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Use of the Analytic Hierarchy Process Method in the Variety Selection Process for Sugarcane Planting

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Abstract: The sugar and alcohol sectors are dynamic as a result of climate alterations, the introduction of sugarcane varieties, and new technologies. Despite these factors, Brazil stands out as the main producer of sugarcane worldwide, being responsible for 45% of the production of fuel ethanol. Several varieties of sugarcane have been developed in the past few years to improve features of the plant. This, however, led to the challenge of which variety producers should choose to plant on their property. In order to support this process, this research aims to test the application of the analytic hierarchy process (AHP) method to support producers to select which sugarcane variety to plant on their property. To achieve this goal, the research relied on a single case study performed on a rural property located inland of São Paulo state, the main producer state in Brazil. The results demonstrate the feasibility of the approach used, specifically owing to the adaptability capacity of the AHP method.

Keywords: multicriteria method; decision-making process; sugarcane; analytic hierarchy process

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1. Introduction

Sugarcane is an important commodity for several developing countries' economies, such as China [1], India [2], Belize [3], and Brazil—the main sugarcane producer in the world. Brazil started producing sugarcane in the 14th century, still in the colonial age, and around the 17th century, the country became the major sugarcane producer worldwide [4]. Nowadays, Brazil is responsible for producing 45% of the ethanol used for fuel in the world. The country is also one of the major exporters of sugar. São Paulo state is the main producer in the country, producing 53.7% of the Brazilian sugarcane in the 2019/2020 harvest, producing 29.03 million tons of sugar and 35.5 billion liters of ethanol. Moreover, the sector represented 26.89% (U.S. $4.07 billion) of the state exportation [5]. The northeastern region of the state received the greatest increase in sugarcane production, which took place in areas that previously held cattle and other agricultural production [6]. Other states in the south-central region of the country also experienced a similar pattern to São Paulo, although of a lower magnitude [7].

Among the reasons for the expansion of Brazilian production of ethanol from sugarcane was the introduction of flex-fuel engines in the internal market, which provides the ability to use any amount of ethanol and gasoline combination in vehicles [6,8]. The global demand for less environmentally harmful fuels played a significant part in this process [8], motivating research on several alternatives for replacing fossil fuels in the agriculture field, e.g., producing biomass from agricultural residues [9]. Brazilian governmental and industrial stakeholders took advantage of these positive scenarios and worked for the development of sugarcane production in the country. The substantial production of sugarcane in the São Paulo state is related to several factors, such as the presence of a large amount of land with appropriate quality for sugarcane, the best infrastructure in the country, and a regional system of innovation to support the development of production [10]. An expansive picture of Brazilian sugarcane-based ethanol production can be found in [11].

Sugarcane cultivation and processing plants have a significant impact on the Brazilian socio-economic structure, being a source of employment and income generation for several municipalities [12]. With the significant reduction in the burning technique previous to the harvesting [6], bioethanol production from sugarcane can also have positive outcomes for environmental sustainability, especially related to reducing CO_2 emission compared with using fossil fuels (see [13] for a review about sugarcane production and sustainability in Brazil). Recent studies show new opportunities to increase environmental sustainability in the sector, such as with circular economy practices [14], which is a concept that can contribute to achieving sustainable and human development [15].

Different varieties of sugarcane present different features that affect the products made from sugarcane as well as the sugarcane growth and production itself [16]. Brazil has been experiencing a significant increase in the number of sugarcane varieties [17]. New varieties of sugarcane are useful for achieving higher efficiency (e.g., lower costs and higher productivity) according to different factors [10], such as the new intensive mechanization (as well as other management aspects) and new environments for plantation (including soil and climatic conditions) [18]. Notwithstanding all the apparent benefits, a massive number of options cannot be easily processed, resulting in difficulty in selecting the best choice [19]. The bounded rationality of individuals affects the efficiency of the decision-makers, including in the agriculture sector [20]. In other words, the higher the number of sugarcane varieties, the more complex the process to select the best sugarcane variety [21].

A decision-making process should be structured based on rules, methods, and procedures and its goal should be the selection of the best-performing option, best expectation, or best evaluation among all the available choices [22]. Within the strategies for decision-making, multicriteria techniques are among the main approaches used, as they consider several factors—different conflicting criteria—related to the decision [23,24].

The use of multicriteria methods is a common approach in agriculture-related literature [14,25]. Within these applications, there is a branch of studies focused on variety selection using the analytical hierarchical process (AHP) method. AHP is a suitable approach to indicate preferences for different objectives [26]. For example, AHP has already been applied to support crop selection considering oilseed crops [27], as well as to select the best grape option for organic viticulture [28]. However, little research has relied on AHP to support the selection process of sugarcane variety (with the exception of [29]). Approaches to support variety selection can be quite useful for producers, especially in locations with low resources [30]. Thus, this research aims to test the application of the AHP method to support producers to select which sugarcane variety to plant on their property. In order to achieve this goal, the research relied on a single case study performed in a rural property located in São Paulo state, Brazil. Therefore, while the generalization of the approach used in this research can be made to other contexts, the specific outcomes (i.e., the variety selected) and the specific variables in the model (i.e., the varieties and their features) should be understood considering this case study. This is because of the external aspects that influence the sugarcane varieties, such as soil and climate. It is expected that the approach presented in this research can be especially useful for the decision-making processes related to variety selection faced by small and medium-sized rural producers.

After this introduction, Section 2 presents the materials and methods used in this research, describing the AHP method and the case study of this research. Next, Section 3 presents the results and discussions of the research's findings. Finally, Section 4 presents the conclusions.

2. Materials and Methods

2.1. Analytic Hierarchy Process

Analytic hierarchy process (AHP) was developed in the 1970s by Tomas L. Saaty, and consists of a multicriteria method used and known to support decision-making in problems with multiple criteria. It is based on the Newtonian and Cartesian method that seeks to solve a problem by decomposing it into factors, which can be decomposed into new factors up to the lowest level [31].

AHP is a method commonly applied to define weights for different criteria, being used in a different set of problems and fields, e.g., [27,28,32], mainly thanks to its robustness and simplicity [33]. These applications can be suitable for supporting the solution of simple issues involving only one person or extremely complex situations related to several variables [33]. Generally, the AHP method follows four main steps: problem modeling, pairwise comparison, judgment scale, and priorities' derivation [34].

The hierarchical structure begins with an overall objective that descends to criteria and then alternatives [35]. The first level of the structure presents the general objective to be achieved. The second level indicates the criteria that contribute to reaching the general objective. The third level contains the decision alternatives for the problem [36] (Figure 1).

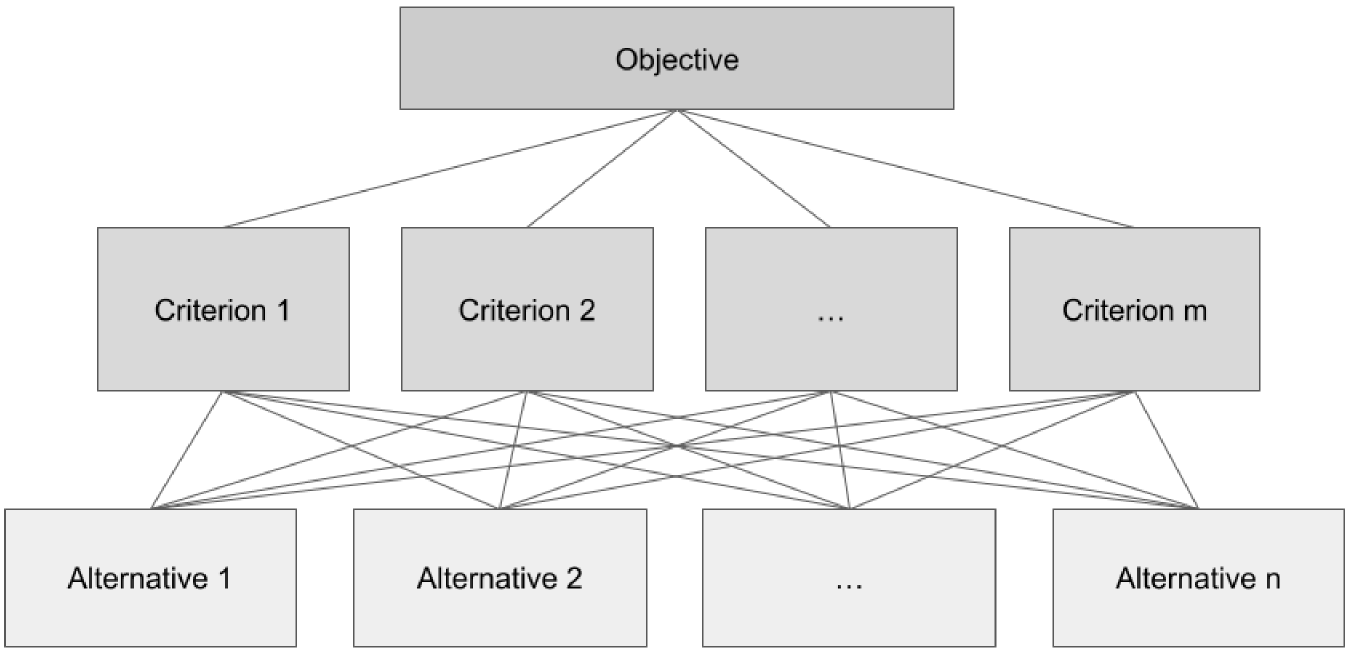

Figure 1. Representation of the basic hierarchical structure of the AHP method. Source: adapted from [37].

After the hierarchical model is developed to address the issue, the next step is the pairwise comparisons for each level of the model by the decision-makers participating in the research. This step aims to achieve a weight factor for each element on the level considering the element right on the next higher level. This process provides a measure of the relative importance of the considered element [36].

The priority definition should be based on the ability of the individuals to perceive the relationship between the objects, comparing the pairs in relation to a criterion or judgment. It is necessary to apply the following steps to achieve this [35,38]:

- Elaborate on the problem to be solved;
- Consider the objectives and results of the problem;
- Identify the criteria that influence the behavior;
- Structure the problem in a hierarchy of different levels, criteria, sub-criteria, and alternatives;

- Parity judgment: to judge pair-by-pair the elements in the hierarchy in relation to each element in the superior level, compounding a matrix of judgment A, using the scale presented in Table 1. The quantity of judgments for the construction of a matrix A is $n \times (n - 1)$, where n is the number of elements.

Table 1. Saaty's fundamental scale for the AHP method.

Intensity of Importance on an Absolute Scale	Definition	Explanation
1	Equal importance	Two options contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	Applied when compromise is needed

Source: adapted from [35].

- Normalization of the judgment matrices: through the sum of the elements of each column of the judgment matrix, their normalized values are obtained. After that, it is necessary to divide each element of these matrices for the summation of the values of the respective column;
- Calculus of the global priorities: it is necessary to identify a global priorities vector that can store the priority associated with each alternative in relation to the main focus;
- Logical consistency: this method calculates the consistency ratio of the judgment, being CR = CI/IR, where IR is the random consistency index obtained for a reciprocal matrix of order n, with non-negative elements and automatically generated. In order to be considered consistent, it is necessary that $CR \leq 0.10$.

2.2. AHP Application

In this research, the AHP method was used to support two medium producers of sugarcane located in the inland of São Paulo state, Brazil, to select varieties of sugarcane to be planted. Both are the owners and are responsible for the decision-making in the property. Thus, the application of the AHP method can support them to select the best option according to their preferences regarding the sugarcane's features. The land has purple oxisol soil, also known as "purple land", a kind of reddish soil that is very fertile. The climate is high-altitude tropical, which is characterized by the concentration of rains in the summer and temperatures below 18 °C in the winter.

The São Paulo state (Figure 2) has an estimated population of 44.7 million inhabitants, being the most populous Brazilian state, representing 21% of Brazil's population. In 2019, the GDP achieved by the state was approximately USD 582.18 billion, representing 31% of the national GDP [39]. The state also has among the country's highest levels of human development and municipal environmental management practices [40].

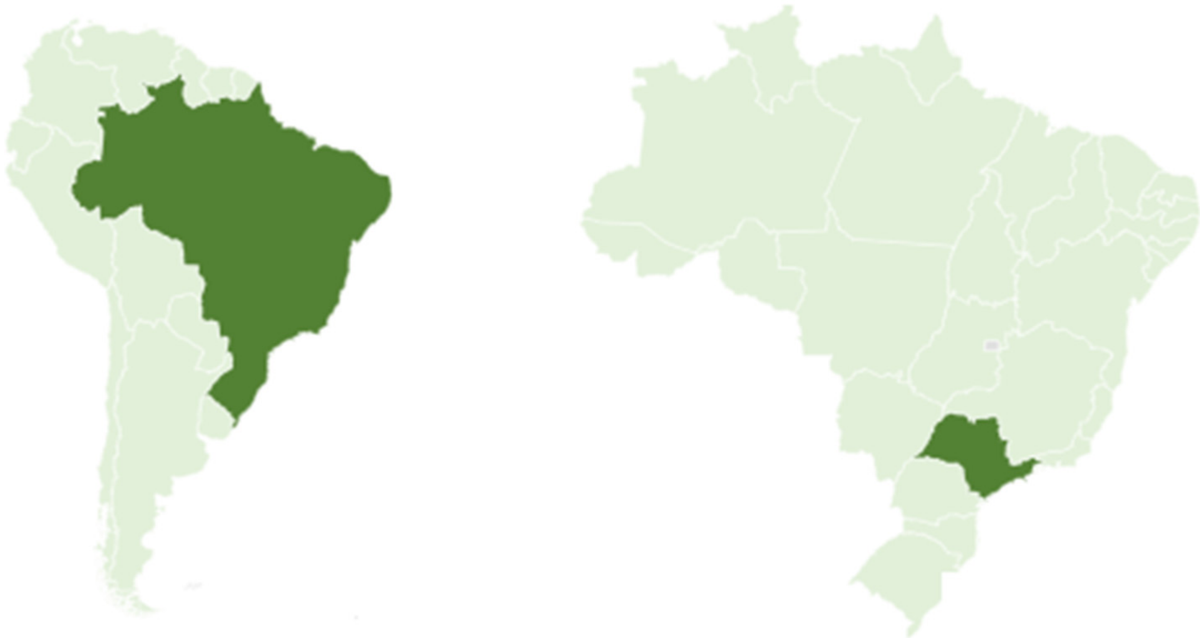

Figure 2. Brazil and São Paulo state location.

For decision applications, the AHP method was carried out in two phases: (1) the hierarchic design and (2) the evaluation [33]. One of the ways to develop the hierarchic design—phase (1)—is by reaching a consensus in a group, with the presence of individuals with knowledge and experience in the analyzed field being recommended [33]. The hierarchical model should be "complex enough to capture the situation, but small and nimble enough to be sensitive to changes" [31] (p. 163). Thus, in order to decompose the problem into hierarchy elements and to establish the criteria to be evaluated, the first author arranged a meeting with an agronomist engineer. The interview with the agronomist engineer was used to understand the most relevant criteria to be considered for AHP and the best varieties of sugarcane to be included in the model. This study considered the following possible varieties as options to be selected: RB867515, RB966928, CT9001, and RB855156, which are the most cultivated varieties in the regions according to the agronomist engineer. The selected criteria were as follows:

1. Potential for sucrose accumulation: this is the sugarcane's capacity that determines the agricultural production. The values vary according to the time of the year and support the steps that compound the industrialization process of the sugarcane [41];
2. Ratoon sprouting: physiological processes that encompass the period from plantation to the beginning of tillering, after the second cut [42];
3. Ton per hectare: mass of sugarcane produced in one hectare, where 1 ton/hectare is equivalent to 0.1 kg/m^2;
4. Longevity: this is the life expectancy of the cane field, that is, the number of cuts between cane field renovation cycles. As planting is one of the most important stages of sugarcane, a variety of sugarcane that has great longevity has a direct impact on production costs and economic return [43];
5. Soil requirement: this consists of the nutrients required by plants for proper growth [44].

Figure 3 represents the hierarchy constructed in this research.

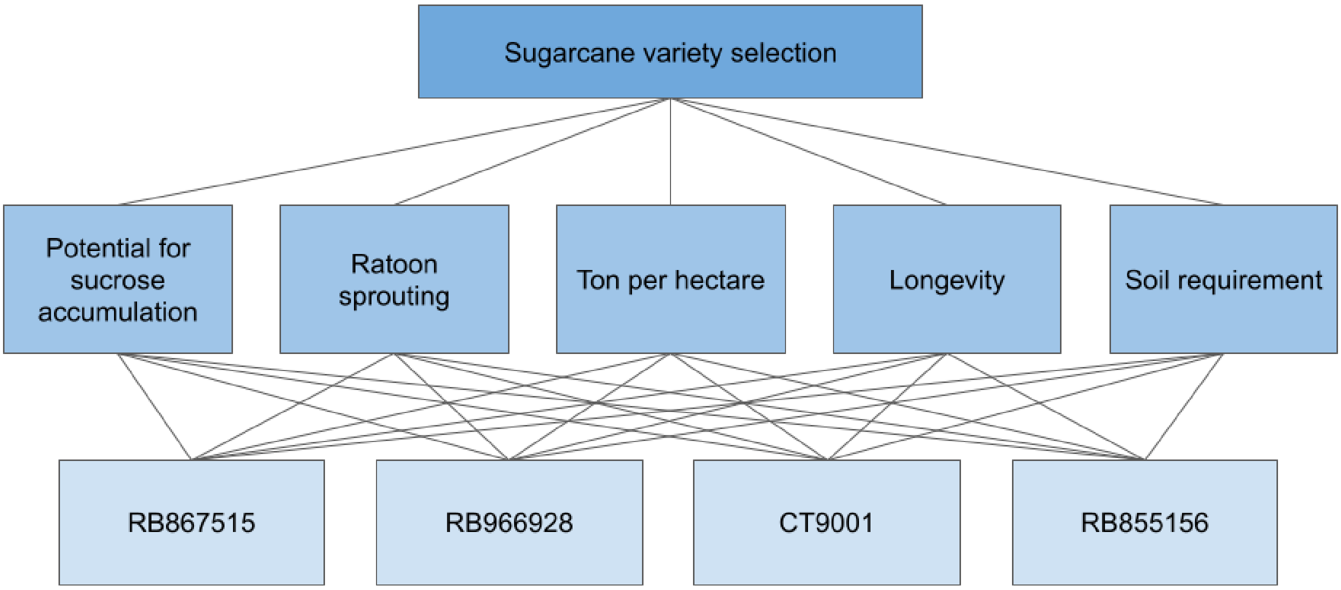

Figure 3. Representation of the basic hierarchical structure of sugarcane used in this research.

There is not a pre-established number of individuals that should be interviewed for the AHP method. In the agriculture-related literature, this number has ranged from large numbers in complex issues, such as 60 [45] and 144 [46], to small numbers when related to decision-making problems for farmers to apply in their work context, such as 1 decision-maker [36] and 3 decision-makers [28]. This last context is the case of this research, as the main goal of the AHP application was to support the farmers in selecting which sugarcane variety to choose on their farm. Thus, for the evaluation phase (phase 2), the first author arranged individual meetings with two local farmers who are co-owners of a farm located in São Paulo's inland and have more than 50 years of experience in agriculture production. From now on, they will be called decision-maker 1 and decision-maker 2. This step was performed in order to conduct the paired comparison of each element on the hierarchical level, creating a matrix of quadratic decisions. The paired comparison used the Saaty's fundamental scale for AHP (Table 1). Next, the authors determined the degrees of preference for each criterion, developing five matrices that compare the degrees of intensity for pairs as a function of each characteristic, referencing the five criteria adopted. With the comparing matrices fulfilled, the authors created an algorithm in C language and in MatLab R2015a to implement the AHP method. The results were validated with the application of the Super Decision Software. Next, the authors evaluated the consistency ratio (CR) of all hierarchies, dividing the consistency index (CI) by the random consistency index (RCI) obtained for one matrix of order n, with non-negative elements and randomly generated. The RCI of the hierarchy must be inferior or equal to 10%. The flowchart in Figure 4 presents all of the research steps.

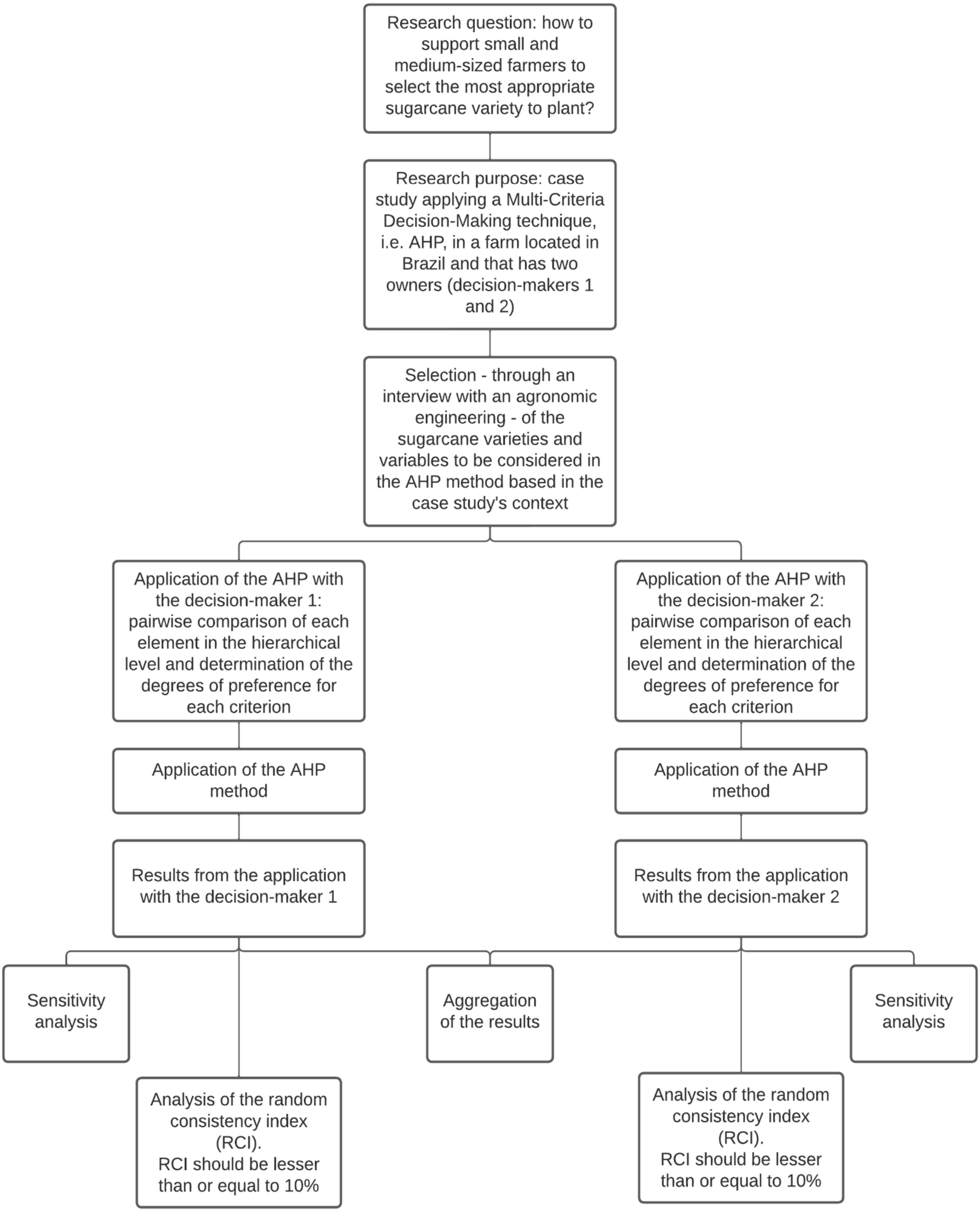

Figure 4. Flowchart describing all of the steps of the AHP method applied in this research.

3. Results

Table 2 presents the prioritization of each alternative (variety of sugarcane) related to each criterion and the main focus of decision-maker 1 and decision-maker 2.

Table 2. Prioritization of each alternative of decision-maker 1 and decision-maker 2 for the variables considered in the AHP application.

Criterion	Decision-Maker	Sugarcane Variety	RB867515	RB966928	CT9001	RB855156
Potential for sucrose accumulation	1	RB867515	1	1/9	1/5	1/3
		RB966928	9	1	5	9
		CT9001	5	1/5	1	3
		RB855156	3	1/9	1/3	1
	2	RB867515	1	1/7	1/3	1/5
		RB966928	7	1	5	3
		CT9001	3	1/5	1	1/5
		RB855156	5	1/3	5	1
Ratoon sprouting	1	RB867515	1	1/9	1/5	1/3
		RB966928	9	1	3	1
		CT9001	5	1/3	1	1
		RB855156	3	1	1	1
	2	RB867515	1	1/7	3	1/3
		RB966928	7	1	7	5
		CT9001	1/3	1/7	1	1/5
		RB855156	3	1/5	5	1
Ton per hectare	1	RB867515	1	1/3	1/5	1/3
		RB966928	3	1	1/3	3
		CT9001	5	3	1	5
		RB855156	3	1/3	1/5	1
	2	RB867515	1	1/5	1/3	1
		RB966928	5	1	5	7
		CT9001	3	1/5	1	3
		RB855156	1	1/7	1/3	1
Longevity	1	RB867515	1	1/5	1	1/9
		RB966928	5	1	5	1/7
		CT9001	1	1/5	1	1/9
		RB855156	9	7	9	1
	2	RB867515	1	1/5	3	1/5
		RB966928	5	1	7	3
		CT9001	1/3	1/7	1	1/3
		RB855156	5	1/3	3	1
Soil requirement	1	RB867515	1	1/5	1/5	1/9
		RB966928	5	1	1/3	1/5
		CT9001	5	3	1	1
		RB855156	9	5	1	1
	2	RB867515	1	1/7	1/5	1/3
		RB966928	7	1	5	7
		CT9001	5	1/5	1	3
		RB855156	3	1/7	1/3	1

With the application of the AHP method, after performing the matrices' normalization and the calculation of the average of each criterion, it was possible to determine the preference matrices, as presented in Table 3 for decision-maker 1 and decision-maker 2.

Table 3. Preference matrix of each variable and sugarcane variety for both decision-makers.

Decision-Maker	Sugarcane Variety	Potential for Sucrose Accumulation	Ratoon Sprouting	Ton per Hectare	Longevity	Soil Requirement
1	RB867515	0.047321	0.059865	0.076463	0.057550	0.049690
	RB966928	0.660862	0.446506	0.244503	0.212166	0.144201
	CT9001	0.199117	0.226610	0.543046	0.057550	0.350881
	RB855156	0.092700	0.267019	0.135988	0.372734	0.455229
2	RB867515	0.05385091	0.099166143	0.088053939	0.104356652	0.050389565
	RB966928	0.551807627	0.638159813	0.6302765	0.567573554	0.638159813
	CT9001	0.101457857	0.050389565	0.200719575	0.062934631	0.21228448
	RB855156	0.292883606	0.21228448	0.080949986	0.265135162	0.099166143

Regarding the sucrose accumulation criterion, both decision-makers indicated a preference for RB966928. However, while decision-maker 1 preferred CT9001 as the second-best variety, decision-maker 2 opted for the RB55156 variety. Regarding the criterion of ratoon sprouting, both decision-makers agreed that the best variety was RB966928 and the second preference was RB855156. Considering the criterion ton per hectare, decision-maker 1 elected CT9001 as the best choice, while decision-maker 2 opted for RB855156. For the longevity criterion, decision-maker 1 considered RB855156 as the best variety, followed by RB966928; decision-maker 2, however, considered the RB966928 variety as the best and RB855156 as the second preference. Finally, considering the soil requirement criterion, decision-maker 1 chose the RB855156 variety, while decision-maker 2 preferred the RB966928 variety.

Table 4 presents a criteria comparison matrix for decision-maker 1 and decision-maker 2. Both decision-makers presented similar options regarding the comparison of the criteria; the majority of comparisons were different in two points of intensity importance. The main difference is that, while decision-maker 1 considers that longevity has a moderate importance over ton per hectare, decision-maker 2 considers that ton per hectare has a strong importance over longevity. In other words, when comparing only these two criteria, decision-maker 1 considers longevity more important while decision-maker 2 considers ton per hectare more important. There was also a difference when comparing the sucrose accumulation criterion with the longevity criterion. While decision-maker 1 considered longevity with very strong importance over the sucrose accumulation criterion, decision-maker 2 considered longevity with moderate importance over sucrose accumulation.

Table 4. Criterion comparison matrix of each variable and sugarcane variety for both decision-makers.

Decision-Maker	Sugarcane Variety	Potential for Sucrose Accumulation	Ratoon Sprouting	Ton per Hectare	Longevity	Soil Requirement
1	Potential for sucrose accumulation	1	1/9	1/5	1/7	1/3
	Ratoon sprouting	9	1	5	5	7
	Ton per hectare	5	1/5	1	1/3	3
	Longevity	7	1/5	3	1	5
	Soil requirement	3	1/7	1/3	1/5	1
2	Potential for sucrose accumulation	1	1/7	1/7	1/3	1/5
	Ratoon sprouting	7	1	3	7	9
	Ton per hectare	7	1/3	1	5	5
	Longevity	3	1/7	1/5	1	3
	Soil requirement	5	1/9	1/5	1/3	1

Next, the authors normalized the comparison matrix of the criteria and calculated the average in order to achieve the final result, which is displayed in Table 5.

Table 5. Result of the AHP application with the preferences of both decision-makers for each sugarcane variety.

Variety	Decision-Maker 1	Decision-Maker 2
RB867515	5.8477466%	9.1871988%
RB966928	35.7146925%	62.6347183%
CT9001	24.3115487%	10.6052233%
RB855156	34.1260123%	17.5728596%

The results in Table 5 present the final quantification of each alternative according to the answers provided by decision-maker 1 and decision-maker 2. Considering decision-maker 1, 5.84% of the quantification was for selecting variety RB867515, 35.71% for choosing variety RB966928, 24.31% for variety CT9001, and 34.12% for variety RB855156. For decision-maker 2, 9.18% of the quantification was for selecting variety RB867515, 62.63% was for selecting variety RB966928, 10.60% was for selecting variety CT9001, and 17.57% was for selecting variety RB855156.

Comparing the final results of both decision-makers, it was possible to notice that, even though there were differences in the percentage for each variety, they presented the same ranking order. In this way, for both decision-makers, the best choice was the RB966928 variety, the second-best choice was RB855156, the third was CT9001, and the last was RB867515.

In order to verify the method's validity, the authors calculated the consistency ratio in the research's matrices, that is, they compared the consistency index with the random consistency index corresponding to the dimension of each matrix. As the consistency ratio of the hierarchy of all matrices was lower than 10%, the method can be considered valid. Therefore, the sugarcane variety RB966928, with numeric results of 35.71% and 62.63% for decision-maker 1 and 2, respectively, should be selected considering the pairwise comparisons provided and the verification of the matrix's coherence. After achieving the final results, the first author presented them to both producers, which reported that the variety RB966928 is usually the one that they prefer and the one they were thinking of planting in the next season. Therefore, the method presented in this research can also be applied to evaluate whether the variety selected by the producers is indeed the one that the producers believe is the best option. Future studies should include longitudinal and economic data in order to verify whether the selected option is indeed the one that presents the best economic outcomes for the producers.

The aggregation of individual judgments (AIJ) method was used in order to aggregate the results of decision-makers into a single group [47] (Table 6). It is noticeable that the decision-makers' ranking was maintained, that is, the selected variety was RB966928 with 49.28%, followed by the RB855156 variety with 27.57%, next was the CT9001 variety with 15.19%, and finally the RB867515 variety with 7.96%.

Table 6. Aggregated results for both decision-makers 1 and 2.

Variety	Aggregated Results
RB867515	7.9622971%
RB966928	49.2800982%
CT9001	15.1858805%
RB855156	27.5717243%

The final priority of the alternatives is mainly determined by the weights assigned to the main criteria. Therefore, small changes in the relative weights can lead to large changes in the final ranking. In this context, sensitivity analysis can be performed based on the scenarios they reflect, increasing or decreasing the weight of individual criteria, resulting in changes in priority and rank [48].

As a final analysis, the authors performed a sensitivity analysis of the chosen criteria. For decision-maker 1, when the weight of the potential for sucrose accumulation criterion was changed, the alternative to be chosen remained RB855156. When the weight of the ratoon sprouting criterion was below 53.05%, the selected variety was RB855156; when it was above 53.05%, then the selected variety changed to RB966928. For the ton per hectare criterion, when its weight was at 0%, the selected varieties were RB855156 and CT9001; as the weight increased, the selected variety became RB966928. The variety chosen was CT9001 when the weight was 36.65%. The chosen alternative was RB966928 when the longevity criterion had a weight lower than 22.59%; when it was above this value, the selected variety was RB855156. On the other hand, when the weight of the soil requirement criterion was below 10.73%, the alternative chosen was RB966928; when it was above this level, the RB855156 variety was chosen. This same analysis was performed for decision-maker 2; however, regardless of the weight of the criteria, the variety chosen was RB966928. These analyses indicate that, for decision-maker 1, there is a system instability that varies, mainly, between the RB855156 and RB966928 varieties, which is justifiable because, as shown in Table 5, the variation between the choice of these varieties is only 1.58866802%. On the other hand, decision-maker 2′s system is stable, making it possible to change the relative importance levels of the criteria without affecting the choice of sugarcane variety, proving to be a robust choice, allowing the decision-maker greater security in relation to his choice.

4. Conclusions

The application of the analytic hierarchy process (AHP) to support a decision enables the analysis of all of the criteria and alternatives in light of each criterion. It can be considered that the goal to select the best variety of sugarcane was accomplished. The method used in this research is a supporting tool to the decision-making process, which does not diminish the farmer's role in it; he/she remains the decision element and source of information for judging the value and construction of the hierarchical model. Besides, the objective of the tool is to deal with the selection process scientifically and to model the subjectivity inherent to the decision-making process, not removing its subjectivity [29].

This research's importance is highlighted by applying a relatively simple method that can support farmers in selecting the best variety of sugarcane to plant. Another application of the method is to analyze whether farmers are selecting the best choice for their farms. Future studies could rely on a bigger sample in order to compare the varieties that farmers are planting and the choice that they reached as the best one with the AHP method. Considering theoretical implications, this research is important to increase the knowledge of AHP usefulness in the agricultural field.

Considering that the agricultural environment is very dynamic owing to environmental changes and the introduction of new technologies and new varieties of sugarcane into the market, the application of AHP proved to be adequate owing to its dynamic capacity of adaptation. Although there is no methodological issue in applying the AHP method with a sample of only two individuals, this can be considered one limitation of this research. Another limitation is that both farmers are from the same region of the state; therefore, future studies could compare the results of farmers in different locations and kinds of farms to better understand the issue. Finally, future studies should include longitudinal and economic data in order to perform further analysis and increase the outcomes of the method.

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