Bi-objective mathematical model for choosing sugarcane varieties with harvest residual biomass in energy cogeneration

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Abstract: Sugarcane crop occupies an area of about 23.78 million hectares in 103 countries, and an estimated production of 1.66 billion tons, adding to this volume more than 6% to 17% concerning residual biomass resulting from harvest. The destination of this residual biomass is a major challenge to managers of mills. There are at least two alternatives which are reduction in residue production and increased output in electricity cogeneration. These two conflicting objectives are mathematically modeled as a bi-objective problem. This study developed a bi-objective mathematical model for choosing sugarcane varieties that result in maximum revenue from electricity sales and minimum gathering cost of sugarcane harvesting residual biomass. The approach used to solve the proposed model was based on the ε-constraints method. Experiments were performed using real data from sugarcane varieties and costs and showed effectiveness of model and method proposed. These experiments showed the possibility of increasing net revenue from electricity sale, i.e., already discounted the cost increase with residual biomass gathering, in up to 98.44%.

Keywords: sugarcane, harvested residual biomass, bi-objective mathematical programming, ε-constraints method, energy cogeneration

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1 Introduction

Growing awareness of the natural resource limitations of the planet has encouraged the development of research aimed at increasing the efficiency in natural resources utilization. Meanwhile, UN Secretary-General Ban Ki-Moon announced 2012 as the International Year of Sustainable Energy for All, which was a way to encourage the goal of doubling the use of renewable energy in the global energy matrix by 2030.

The agricultural residual biomass is composed of crop residues (stalks, leaves, and pruning) and residues generated by industrial processing of agricultural origin products (cotton ginning, sugarcane crushing, and soybean crushing). Many papers have been published on the use of residual biomass from various crops, including sugarcane[1], nuts[2] and herbaceous materials (wheat, oats, and barley)[3].

The agricultural residual biomass can be converted into electricity or heat by cogeneration process. At present, two thirds of Europe's renewable energy comes from biomass. In addition, member countries of the European Union agreed to increase the share of renewable energies to 21% of its electricity and 25% of its heating by 2020. To achieve this goal it has been estimated that consumption of biomass should increase from current 13 million tons to 100 million tons by 2020.

Sugarcane is one of the most widespread crops in the world and a great generator of residual biomass. The

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most recent data from FAO[4] shows that, during the year of 2009, sugarcane was planted in 103 countries, in an area of over 23.78 million hectares and a production of about 1.66 billion tons. Brazil is the world's largest producer, followed by India and China. The ten largest producers of sugarcane in the world, with their respective areas planted according to the FAO[4] are presented in Table 1.

Table 1 Ranking of ten largest sugarcane producers in the world and their respective areas planted

Ranking	Country	Area (10^3 ha)	Production (10^6 ton)
1	Brazil	8 514.37	671.40
2	India	4 420.00	285.03
3	China	1 707.58	116.25
4	Thailand	932.47	66.82
5	Pakistan	1 029.40	50.05
6	Mexico	710.59	49.49
7	Colombia	379.51	38.50
8	Australia	391.29	31.46
9	Argentina	355.00	29.95
10	USA	353.66	27.46

The production of sugarcane generates a large quantity of residual biomass. Ripoli et al.[1] reported that for each ton of sugarcane there is over 6% to 17% of residual biomass produced in term of the newly harvested biomass.

At present, sugarcane crop residue can still be disposed by lighting the fire before harvesting, but in many regions of Brazil, this practice is banned because of its negative impact on the environment and thus being replaced by mechanized cutting[5]. The sugarcane crop residue must receive a destination, since they cannot remain on the field already that facilitates proliferation of sugarcane diseases.

An alternative would be to use sugarcane crop residue to generate electricity. Bagasse which is the residue from sugarcane crushing to produce sugar or ethanol and has been used in energy cogeneration by mills for a long time. At least, 13 countries in Africa, Asia, Latin America and Oceania are using cogeneration technology[6].

In Brazil, energy generated through use of sugarcane biomass was utilized in mill itself. Progressively, electricity sale has become an income source to mill. At present, only one third of electricity generated in most modern mills in Brazil is utilized in production processes, other two thirds is sold. Just in 2009/2010 harvest, the mills of Brazil injected into the electrical grid 5,000 MW on average, this represented 4% of capacity of installed generation by Brazil[7].

In 2008, contracts were signed with 31 mills for sale of 548 MW in the first public sale specifically for biomass energy performed in Brazil, ensuring fixed annual revenues of US$ 398 million (money values were originally calculated in the currency of Brazil and then converted to the dollar at the exchange rate of US$ 1.00 = R$ 1.80) for a period of 15 years[9]. Since electricity generation using sugarcane bagasse is a reality, an alternative is to use sugarcane crop residue in energy cogeneration. There are studies that justify this statement[1,8].

The utilization efficiency of sugarcane crop residue in cogeneration depends on the technologies employed in collecting, handling, compacting, gathering and transportation, besides the conversion process of calorific power into electrical energy. Ripoli et al.[1] studied these issues and demonstrated that use of sugarcane crop residues in energy cogeneration can be profitable.

Mills that adopt cogeneration technology have a decision problem to solve, which is to choose sugarcane varieties that result in lower gathering cost of sugarcane crop residue and greater revenue from electricity sales. Given wide sugarcane variety of different characteristics, there may be varieties with approximate gathering costs, but very different calorific power, and the opposite can also occur.

This work has been hypothesized that it is possible to increase revenue from electricity sale generated by cogeneration just choosing the sugarcane varieties to be planted in the plots available considering the gathering cost of crop residue, being the transport the main component this cost. To test this hypothesis, we elaborated a decision problem and developed a mathematical model that represents it. This problem is described as follows.

The problem consists of choosing between the n sugarcane varieties i available and adapting to the region of the mill, which should be planted in the k plots j of area L_j available, in order to generate greater sales revenue and lower residue gathering and transportation costs to plot j, located at distance D_j of the mill.

Since maximize revenue from electricity sale and minimize gathering cost are conflicting, a bi-objective approach was used to develop a decision support method for choosing sugarcane varieties. Multi-objective models have been applied to problems related to sugarcane biomass. For example, Buddadee et al.[9] developed a mathematical model to decide which to do with the excess sugarcane bagasse, produce electricity or ethanol. Florentino and Pato[10], on the other hand, developed a bi-objective mathematical model for problem of choosing sugarcane varieties, solved by genetic algorithm.

Bi-objective mathematical model was solved through the ε-constraints method. This method was implemented using the package of linear programming and mixed-integer programming GLPK (GNU Linear Programming Kit) version 4.46[11].

2 Materials and methods

2.1 Multi-objective optimization

2.1.1 Multi-objective decisions

Many real-world problems have conflicting objectives, i.e., it is impossible to improve one objective without deteriorating the other one. These problems are known as multi-objective problems and are different from the mono-objective problems regarding the meaning of solution concept. In multi-objective optimization, each objective corresponds to an optimal solution; hence these problems do not present a unique solution but a solution set known as efficient solutions or efficient frontier.

A solution is efficient if an improvement in one of the objectives can be achieved only at expense of at least one of the other objectives, i.e., the deterioration of one or more of the others objectives, to learn more about multi-objective optimization read Ehrgott [12].

In solving multi-objective problems one step to be performed is to determine the efficient frontier. The specialized literature reported various methods for determining a part or all efficient solutions.

The first method developed to solve multi-objective optimization problems, called classical methods, converts the original problem into an equivalent problem with a unique objective. This equivalent problem has some additional constraints for their solution. The main classical methods are weighted sum method and ε-constraints method. The weighted sum method consists of adding all objectives simultaneously using different weighted coefficients for each objective. Thus, original multi-objective problem is transformed into a mono-objective scalar problem, and sum of coefficients should be equal to one.

In this study the ε-constraints method was used. The main advantage of ε-constraints method is assurance in finding the efficient solutions. The disadvantages are that the inclusion of additional parameters directly affects the results obtained and a uniform distribution of additional parameters does not ensure the efficient solutions diversity.

2.1.2 The ε-constraints method

Ehrgott[12] reported that the ε-constraints method was introduced by Haimes et al.[13], and an extensive discussion can be found at Chankong and Haimes[14].

This method consists in reformulating a multi-objective problem considering some of your objectives while maintains other objectives constrained for values defined by a decision maker. For example, given f_1 the most important objective, the problem can be reformulated as follows:

$$\begin{gathered} Min f_1(x) \\ s.t. \\ f_r(x) \le \varepsilon_r \quad r = 2,\cdots,m \qquad (1) \\ x \in S^* \end{gathered}$$

where, ε_r is upper bound of objective r, r = 2, ..., m, and S^* is the set of feasible solutions to the problem.

This method is founded in the following theorems.

Theorem 1: The solution x^* is efficient, if and only if, there are $\varepsilon_r \in \mathrm{R}^+$, so that, x^* is an optimal solution of the problem (1) for all the r = 2, ..., m.

Theorem 2: If x^* is unique solution of (1), for some r = 1, ..., m, x^* is an efficient solution.

Theorem 3: If x^* is an efficient solution, x^* solve the problem (1), $\forall\, r$.

If the bounds (ε_r) were not properly selected, the subspace obtained by the constraints can be empty, i.e., the problem (1) has no solution. Whereas the problem addressed has two objectives, one became the objective function and the other is a constraint.

During construction of the efficient frontier it is necessary to initially determine a set of values for ε, from this moment denoted by ε_e, where p is the cardinality of the set ε_e. The values of ε_e are calculated using Equation (2).

$$\begin{gathered}\varepsilon_e = \varepsilon_{e-1} + \Delta, \quad e = 2, \cdots, p \\ \Delta = \frac{UB - LB}{p-1}\end{gathered} \tag{2}$$

where, Δ is a real number that represents a uniform distance among the values ε_e; UB is upper bound of the efficient frontier and LB is lower bound of the efficient frontier. In addition, the first value of ε_e is equal to lower bound of the efficient frontier, i.e., $\varepsilon_1 = LB$.

2.2 Gathering cost of sugarcane crop residue

The equations used to calculate parameters of sugarcane varieties were presented in the mathematical model, the Equations (3) to (8), were taken from Florentino et al.[8], the other equations were developed in this work.

There are four costs related to residues gathering of sugarcane crop in accordance with four steps which are windrowing, compression, putting in truck and finally shipping to mill.

The cost to windrowing, compacting and loading of the truck with crop residue of variety i, C_i (US\$/m^3), is calculated using Equation (3).

$$C_i = \frac{C_{wcl}}{V_i} \tag{3}$$

where, C_{wcl} (US\$/ton) is the cost for windrowing, compacting and loading of the truck with crop residue and V_i (m^3/ton) is the volume occupied by crop residue of sugarcane variety i after compacted.

The cost calculated using Equation (3) can be converted to US\$/ha using Equation (4).

$$CC_i = Q_i C_i \tag{4}$$

where, Q_i (m^3/ha) is an estimate of volume of crop residue produced by variety i per hectare of sugarcane planted.

The cost (C_{Dj}) for the truck to travel through D_j distance of the j field to mill, in US\$, is calculated using Equation (5).

$$C_{Dj} = D_j C_f P \tag{5}$$

where, D_j is the distance from the j field to mill (km); C_f is fuel consumption of the truck per kilometer (L/km) for transportation of crop residues and P is price of fuel per liter (US\$/L).

Thus, the transporting cost of crop residues of sugarcane variety i, produced in the plot j (US\$/ha) is calculated using Equation (6).

$$TC_{ij} = (\frac{Q_i}{V_t}) C_{Dj} \tag{6}$$

where, V_t (m^3) is the available volume of the truck.

Therefore, gathering cost (GC_{ij}) of crop residues for sugarcane variety i planted in the plot j is determined by adding Equations (4) and (6), and multiplied by area of the plot j, L_j (ha), according to Equation (7).

$$GC_{ij} = (CC_i + TC_{ij}) L_j \tag{7}$$

2.3 Electricity sale revenue

The cogeneration process transforms the calorific power generated by burning of crop residues in the mill boiler into electrical energy. The calorific power (CP_{ij}) of crop residues of sugarcane variety i, planted in the plot j, in MJ, is calculated using the Equation (8).

$$CP_{ij} = C_{pvi} Qv_i L_j \tag{8}$$

where, C_{pvi} is the calorific power of crop residues of sugarcane variety i, (MJ/ton), and Qv_i is the estimated amount of crop residues produced by variety i (ton/ha).

Revenue from electricity sale, (R_{ij}), produced through the transformation of calorific power of crop residues of variety i, (CP_{ij}), planted in the plot j, is calculated using the Equation (9).

$$RV_{ij} = CP_{ij} SP \rho \mu \tag{9}$$

where, SP is sale price of electricity (US\$/MWh); ρ is the conversion factor of calorific power for electricity (1/3600 Wh/J); and μ is efficiency of boiler and generator system, which is 25% suggested by Ripoli et al.[1].

2.4 Sugarcane varieties parameters

A sugarcane varieties mixture harvested must fulfill two parameters. The first parameter is the minimum supply (A in ton/ha), established for the Pol (polarisation) which is a measure of the sucrose content in sugar. Each sugarcane variety, i, has an estimated production of sucrose represented by A_i.

The second parameter is the amount of fiber present in sugarcane (ton/ha), which must be within the interval comprised for a minimum quantity, F_I, and a maximum quantity, F_S. Each sugarcane variety, i, has an estimated production of fiber represented by F_i.

2.5 Bi-objective mathematical model of the proposed problem

The method proposed in this study is to find efficient solutions considering a given value of residue gathering cost, and in followed determine sugarcane varieties and plot combination, which result in higher revenue from electricity sales. The maximization of revenue from electricity sale is chosen as the objective function; hence, the minimization of gathering cost of crop residues becomes a constraint. The mathematical model developed for this problem is shown below.

$$Max\sum_{i=1}^{n}\sum_{j=1}^{k}R_{ij}X_{ij} \tag{10}$$

Subject to

$$\sum_{i=1}^{n}\sum_{j=1}^{k}GC_{ij}X_{ij} \le \varepsilon_e \tag{11}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{k}A_iL_jX_{ij} \le AT \tag{12}$$

$$F_IT \le \sum_{i=1}^{n}\sum_{j=1}^{k}F_iL_jX_{ij} \le F_ST \tag{13}$$

$$\sum_{i=1}^{n}X_{ij} = 1, \quad \forall j = 1,2,\cdots,k \tag{14}$$

$$X_{ij} \in \{0,1\}, \quad \forall i = 1,\cdots,n \ e \ j = 1,\cdots,k \tag{15}$$

where, ε_e is an upper limit for gathering cost of crop residues and T is the total area available for the plantation, i.e., the sum of all areas of the plots L_j.

The objective function (10) maximizes revenue from electricity sale. The constraint (11) represents the second objective of the problem which is to minimize gathering cost of crop residues, with upper bound given by ε_e. The constraint (12) ensures that weighted mixture of sugarcane varieties will provide the required minimum amount of sucrose. The constraint (13) ensures that weighted mixture of sugarcane varieties will provide the fiber amount within of recommended interval. The constraints set (14) ensures that all plots will be used and only one variety will be planted per plot. Finally, the constraint set (15) defines decision variables. If $X_{ij} = 1$, then the variety i will be planted in the plot j, and if $X_{ij} = 0$, otherwise.

2.6 Data used in experiments

The real data regarding costs, fuel consumption, mill demands and truck capacity are presented in Table 2.

The data related to characteristics of sugarcane varieties used to calculate model parameters are presented in Table 3.

Table 2 Data concerning costs, fuel consumption, electricity sale price, mill demands and truck capacity

Cwcl US\$/ton	*Cf* l/km	*P* US\$/l	*SP* US\$/MWh	*A* ton/ha	F_I ton/ha	F_S ton/ha	*Vt* m^3
2.05	0.37	1.19	77.22	14	11	15	60

Table 3 Data concerning characteristics of sugarcane varieties adaptable to mill region

i	Variety	V_i m^3/ton	Qv_i ton/ha	Cpv_i MJ/ton	A_i ton/ha	Q_i m^3/ha	F_i ton/ha
1	SP80-1816	7.96	33.36	2 671.99	16.42	354.20	13.94
2	RB72454	8.61	37.58	2 649.95	20.40	299.28	12.90
3	SP80-3280	9.37	36.72	2 602.14	18.46	316.18	12.63
4	SP81-3250	10.62	34.25	1 947.85	18.38	320.85	11.32
5	RB85536	9.78	26.43	2 211.95	17.05	258.46	12.51
6	RB855113	10.87	29.38	2 310.37	17.54	319.38	10.91
7	SP791011	8.91	24.09	1 977.47	15.80	214.72	10.33
8	RB835486	9.56	21.53	2 444.20	12.84	205.77	9.28
9	RB711406	12.32	33.20	2 008.83	20.77	410.29	16.12
10	SP701143	7.05	22.14	1 924.80	15.01	155.98	11.59

Source: Florentino and Pato[10].

The data about distance to mill and plot areas are presented in Table 4.

Table 4 Data concerning to areas of plots and distances these to mill

j	D_j/km	L_j/ha
1	3.49	8.49
2	2.49	4.52
3	16.08	58.18
4	3.49	4.22
5	2.59	5.74
6	2.59	6.61
7	15.33	30.41
8	8.30	5.08
9	9.24	12.01
10	12.63	54.95
11	16.43	38.66
12	8.25	3.78
13	7.80	10.43
14	8.59	6.15
15	2.25	8.79
16	17.20	57.79
Sum	136.75	315.81

Source: Florentino and Pato[10].

2.7 Technologies and equipment used

Bi-objective mathematical model proposed was implemented using the package of linear programming and mixed-integer programming GLPK (GNU Linear Programming Kit) version 4.46[13].

The tests performed with the method were run in a notebook Acer 1.86 GHz, 2 GB of RAM and Windows Vista operating system.

3 Results and discussion

In order to evaluate effectiveness of the proposed method to construct efficient frontiers, some experiments were performed. The first step was to determine the values of ε_e according to Equation (2).

Initially, gathering costs related to the extreme values of efficient frontier, LB and UB, were calculated according to the procedure described below. The value of UB was calculated running the model using a very large value of ε_e. It is set as if there was not a limitation to the gathering cost. In this case the maximum values of revenue from electricity sale and gathering cost were calculated. The values obtained were $R_{\max}$ = US\$ 1.69×10^5 and UB = US\$ 3.17×10^4. The value of LB was calculated by replacing the objective function by left side of constraint (11), followed by running a new model for minimization. In this case the minimum values of gathering cost and revenue from electricity sale were calculated. The values obtained were $R_{\min}$ = US\$ 0.73×10^5 and LB = US\$ 1.91×10^4. After calculating the values of LB and UB, it was possible to determine the value set of ε_e which is necessary for choosing a value for p.

The efficient frontier can have a very large number of solutions, so for the first experiment p = 10 was adopted. The aim of this experiment was to present some values of efficient frontier and analyze the results of the two objectives of the problem.

The results of revenues from electricity sales, gathering costs, values of ε_e and the difference between the values of ε_e and gathering costs are presented in Table 5.

Table 5 Results for the two objectives of the problem and bounds ε_e of the experiment to p = 10

e	R_e (US\$)	GC_e (US\$)	ε_e (US\$)	ε_e-GC (US\$)
1	73 549.26	19 084.23	19 084.23	0
2	88 853.80	20 457.43	20 480.85	42.15
3	100 455.86	21 840.34	21 877.47	66.83
4	110 817.91	23 270.33	23 274.09	6.77
5	121 236.46	24 666.03	24 670.71	8.41
6	131 791.27	26 032.01	26 067.33	63.57
7	140 802.04	27 462.78	27 463.95	2.09
8	149 981.55	28 854.27	28 860.57	11.33
9	158 919.29	30 167.36	30 257.19	161.69
10	168 655.36	31 653.81	31 653.81	0

The variation between the extremes of gathering cost was US\$ 12 569.58 and the extremes of revenue from electricity sale was US\$ 95 106.10. This showed that revenues increased at a rate greater than the increase of cost.

The revenue increase was 656% superior to the gathering cost increase among the efficient frontier extremes. This demonstrated that for the optimal choice of sugarcane varieties it was possible to obtain revenue from electricity sales.

The choice of appropriate solution is of the decision maker, i.e., should choose one of the solutions of the efficient frontier. Given the first experiment, for example, choosing point 2, instead of point 1, the gathering cost increased US\$ 1 373.21, but the increase in revenue from electricity sales is US$ 15 304.54, which represents a gain of US$ 13 931.33.

The net revenue variable (NR_e), which equals revenue from electricity sales discounted the gathering cost of crop residue (R_e - GC_e), was created in order to measure the revenue increase from the optimal choice of sugarcane varieties. Two more variables were also created.

The variable named the net revenue increase (NRI_e) was created to measure the percentage increase for one point of efficient frontier to another. The analysis of this variable showed that as the revenue from electricity sales reaches the maximum value, the marginal increase is getting smaller.

The variable named accumulated increase of net revenues ($ANRI_e$) was created to show the increase in revenue from electricity sales for the point of lower revenue to the point of efficient frontier indicated by e.

Given the first experiment the values regarding the variables NR_e, NRI_e, $ANRI_e$, in addition revenue from electricity sale per hectare for each solution of the efficient frontier are presented in Table 6.

Table 6 Revenue from electricity sale per hectare planted and variation in revenue through efficient frontier in the experiment for p = 10

e	R_e/ha (US$)	NR_e (US$)	NRI_e/%	$ANRI_e$/%
1	232.89	54 465.03	—	—
2	281.35	68 396.37	25.58	25.58
3	318.09	78 615.52	14.94	40.52
4	350.90	87 547.58	11.36	51.88
5	383.89	96 570.43	10.31	62.19
6	417.31	105 759.26	9.52	71.70
7	445.84	113 339.26	7.17	78.87
8	474.91	121 127.28	6.87	85.74
9	503.21	128 751.93	6.29	92.04
10	534.04	137 001.55	6.41	98.44

Based on the values of the variable $ANRI_e$ (Table 6), it showed that it was possible to increase the net revenue from electricity sale, i.e., already discounting the gathering cost in up to 98.44%.

The electricity generation using cogeneration considering the efficient frontier extremes varied from 952.44 MWh to 2 184.03 MWh, a variation of 129.31%. This increase was higher than the 98.44%, observed in the increase in net income, since it was not discounted the gathering cost. The values of electricity generation regarding the first experiment are shown in Table 7.

Table 7 The electricity generation estimated by experiment for p = 10

e	EP_e (MWh)
1	952.44
2	1 150.62
3	1 300.87
4	1 435.05
5	1 569.97
6	1 706.65
7	1 823.34
8	1 942.21
9	2 057.95
10	2 184.03

Other experiments were performed to verify and assess the ability of proposed method to generate the largest possible number of efficient frontier values for the sample data. The effective solutions set is unknown, hence, five experiments with the p value varying from 300 to 10 000 were performed. Some values of ε_e did not result in new efficient solutions, because the value added to gathering cost was not sufficient to generate a new combination of sugarcane varieties with higher revenue from electricity sales. The number of effective solutions generated, time used and p values are shown in Table 8.

Table 8 Experiments results for different values of p

Exper.	p	Number of frontier solutions	CPU Runtime (s)
1	300	282	40.26
2	500	450	67.06
3	1 000	804	126.92
4	5 000	2 643	632.36
5	10 000	3 894	1 273.32

The experiment with p equal to 300 found 282 efficient solutions in just 40.26 s, which is already a very large number of options available to decision makers of mills. In addition, proposed method can find a greater number of efficient solutions when the value of p increased.

The number of efficient solutions for any multi-objective problem is unknown. Therefore, five experiments were performed using increasing amounts of p, thus increasing the number of efficient solutions was found. It could be used for p values greater than 10 000 to find more efficient solutions than the 3 894 found in five experiments.

The efficient frontier can be represented through a scatter chart with the abscissa and the ordinate representing the objectives of the problem. Figure 1 showed the efficient frontier of the experiment with p = 300 and 282 efficient solutions found.

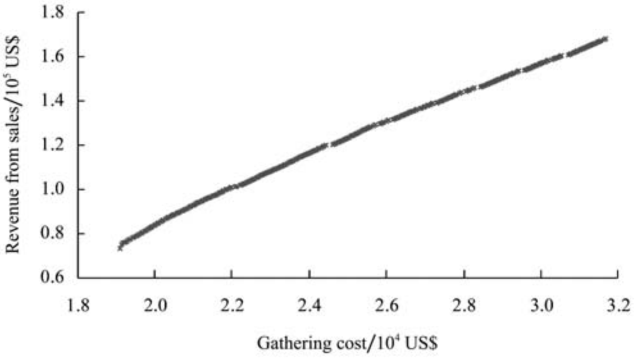

Figure 1 Efficient frontier with 282 solutions to the objectives of maximization of revenue from electricity sales and minimization of gathering cost

4 Conclusions

This work showed that it is possible to increase revenue from electricity sale at a rate greater than the increase in gathering cost of crop residue if just choosing the sugarcane varieties and suitable plots. Since interval variation for efficient frontier of gathering cost was US$ 12 569.58, the variation in revenue from electricity sales was US$ 95 106.10, approximately 656% higher. In addition, an experiment showed that net revenue from electricity sales, i.e., already discounting increase of gathering costs, increased in 98.44% from the lower bound to the upper bound of efficient frontier.

The proposed method was effective in finding a large number of solutions for the bi-objective problem proposed. Since the last experiment found 3 894 solutions that maximize revenue from sales of electricity generated using cogeneration and minimize gathering cost of crop residues.

The use of bi-objective mathematical model and the ε-constraints method showed to be useful to decision makers of mills. Because for a given number of plots and sugarcane varieties, available choose sugarcane varieties would result in maximum revenue from electricity sales and minimum gathering cost of sugarcane residual biomass.

A limitation to the use of mathematical optimization is the computational runtime to determine the optimal solution. In this work it was not an obstacle, since in experiment more challenging, the runtime used was of 1 273.32 s, or approximately 21 min.

The UN has encouraged countries to increase the share of sustainable energy sources in the energy matrix. One way of encouragement was to announce the year 2012 as International Year of Sustainable Energy of All. This confirms the need to increase the cases number of residual biomass utilization in electricity cogeneration. Thus, this study aimed to contribute in efforts to make use of residual biomass of sugarcane harvesting for electricity cogeneration as a financially profitable activity.

The mathematical model presented in this study can be applied to other regions and countries, being only necessary to change the data of sugarcane varieties, costs and selling prices of electricity.

A suggested future paper would be to perform further experiments with other sugarcane varieties adapted in different regions and countries, with their respective costs and selling prices of electricity in order to verify that the results are as good as in this example.

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