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Review

# Route optimization in mechanized sugarcane harvesting

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ABSTRACT

Sugarcane cultivation is important for the economy of many countries, particularly for Brazil. This plant has been used to produce sugar, ethanol, second generation ethanol, fertilizers, as well as bioelectricity. Due to production growth and the establishment of mechanized sugarcane harvesting, this process needs to be optimized. High costs are linked to mechanized harvesting, which affect the total cost of production. One of the costs of harvesting is related to the long time the sugarcane harvesting machine takes to change the crop row to be cut. To help reduce costs, this work proposes a mathematical model to the Route Planning Problem for Mechanized Harvesting. This mathematical model minimizes the time of maneuvering the harvesting machine and, consequently, reduces fuel and labor costs, among others. Computer tests were performed using data supplied by a company from the sugarcane energy sector located in the state of São Paulo, Brazil. The results were compared to the traditional routes used by the company and proved the efficiency of the mathematical model in supplying solutions that minimize the time of harvesting machine maneuvers. Not only are there economic benefits, but also environmental ones that can be obtained.



**Contents**



## 1. Introduction

Sugarcane has a major importance in the Brazilian economy. The country is the biggest producer of sugarcane in the world, followed by India and China, and is the largest producer of sugar and ethanol. Brazil is responsible for approximately 20% of sugar production and 40% of the sugar exported in the world. Sugarcane is also hugely important in terms of the environment as ethanol is one of the best alternatives for reducing gas pollutant emissions, which are the fundamental cause of the greenhouse effect. According to data from the Companhia Nacional de Abastecimento (CONAB, 2015), changing gasoline to ethanol could reduce up to 70% of gas pollutant emissions.

Until 2014, sugarcane harvesting in Brazil was predominantly manual. In this harvesting strategy, the sugarcane had to be burned so it could be cut by workers, and then transported to the plant. Although ethanol is beneficial to the environment, this strategy had many negative impacts on the environment and human health because of sugarcane burning. However, due to an Agro Environmental Protocol proposed by the Sugarcane Industry Association

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(UNICA – União da Indústria de Cana-de-Açúcar) and the government of the state of São Paulo, a legislation was introduced imposing that from 2017 the harvesting should only be mechanized. Mechanized harvesting totally eliminates sugarcane burning and also increases profits because the straw remaining from the sugarcane can be used. This byproduct has been used to produce energy and second generation ethanol.

With the advent of mechanized harvesting, new technologies emerged and improvements were made in all planting and harvesting processes. In order to have more economic benefits in mechanized harvesting, quality control related to sugarcane planting has become priority, as well as the need for efficient techniques for mechanized harvesting. Benedini and Conde (2008) affirm that planning of harvesting machine routes is needed because the machines take about 1.5–2.0 min to be maneuvered and change the sugarcane crop row. Although optimization techniques have been proposed in various agricultural sectors, strategies to help sugarcane harvesting machine routes to try and reduce the number of maneuvers is a study that still needs to be developed.

Concerning routes, some papers in the literature have proposed approaches to reduce the distances that vehicles have to travel to carry out tasks and, by and large, do not consider minimizing costs on fuel, labor, reducing time, among others as optimization criteria. Oksanen and Visala (2009) proposed two approaches to solve the coverage path planning problem in fields performed by agricultural machines. The approaches are applicable to both robots and human-driven machines. Whole fields should be covered and the objective was to find as an efficient route as possible. Advantages and disadvantages were found in both approaches and neither of them solved this problem optimally. Zhou et al. (2014) developed a planning method that generates feasible areas for agricultural machines to perform operations in fields with obstacles where machine traffic is not possible. However, according to the authors, this method cannot be applied to harvesting. In a paper by Bochtis et al. (2015), a route planning approach for orchard operations was developed and tested using a deterministic behavior robot. The core of the planning method was to generate optimal route planning based on adapting the B-pattern area coverage, an approach developed for arable farming operations.

Conesa-Munoz et al. (2016) proposed a general approach to optimize the route planning problems with more than one vehicle with the same or different features (different speeds or different turning radii), variability of the field and the possibility of refilling the tank. Criteria such as travelled distance, the time required to perform the task and the input costs should be optimized. The proposed approach was solved using a simulated annealing algorithm and has special relevance for route planning in site-specific herbicide applications. Tests using illustrative problems were carried out to validate the strategy. Seyyedhasani and Dvorak (2017) proposed the allocation and ordering of field paths among a number of available machines using the vehicle routing problem, thus minimizing the time to complete a task in the field. A heuristic algorithm and a meta-heuristic algorithm were used to solve the problem. Both techniques were evaluated using computer simulations in a hypothetical basic rectangular field and in a real-world field.

Due to the importance of the Brazilian sugarcane sector, many optimization mathematical models have been proposed to reduce sugar and ethanol production costs. Grisotto (1995) presented a model to represent the activities that include loading, transporting and unloading sugarcane. To solve the problem, a heuristic that uses interior points method was proposed. Yoshizaki et al. (1996) proposed a mathematical model to optimize the ethanol distribution in Southeast Brazil. Colin et al. (1999) proposed a linear programming model to optimize the logistics system for sugar distribution and storage considering a central deposit and a number of secondary deposits. Solutions were obtained using linear programming software.

Iannoni and Morabito (2006) presented a study on the processes related to sugarcane arriving at a mill making use of discrete simulation to analyze the performance of the system and investigate alternative configurations and policies for its operations. Simulations were performed using Arena software. Kawamura et al. (2006) presented a multiperiod linear programming model, which considers decisions regarding transportation and storage of a cooperative of sugar and ethanol producers. The model was implemented using the "What's Best!" software package, industrial version 5.0. Tests were performed using real data. Florentino et al. (2013) proposed an integer nonlinear mathematical model to help plantation planning, as well as sugarcane harvesting aiming to increase productivity in a five-year period. To solve the problem, a genetic algorithm was proposed and tests were performed with random generated instances.

Although the costs entailed with mechanized harvesting are highly representative in the total production cost, to the best of our knowledge, there is no study which addresses this problem. In order to improve the efficiency of the harvest process, routes which will be covered by the harvesting machine need to be planned taking into account the time spent by the machine to execute the maneuvers. Due to the lack of studies in the literature that optimize the sugarcane harvesting process and the need to reduce these costs, this paper contributes to the literature by proposing an integer programming model for the Route Planning Problem for Mechanized Harvesting (RPPMH) aiming to minimize the time the harvest machine takes to maneuver and, consequently, reduce the fuel and labor costs, among others.

The mathematical model proposed is based on the Rural Postman Problem (Orloff, 1974; Eiselt et al., 1995; Pearn and Wu, 1995; Corberan et al., 2006), which is a widely studied problem in the literature and one of the most important optimization problems, applicable in many real situations (Mullaseril et al., 1997; Archetti et al., 2014; Arbib et al., 2014). Computational tests were performed using data supplied by a company from the sugarcane energy sector from the state of Sã Paulo, Brazil. The obtained results were compared with the traditional harvest routes used by the company and confirmed the efficiency of the model in providing solutions that minimize the number of harvesting machine maneuvers, generating economics benefits and other advantages.

The paper is organized as follows: in Section 2, the mathematical model proposed for RPPMH is described; in Section 3, computational tests performed using real data are shown; Section 4 presents the analysis and discussions of the results; and finally in Section 5, the conclusions of this study are drawn.

## 2. Mathematical model for the route planning problem for mechanized harvesting

In Rodrigues and Abi Saab (2007), the authors highlight that the change in the process of sugarcane harvesting is not only a matter of replacing the technique. This change means adapting aspects such as: soil preparation in agriculture, the equipment in the field, maintenance and support teams, training people involved, as well as transport changes and the arrival of the sugarcane at the mill. Even with all the preparation and planning for the sugarcane crops, the sector is also attempting to improve the harvesting process.

The proposed mathematical model for the Route Planning Problem for Mechanized Harvesting (RPPMH) aims to minimize the time that the harvesting machine takes to perform maneuvers given that the layout of the plantation area to be harvested is known. Furthermore, the model ensures that all sugarcane rows are covered by the harvest machine.

During the whole harvest period (from April to November of each year in Brazil), there are many machines that work almost non-stop. Therefore, planning that allows for a few seconds of machine time gain per hectare will have an impact in terms of hours on a harvest and, consequently, tons of sugarcane. To do this, the sugarcane rows in the plots need to be mapped out, as well as the information on the sugarcane rows that can be connected regarding their topography.

In cases where there is a sugarcane track, if the harvesting machine continuously goes down this line without maneuvering to change rows, there will be a longer sugarcane row. Using this technique, also called "*direct shot*" or "*long shot*", longer sugar cane rows can be simulated which require less maneuvering of the harvester, having a direct impact on the company's productivity and economy. According to Benedini and Conde (2008), a harvester takes around 10 s of maneuvering time to cross the tracks between the sugarcane plantation area and start a new row of sugarcane, while the maneuver to change a row takes 1.5 – 2.0 min.

### 2.1. Mathematical model

The RPPMH arose after the establishment of mechanized sugarcane harvesting. This problem consists of deciding the best route to be taken by the harvesting machine, knowing the layout of the plantation area. The proposed mathematical model that describes this problem minimizes the time it takes to maneuver the harvesting machine, ensuring that all sugarcane rows are covered. The maneuvering time consists of the time that the machine is running, but not harvesting.

In practice, due to the topography of each sugarcane farm, the harvesting process is done in sections, as illustrated in Fig. 1. Each section accounts for specific number of plots and each section is harvested independently. Thus, planning the harvesting machine routes must be done in sections.

It is important to mention that during the harvest, the sugarcane can be unloaded for transshipment on both (left and right) sides of the harvesting machine. The machine operator does this using a single command. Fig. 2 illustrates the machine used for the harvesting process. In this machine, the part consisting of components 1, 2, 5, 20, 21 altogether in Fig. 2 can easily be changed to the left or right side.

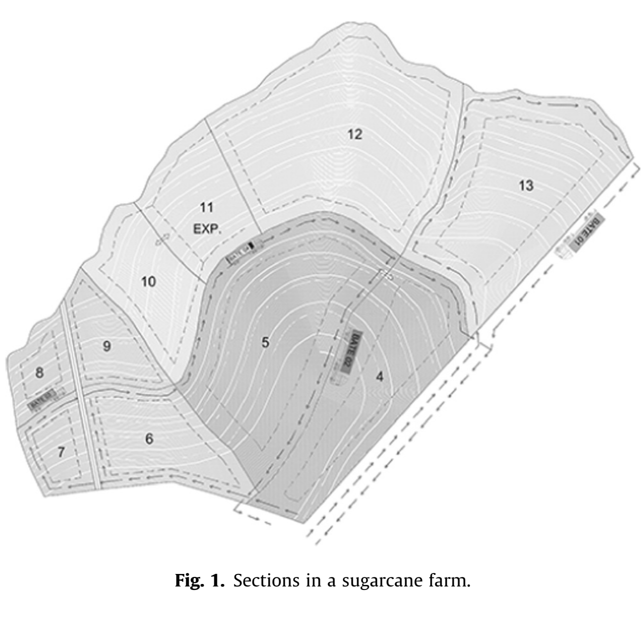


**Fig. 1.** Sections in a sugarcane farm.

A situation that rarely arises because it causes trampling and spoils the plantation is harvesting a sugarcane row between two rows that were not yet harvested. However, if this is necessary, there are machines that are able to internally store the harvested sugarcane and after, unload it in the transshipment.

Due to the flexibility of the harvesting machine used, the sections can be considered as a non-oriented graph. Each sugarcane row corresponds to an edge limited by two nodes of the graph (each node represents the beginning and the end of a sugarcane row) as illustrated in Fig. 3.

The edges of the graph have associated costs that represent the time of the harvesting machine maneuvers. Therefore, this problem is equivalent to the Rural Postman Problem (Eiselt et al., 1995), which is a well-known and important problem of the optimization area and used in many applications. Given graph $G = (V, A)$, where $V = \{v_1, v_2, \ldots, v_n\}$ corresponding to a set of nodes, let $A = \{(i,j), i \neq j\}$ be the set of edges among the nodes and $A_r \subset A$, be a subset of mandatory edges.

The problem consists of determining a closed path of minimum costs, that start at an origin node and pass through each edge from $A_r$ only once. The mandatory edges $A_r$ correspond to the sugarcane lines.

**Parameters**

- $A$: set of edges of the graph;
- $A_r$: set of mandatory edges (they correspond to the sugarcane rows);
- $t_{ij}$: time to maneuver the harvesting machine associated to edge $(i, j)$, $(i, j) \in A$.

**Decision variables**

- $x_{ij} : \begin{cases} 1, & \text{if the edge } (i,j) \text{ is traveled by the harvest machine} \\ 0, & \text{otherwise} \end{cases}$

The mathematical model for the RPPMH is defined as:

$$Min \sum_{(i,j) \in A} t_{ij}x_{ij} + t_{ji}x_{ji} \tag{1}$$

Subject to:

$$\sum_{\{j:(i,j) \in A\}} x_{ij} - \sum_{\{j:(j,i) \in A\}} x_{ji} = 0, \quad i = 1, 2, \ldots, n; \tag{2}$$

$$x_{ij} + x_{ji} = 1, \quad \text{for all } (i,j) \in A_r, \tag{3}$$

$$\sum_{(i \in S)} \sum_{(j \in S)} x_{ij} \leqslant |S| - 1, \quad \text{for } S \subset v_1, v_2, \ldots, v_n \text{ and } S \neq \emptyset \tag{4}$$

$$\sum_{(o,j) \in A} x_{oj} \geqslant 1 \tag{5}$$

$$\sum_{(i,o) \in A} x_{io} \geqslant 1 \tag{6}$$

$$x_{ij} \in \{0, 1\}, \quad \text{for all } (i,j) \in A. \tag{7}$$

In the mathematical model (1)–(7), the objective function (1) minimizes the time the harvest machine maneuvers. Constraints (2) ensure the route continuity. Constraints (3) ensure that the all sugarcane rows (mandatory edges) are covered once by the harvest machine. Constraints (4) prohibit the construction of illegal sub routes, i.e., disconnected sub routes. Constraints (5) and (6) together ensure that the harvest machine begins its route from a place of origin and returns to the same place at the end of the route (in these restrictions, o represents the origin node) and the constraints (7) show that the variables are binary.

In an atypical situation in which it is necessary to harvest a sugarcane row in the middle of two sugarcane rows that were not harvested, feasible solutions are obtained because they satisfy the

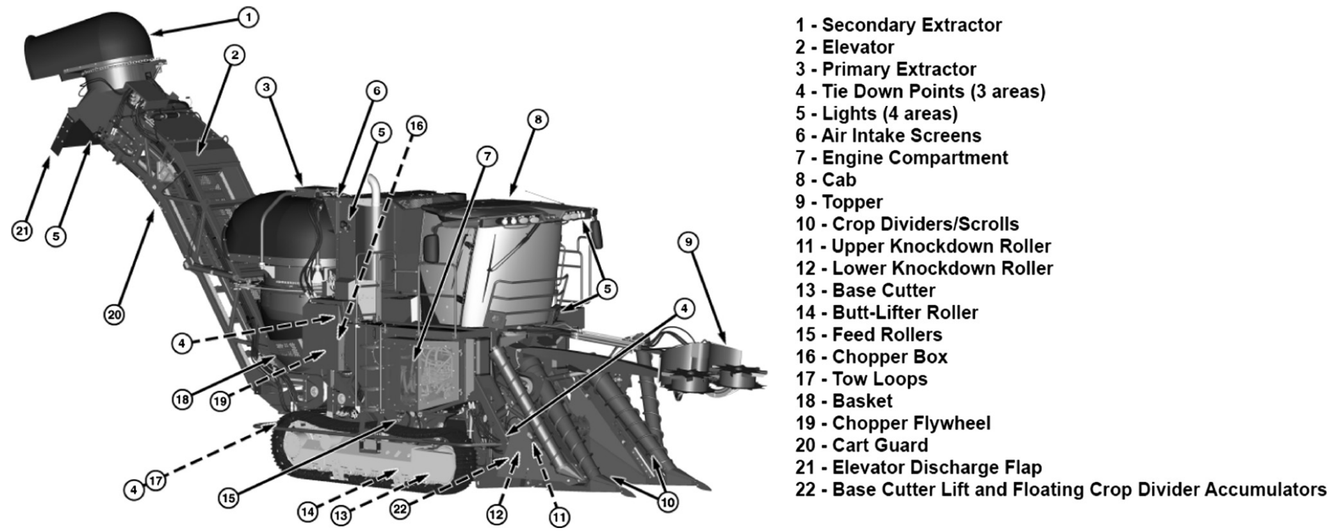


**Fig. 2.** John Deere CH670 Harvester – Deere (2017).

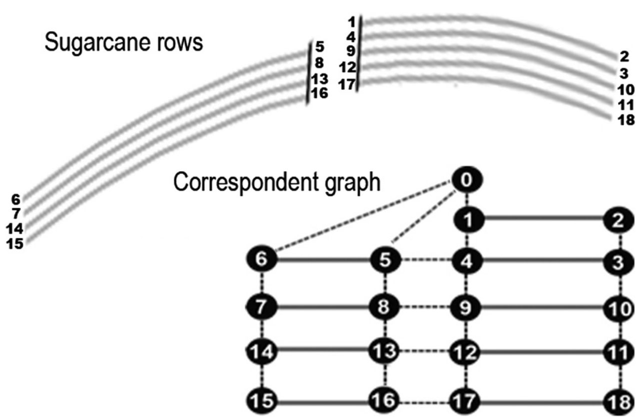


**Fig. 3.** Sugarcane rows and the correspondent graph.

constraints (2)–(7). However, routes like these are not returned by the model (1)–(7) because it always provide routes with the shortest maneuver time, which are obtained when sugarcane rows are harvested sequentially.

As a natural consequence of the model (1)–(7), the fuel consumption and labor costs are minimized. In addition there is an environmental benefit as the fuel consumption is reduced in this process and it minimizes the gas pollutant emissions.

## 3. Computational tests

In order to evaluate the model (1)–(7), computational tests were carried out using data supplied by a sugarcane energy company in the state of São Paulo, Brazil, which comprises four production units. The tests were run using the solver CPLEX 12.3 in a 64 bit version and using the IBM ILOG CPLEX Optimization Studio as an interface accessed by Java programming language. The data were stored in a free version of the database management system – Oracle Database 11g Express Edition Release 2. The tests were performed in a second generation i7 processor computer with 16 Gb of RAM memory.

The tests include 50 real instances supplied by the company, whereby each one corresponds to a section in a chosen agricultural setting. The average time of maneuvers used in all the tests was 120 s. Although this amount of time was mentioned in the literature by Benedini and Conde (2008), it was proven by analysis in the harvesting process in the company. This value represents the arithmetic average of the maneuver times for the sugarcane row change provided by the company for the sections used in the tests.

Table 1 presents information about the instances and results. This table shows data concerning the number of the instance (Instance), the number of plots in a section (N° of plots), the total area of the section (Area), in hectares (ha), the number of rows in each section (N° of rows), the total time of maneuvers made by the harvester obtained by the proposed mathematical model (Optimized), in seconds (s), the traditional (Traditional) maneuver times, in seconds (s), and the processing times (Computational Time), in seconds (s). The traditional times of maneuvers consists of the time taken to maneuver the machine to perform the harvest without any route planning. This situation is very common in most sugarcane energy companies. The processing times refer to the total time used by the developed algorithm from reading the data to the results shown.

Fig. 4 shows the traditional route used by the company (a) and the optimized route given by the mathematical model (b) for instance 22 (this instance was chosen due to the map sizes). In this figure, it can be observed that in the optimized route there are fewer maneuvers compared to the traditional route.

In addition to the tests carried out using real data, instances of random sizes were generated using larger sizes. The purpose of these tests was to check the model behavior for instances with a large number of sugarcane rows because in real situations a section with 500 rows is considered very large. In Table 1, it can be observed that the largest section has 343 rows.

Based on the randomly generated instances, it was observed that the hardware used limited running larger instances in the experiment. The model execution failed after 20,000 sugarcane rows due to a lack of memory in the computer used in the tests. For smaller amounts of sugarcane rows, an optimal solution could be obtained for the problem in acceptable computational time. As usual, the real sections did not exceed this number of sugarcane rows, and therefore, we can state that the proposed model and the Cplex solver are adequate to provide good solutions for the Route Planning Problem for Mechanized Harvesting when real data instances are considered.

**Table 1**
Data and results for the performed tests.

| Instance | N° of plots | Area (ha) | N° of rows | Total time of maneuvering | | Computational time (s) |
|---|---|---|---|---|---|---|
| | | | | Traditional (s) | Optimized (s) | |
| 01 | 3 | 6.6 | 95 | 11,320 | 9120 | 3.559 |
| 02 | 5 | 35.8 | 232 | 27,760 | 21,930 | 10.500 |
| 03 | 4 | 45.4 | 295 | 35,320 | 20,250 | 3.554 |
| 04 | 4 | 16.7 | 242 | 28,960 | 22,690 | 148.853 |
| 05 | 2 | 25.3 | 164 | 19,600 | 15,750 | 5.268 |
| 06 | 2 | 10.4 | 150 | 17,920 | 14,520 | 4.917 |
| 07 | 3 | 10.9 | 158 | 18,880 | 15,250 | 12.332 |
| 08 | 2 | 17.5 | 253 | 30,280 | 17,520 | 3.320 |
| 09 | 2 | 7.7 | 111 | 13,240 | 7960 | 2.545 |
| 10 | 3 | 26.7 | 173 | 20,680 | 11,880 | 2.831 |
| 11 | 2 | 21.8 | 141 | 16,840 | 10,020 | 2.660 |
| 12 | 4 | 28 | 182 | 21,760 | 17,260 | 5.879 |
| 13 | 2 | 11.9 | 172 | 20,560 | 16,280 | 5.133 |
| 14 | 2 | 5.2 | 75 | 8920 | 5070 | 2.335 |
| 15 | 2 | 5.6 | 81 | 9640 | 5460 | 2.321 |
| 16 | 2 | 12.2 | 176 | 21,040 | 16,530 | 19.443 |
| 17 | 2 | 5.2 | 75 | 8920 | 4960 | 2.402 |
| 18 | 4 | 24.1 | 156 | 18,640 | 15,240 | 4.484 |
| 19 | 3 | 4.5 | 65 | 7720 | 4310 | 2.242 |
| 20 | 2 | 14.4 | 208 | 24,880 | 19,490 | 7.435 |
| 21 | 2 | 10.7 | 155 | 18,520 | 10,600 | 2.723 |
| 22 | 2 | 2.1 | 30 | 3520 | 2750 | 2.105 |
| 23 | 2 | 4.7 | 68 | 8080 | 6660 | 3.137 |
| 24 | 5 | 36.2 | 235 | 28,120 | 17,010 | 3.317 |
| 25 | 2 | 4.7 | 68 | 8080 | 6440 | 3.165 |
| 26 | 6 | 26.3 | 170 | 20,320 | 16,249 | 19.965 |
| 27 | 2 | 28.2 | 183 | 21,880 | 13,190 | 2.922 |
| 28 | 2 | 6.7 | 97 | 11,560 | 6940 | 2.478 |
| 29 | 2 | 19.1 | 276 | 33,040 | 26,990 | 1,513.583 |
| 30 | 2 | 30.9 | 200 | 23,920 | 18,970 | 43.296 |
| 31 | 2 | 15 | 217 | 25,960 | 14,630 | 3.543 |
| 32 | 5 | 44.3 | 287 | 34,360 | 19,730 | 3.628 |
| 33 | 2 | 14.6 | 211 | 25,240 | 14,790 | 3.081 |
| 34 | 2 | 13.7 | 198 | 23,680 | 18,510 | 55.302 |
| 35 | 4 | 52.8 | 343 | 41,080 | 18,510 | 56.711 |
| 36 | 6 | 42.7 | 277 | 33,160 | 19,740 | 3.582 |
| 37 | 5 | 23.5 | 152 | 18,160 | 14,530 | 4.511 |
| 38 | 2 | 6.7 | 97 | 11,560 | 6720 | 2.404 |
| 39 | 2 | 16.2 | 234 | 28,000 | 21,950 | 103.926 |
| 40 | 2 | 7.6 | 110 | 13,120 | 10,370 | 4.405 |
| 41 | 2 | 1.2 | 45 | 5320 | 2240 | 1.971 |
| 42 | 2 | 28.9 | 187 | 22,360 | 12,900 | 2.961 |
| 43 | 5 | 57.9 | 287 | 34,360 | 21,160 | 3.690 |
| 44 | 4 | 30.6 | 198 | 23,680 | 18,950 | 10.922 |
| 45 | 2 | 15.4 | 223 | 26,680 | 16,010 | 3.285 |
| 46 | 4 | 21.2 | 137 | 16,360 | 9320 | 2.645 |
| 47 | 2 | 10.9 | 158 | 18,880 | 14,810 | 6.638 |
| 48 | 3 | 57.8 | 312 | 37,360 | 31,310 | 28.116 |
| 49 | 4 | 27.1 | 176 | 21,040 | 16,750 | 51.423 |
| 50 | 4 | 29.7 | 193 | 23,080 | 12,960 | 3.073 |

## 4. Analyzing the results

To make it easier to analyze the solutions, Fig. 5 shows the sum of traditional and optimized times of maneuvers. The traditional time of maneuvers was obtained according to the geo-referenced data from last over the last years provided by the mill.

In Fig. 5, it can be observed that the optimized time taken for the machine to cover all the sugarcane rows was 31.64% less regarding the needed time for the traditional harvest. This reduction means that the company can save fuel and also finish the harvest process more quickly, saving on labor costs.

Due to the characteristics of the RPPMH, it can be considered an Arc Routing Problem, more specifically the problem can be shown by a graph that has an Eulerian circuit. This happens because the harvest machine leaves from a starting point, covers the mandatory edge just once and comes back to the starting point, making a linked graph. This characteristic is very special and makes the problem polynomial, i.e., it allows the model to be solved in polynomial time. This characteristic also accounts for the fact that the model solves a problem with a large amount of sugarcane rows in an acceptable computational time.

Field tests were performed using the solutions obtained by the mathematical model. The proposed strategy was evaluated by the managers from the mill and they met their expectations. Due to the efficiency and ease to adopt the proposed strategy, it is currently used by the mill in the harvest period.

Beside the reduction in time to carry out the harvest, other benefits can be observed including less expenses on fuel, reduction in labor costs, less wear of the harvest machines and less emission of pollutant gases in the environment, among others. Furthermore, this strategy is flexible and can be adapted for other kinds of harvest.

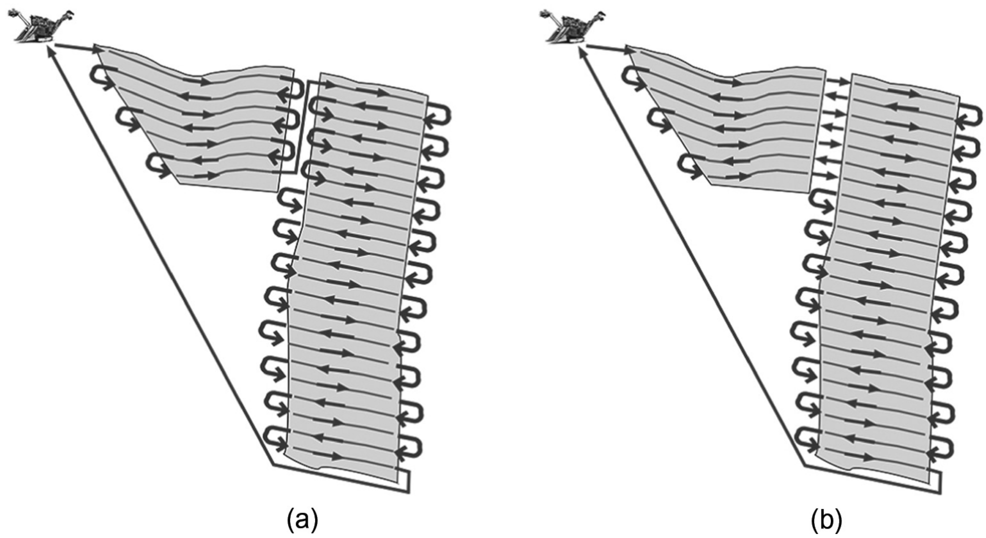


**Fig. 4.** Instance 22 – (a) traditional route; (b) optimized route.

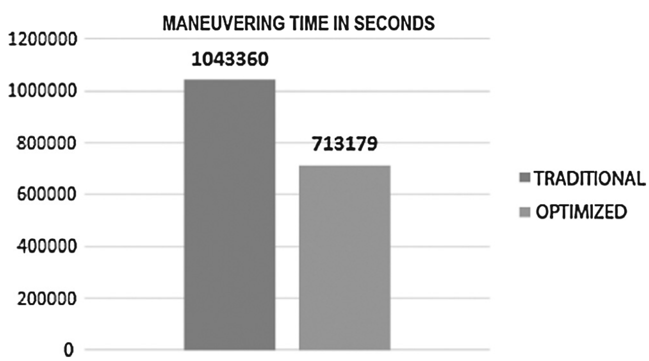


**Fig. 5.** Traditional and optimized time comparisons.

## 5. Conclusion

This article proposes a mathematical model to minimize the time of maneuvering a harvesting machine in a mechanized sugarcane harvesting process. The problem of planning the harvesting machine route is a real- life problem, which is very common in the sugarcane energy sector.

Computational tests were carried out using data from a Brazilian sugarcane energy company, which confirmed the model efficiency in providing solutions that minimize the maneuvering time of the harvesting machine. Based on the obtained solutions, a 31.64% time reduction was observed compared with the traditional harvest process for the same area when the route of the harvest machine was not planned.

Given the importance of the sugarcane energy sector for the Brazilian economy and the constant effort of this sector to optimize mechanized harvesting processes, this study presents an approach for solving a practical problem that involves one of the main processes from a fundamental sector in the Brazilian economy.

Besides reducing the harvest time, it is important to highlight that optimizing the harvesting machine route reduces the fuel consumption, the wear of the harvest machines and the labor costs, increasing the profit of the company. Furthermore, there is an important environmental contribution due to the fact that by optimizing the route, there is less $CO_2$ emission and other polluting gases.

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