Environmental aspects in a multiobjective optimization study of a sugarcane biorefinery

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Abstract
Processes integrating production of first and second generation ethanol (E1G and E2G) are an option to increase ethanol production from sugarcane without increasing land area dedicated to produce crops for biofuel production. In this integrated process, sugarcane juice is used to produce E1G by fermentation of mainly sucrose, and sugarcane bagasse serves both as fuel for the cogeneration system and feedstock for the E2G production process steps. This integrated process produces bioethanol and bioelectricity (surplus sold to the grid) and generates, as main effluents, carbon dioxide (both from the combustion and from the fermentation steps) and vinasse. In order to reduce the impact of effluent generation, vinasse is concentrated in multiple-effect evaporators, which consumes steam. In order to evaluate conflicting process and environmental objectives (maximization of industry products throughput and minimization of vinasse leaving the process), multiobjective optimization studies, using non-dominance and Pareto Front approach are conducted with multiobjective particle swarm optimization algorithm, using EMSO software. The results present a set of non-dominated solutions, with different environmental aspects and leading to different throughputs. This set may guide decision makers on how to operate the process, looking for greater profits, while, at the same time, ensuring a more sustainable process.

Keywords
Sugarcane biorefinery; second generation ethanol; bioelectricity; vinasse concentration; multiobjective optimization; Pareto Front

INTRODUCTION

In first generation ethanol (E1G) production from sugarcane, sugarcane juice is used to produce bioethanol (and possibly sugar), and sugarcane bagasse is used as fuel for the cogeneration system, which produces steam and electric power, with surplus of the latter being sold to the grid. Due to concerns on increased land use dedicated to crops for biofuel production, instead of food, second generation ethanol (E2G) produced from bagasse can come as an answer to, at least, not increasing land use for this purpose. However, in E1G and E2G integrated process, bagasse has also to be used as feedstock for the E2G production steps, in which both cellulose and hemicellulose are hydrolyzed into building sugars, which are fermented into bioethanol. Lignin and unhydrolyzed cellulose are used as complementary boiler fuels. Besides CO_2, sugarcane biorefineries produce large amounts of vinasse (around 10 times the amount of bioethanol), a pollutant with high concentration of organic matter. For its content of cations such as potassium, calcium and magnesium, vinasse is frequently used in fertigation systems, but not all vinasse can be used in an economic and environmental conscious base, due to logistics costs and soil contamination. Salinization, leaching of metals present in the soil to groundwater, and changes in soil quality are some of the possible negative effects of direct application of vinasse in the soil (Christofoletti et al., 2013). A process alternative to alleviate this problem is vinasse concentration, in multiple-effect evaporators, since fertigation not always can dispose of total volume of vinasse produced. Concentrated vinasse has improved fertilizer quality, besides the benefit of decreasing water use in the plant. However, this alternative increases steam consumption by the process, which is already increased by increased ethanol production (E1G + E2G). Also, with E2G production, vinasse production is increased (when compared to a sole E1G process). This poses a conflict between process and environmental objectives. In order to increase throughput of bioethanol, more bagasse should be diverted to the second generation ethanol production steps of the process, and, consequently, more vinasse is produced and less bagasse is available to produce steam to the process and bioelectricity to the grid.

This work presents three optimization studies with conflicting objectives (maximization of industry products throughput and minimization of concentrated vinasse leaving the process). Process is modelled and simulated in EMSO (Soares and Secchi, 2003), an equation-oriented process simulator. A multiobjective particle swarm optimization algorithm, MOPSO (Raquel and Naval, 2005), is coupled to EMSO as a plugin (Gonçales et al., 2012) and is used in these studies.

METHODOS

The biorefinery processes 600 t/h of sugarcane and uses acid pretreatment in E2G unit. The integrated process was simulated in EMSO (Figure 1). E1G process was modeled according to the established industry in Brazil, and E2G is produced both from hexose and pentose fractions of bagasse. Glucose liquor from cellulose enzymatic hydrolysis is mixed with sugarcane juice from first generation, concentrated and then fermented by *Saccharomyces cerevisiae*, while pentose rich juice is separately concentrated and fermented by *Pichia stipitis*. In order to increase steam production, lignin removed from bagasse, 42% of available sugarcane trash (35 t/h) and the rest of cellulose (the unhydrolyzed fraction) are sent to the boiler. The co-generation system is comprised of a boiler of 65bar, one back-pressure turbine (exhausting pressure of 2.5bar), and one condensing turbine. Details about process specifications can be found in Oliveira et al. (2015) and in Ensinas et al. (2014). Multiple-effect evaporators are used to concentrate the mixture of glucose liquor and sugarcane juice up to 22 ºBx (ºBx denotes Brix value, percentage of soluble solids in a stream). Another set of multiple-effect evaporators is used to concentrate vinasse. Vinasse that comes from distillation column is divided into two fractions and the fraction that passes through the evaporators is concentrated up to 11.4 ºBx. Steam produced in the first effect of both sets are used as hot utility in heat exchangers and distillation columns reboilers.

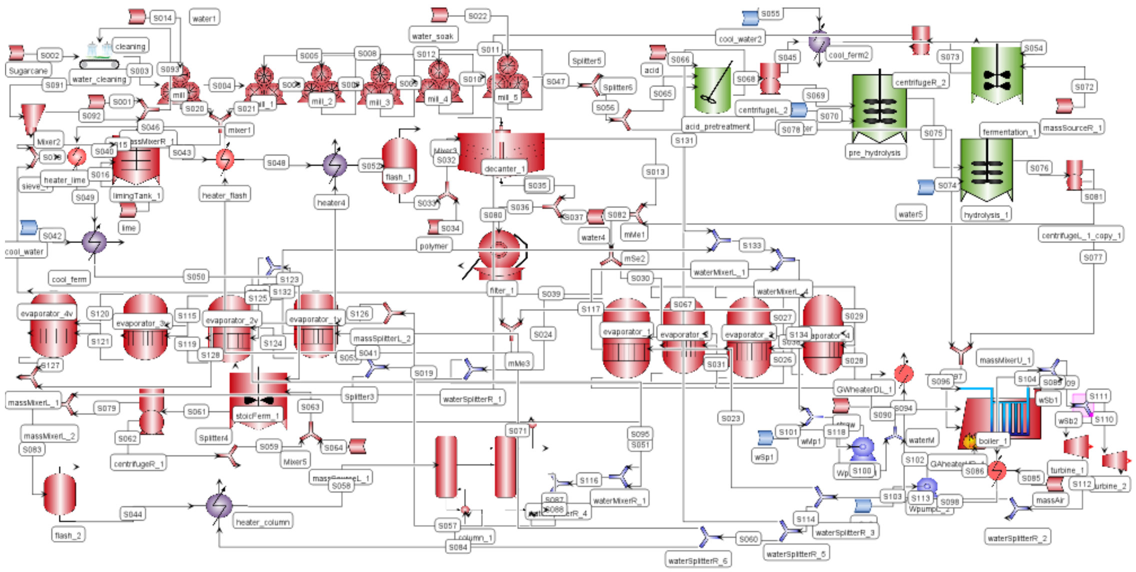

Figure 1. EMSO flowsheet of the sugarcane biorefinery.

Three multiobjective optimization problems are studied in this work (Eq.1-3). Figure 2 depicts a schematic representation of the integrated E1G + E2G and bioelectricity production process. In this figure, the three objective functions are respresented: concentrated vinasse production (Obj1, to be minimized), electric power (Obj2, to be maximized), and bioethanol throughput (Obj3, to be maximized). Also in Figure 2 the decision variables are represented: the fraction of bagasse diverted to the E2G production steps (Var1) and the fraction of vinasse that is concentrated up to 11.4 ºBx (Var2). The stochastic optimization algorithm MOPSO uses the Pareto Front approach and non-dominated solutions found during journey of particles are collected in an external file. Crowding distance tool is used in order to favour search in least populated regions of the search space (Gonçales et al., 2012). MOPSO parameters were 15 particles, 15 iterations, inertia factor equals 0.4, cognitive and social parameters equal 2.0. In the three studies feasible path approach is used. It is important to stress that the simulated production plant must be energetically self-sufficient. If a pair of decision variables leads process not to be energetically self-sufficient, the set of equations comprising the plant model does not converge, when solved simultaneously. Whenever this situation occurs, MOPSO receives, for this pair of decision variables, unfavorable function values.

RESULTS AND DISCUSSION

Figures 3 and 4 present, respectively, the non-dominated solutions found by MOPSO and the decision variables for the three optimization problems. In Table 1 it is possible to see details of process conditions of some of these non-dominated solutions (two for each optimization problem). In this table, values for objective functions, in each optimization problem, is highlighted in gray.

$$\text{Optim1}\begin{cases} \min\limits_{Var1,Var2} (Obj1) \\ \max\limits_{Var1,Var2} (Obj2) \\ s.a. \quad 0 \le Var1 \le 1 \\ \qquad\; 0 \le Var2 \le 1 \end{cases} \tag{1}$$

$$\text{Optim2}\begin{cases} \min\limits_{Var1,Var2} (Obj1) \\ \max\limits_{Var1,Var2} (Obj3) \\ s.a. \quad 0 \le Var1 \le 1 \\ \qquad\; 0 \le Var2 \le 1 \end{cases} \tag{2}$$

$$\text{Optim3}\begin{cases} \min\limits_{Var1,Var2} (Obj1) \\ \max\limits_{Var1,Var2} (Obj2) \\ \max\limits_{Var1,Var2} (Obj3) \\ s.a. \quad 0 \le Var1 \le 1 \\ \qquad\; 0 \le Var2 \le 1 \end{cases} \tag{3}$$

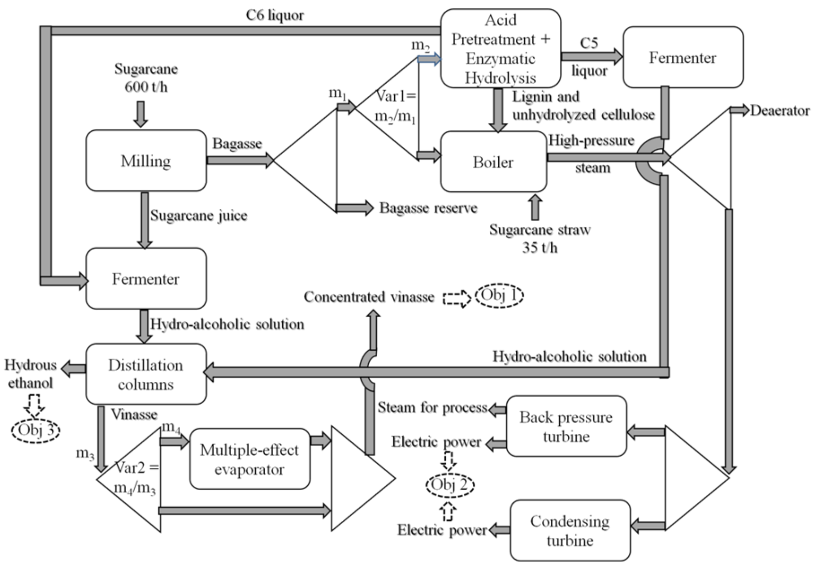

Figure 2. Schematic representation of the process, with representation of studied objective functions and decision variables.

In Optim1, the algorithm indicates that, since it is desired to minimize concentrated vinasse production and maximize electric power, virtually no bagasse should be diverted to E2G process steps (Var1 is practically zero). Bagasse should be burned in order to produce more steam, which serves both to concentrate vinasse and produce electric power. In all non-dominated solutions in Optim1, Var2 assumes high values (from 0.72 to 0.99), since the requirement to concentrate vinasse as much as possible forces high fraction of vinasse that comes from distillation column to be diverted to multiple-effect evaporators (in order to vaporize large amounts of water). Among non-dominated solutions, electric power varies only 2.2%, while concentrated vinasse flow varies 153.9%, with different Brix values. Bioethanol throughput and vinasse flow coming from distillation column virtually do not vary among non-dominated solutions, since practically no E2G is produced. Since much steam is being produced (practically all bagasse is burned), around 30% of high-pressure steam can be diverted to condensing turbine, values relatively high, when compared to Optim2 problem.

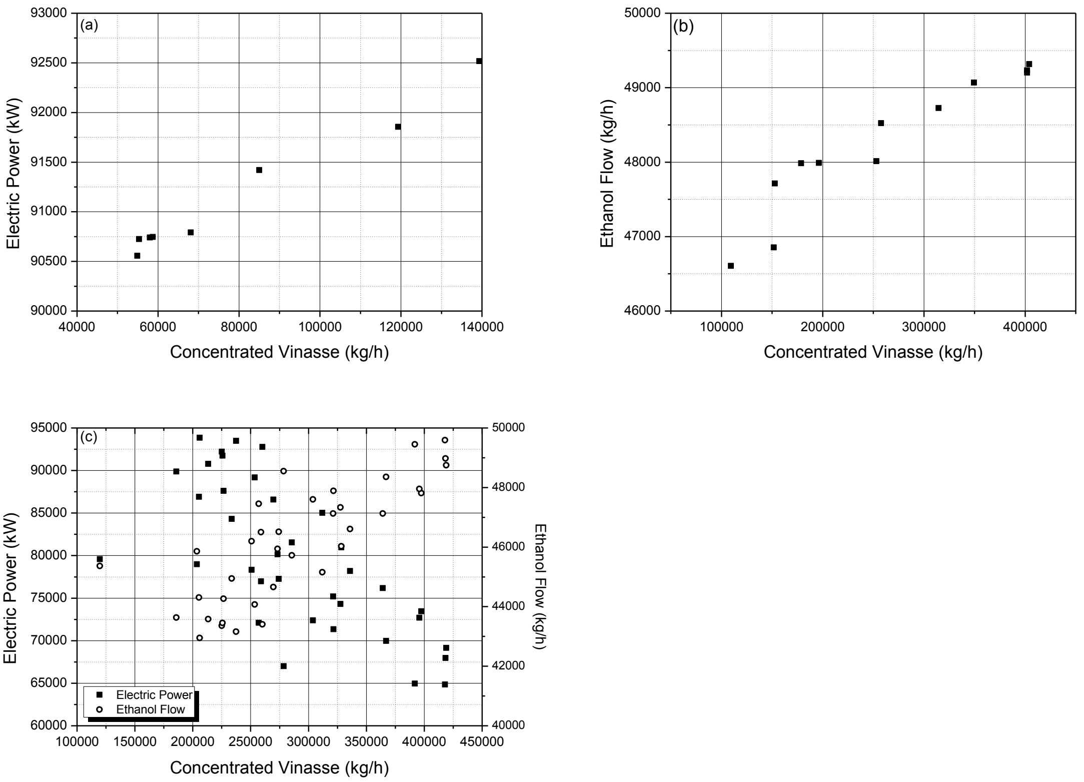

Figure 3. Non-dominated solutions found in (a) Optim1, (b) Optim2 and (c) Optim3.

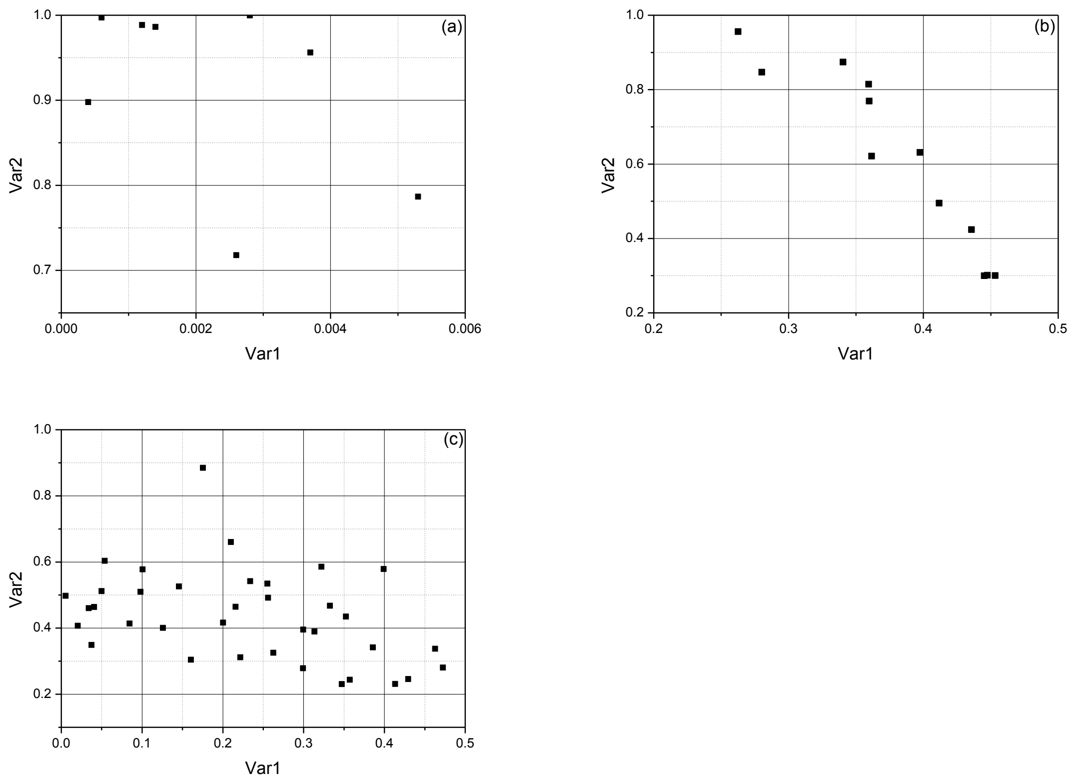

Figure 4. Values of decision variables corresponding to the non-dominated solutions found in (a) Optim1, (b) Optim2 and (c) Optim3.

Table 1. Some non-dominated solutions for the three optimization problems.

	Optim1		Optim2		Optim3	
	Var1		Var1		Var1	
	0.04×10^{-2}	0.28×10^{-2}	0.26	0.45	0.53×10^{-2}	0.47
Var2	0.90	0.99	0.96	0.30	0.50	0.28
High-pressure steam to condensing turbine (%)	30.7	29.0	6.8	2.3	36.4	8.5
E1G +E2G (kg/h)	42,878	42,911	46,607	49,317	42,948	49,589
Vinasse from distillation column, kg/h (ºBx)	353,520 (1.76)	354,402 (1.76)	452,772 (2.36)	525,174 (2.65)	355,369 (1.77)	532,445 (2.67)
Concentrated vinasse, kg/h (ºBx)	85,005 (7.30)	54,890 (11.38)	109,424 (9.75)	404,109 (3.44)	205,946 (3.06)	418,008 (3.41)
Electric Power (kW)	91,420	90,557	73,039	65,919	93,853	64,848

Optim2 non-dominated solutions possess decision variables that are more spread over search space. However, while Var2 varies a lot (from 0.30 to 0.96), Var1 is limited to values lower than approximately 0.45, because of the requirement that the production plant must be energetically self-sufficient. If a high fraction of bagasse is diverted to the E2G production steps, the thermal demand of the integrated process cannot be supported by the burn of fuel sent to the boiler. Since E2G is produced in all non-dominated solutions (differently from Optim1 solutions), higher flows of vinasse come from distillation column, when compared to Optim1 solutions. This vinasse is concentrated as much as possible in each non-dominated solution. Among non-dominated solutions, bioethanol throughput vary 5.8%, while concentrated vinasse flow varies 269.3%, with different Brix values. Since bioethanol throughput is forced to be maximized, thermal demands of integrated process are higher and less fuel is available, when compared to Optim1 non-dominated solutions, and so, electric power in all non-dominated solutions in Optim2 is considerably lower than in those solutions. In all non-dominated solutions in Optim2, low percentages of high-pressure steam are diverted to condensing turbine, since electric power is not being maximized and the plant must be energetically self-sufficient.

Finally, in Optim3 the three objective functions are studied simultaneously, with environmental and the two process goals being optimized. Much more non-dominated solutions are found. As in Optim2, Var1 is limited to values lower than approximately 0.45, because of the requirement that the production plant must be energetically self-sufficient, although in this optimization problem values pratically equal to zero are present. Var2 varies from 0.23 to 0.89. Among non-dominated solutions, bioethanol throughput vary 15.5%, electric power varies 44.7%, while concentrated vinasse flow varies 250.2%, with different Brix values. Percentages of high-pressure steam diverted to condensing turbine vary greatly among non-dominated solutions.

It is possible to see that, when maximization of bioethanol throughput is sought (Optim2 and Optim3), minimum flows of concentrated vinasse are higher than when this objective function is not part of the goals of the decision maker. This is obviously an expected result since vinasse is a waste of wine, produced when sugarcane juice, glucose and pentose liquors are fermented.

The greatest throughput of bioethanol is these studies was obtained in Optim3: 49,589 kg/h. Corresponding process conditions are Var1 = 0.47, Var2 = 0.28, 418,008 kg/h of concentrated vinasse (with 3.41 ºBx) and 64.848 kW of electric power (the least one obtained for the three studies). Electric power production was highest (93,853 kW) when Var1 = 0.53×10^{-2}, Var2 = 0.50, found in Optim3. Corresponding concentrated vinasse flow and bioethanol throughput are, respectively, 205,946 kg/h (with 3.06 ºBx) and 42,948 kg/h. The lowest flow of concentrated vinasse is naturally found when bioethanol maximization is not an issue (Optim1): 54,890 kg/h of vinasse with 11.38 ºBx are produced, together with 42,911 kg/h of bioethanol and 90,557 kW of electric power, when Var1=0.28×10^{-2} and Var2 = 0.99.

Naturally, the decision on how the process should be operated depends on economic factors, like industry products prices or investments made, and environmental politics and concerns. Although the multiobjective optimization algorithm does not guarantee that the non-dominated solutions found really belong to the true Pareto Fronts, since it is a stochastic method, this tool may help the decision makers to choose operating conditions, in order to obtain greater profits, while, at the same time, ensure a more sustainable process. The feasible path approach allowed the use of this stochastic optimization method in an equation-oriented process simulator by relieving the method of the task of handling all models equations as constraints of the optimization problem.

CONCLUSIONS

The optimization studies conducted in this work dealt with conflicting objectives in a sugarcane biorefinery that integrates E1G, E2G and bioelectricity production. Vinasse, waste generated in distillation of wine, is produced in large amounts, which can be reduced by concentration of this effluent in multiple-effect evaporators. This, however, increases thermal demands of the plant, such as either greater amounts of fuel has to be diverted to the boiler (which reduces E2G production) or less electric power is generated. MOPSO provided sets of non-dominated solutions to each optimization problem. Different profits and environmental indices would be associated to each solution and the decision on how to operate the process may be guided by this tool.

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