this agricultural planning.

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