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Multi-objective optimization of an industrial ethanol distillation system using direct and indirect heating

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Academic Work

Introduction – Ethanol Industry

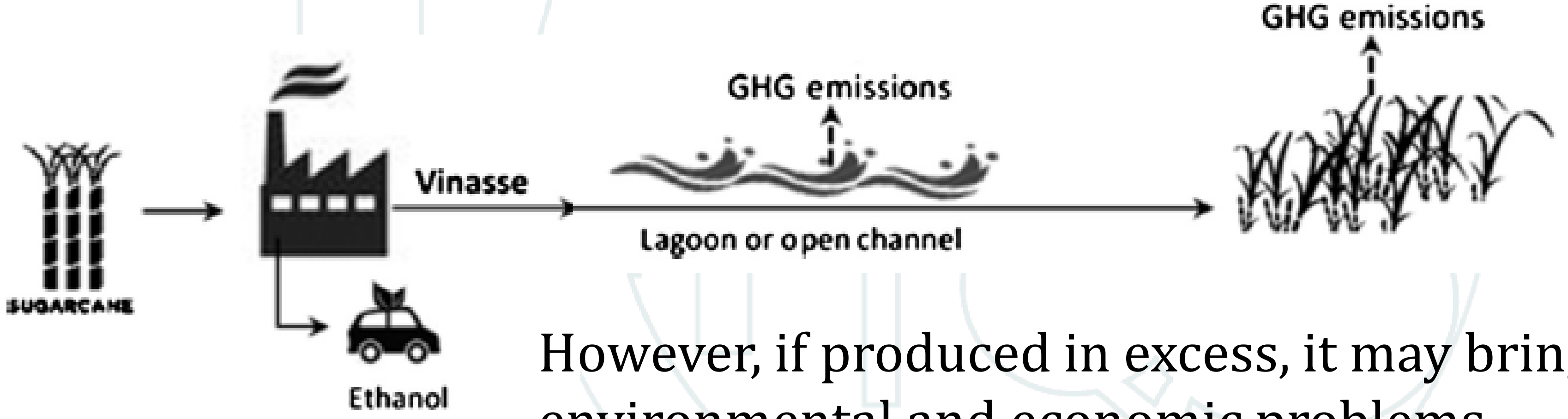
- Sugarcane biofuel processing has been one of the most important and strategic sectors in the Brazilian economy during the last decades.

- Brazil is the world's largest sugarcane ethanol producer, producing more than 30 billion liters per year (CONAB, 2016).

- However, the success of Brazilian distilleries depends on how they overcome the new scientific challenges faced, mainly regarding the optimization of process, energy integration, cogeneration, and waste management (Amorim et al., 2011).

Introduction - Vinasse

One of the main challenges is related to the reduction of the sugarcane vinasse. This liquid wastewater of the biomass distillation is rich in minerals and is commonly used to irrigate sugarcane crop, known as fertirrigation.



Moraes et al. (2017)

However, if produced in excess, it may bring environmental and economic problems.

Introduction – Environmental Problems

Among the environmental issues, the direct application of vinasse in the soil may cause:

- Salinization and leaching of metals present in the soil to groundwater (it also might kill animals and aquatic plants).
- Changes in soil quality due to unbalance of nutrients, alkalinity reduction, and crop losses.
- Vinasse is an additional source of greenhouse gas emission to the atmosphere that result from aerobic and anaerobic decomposition of the organic matter that occurs during transportation, temporary storage or after the application in the soil.

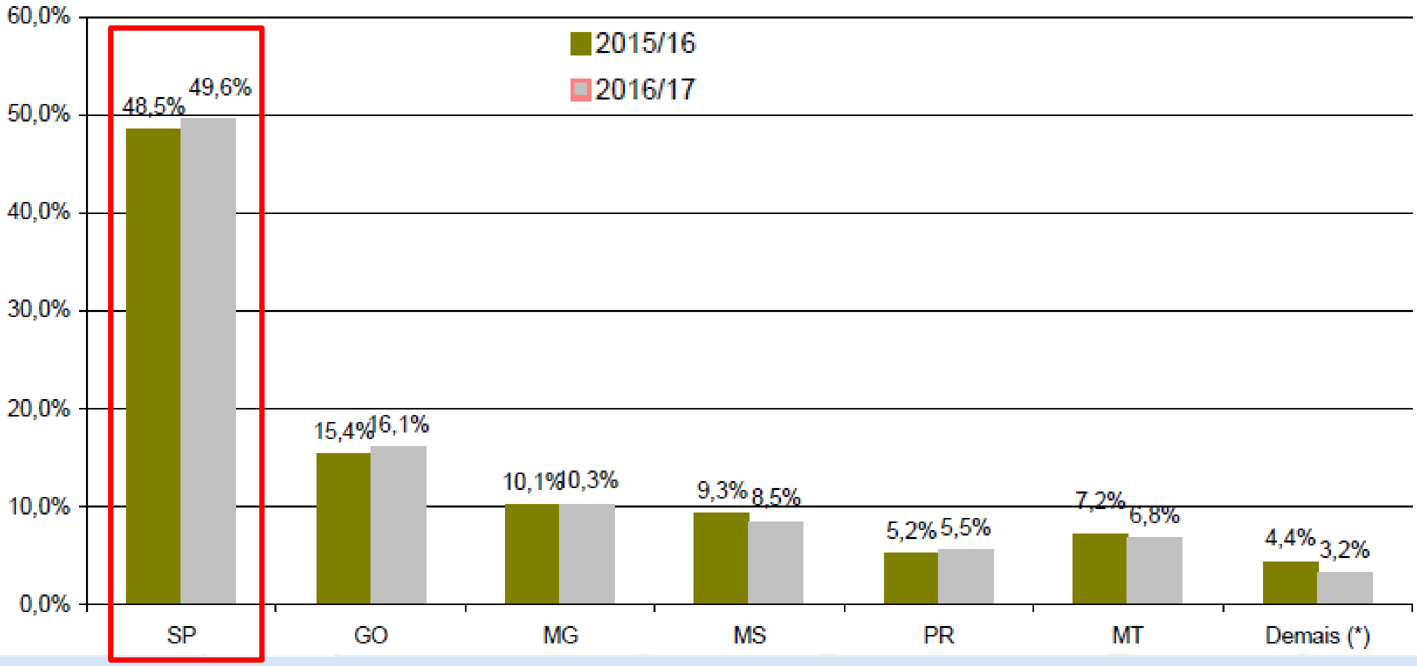
Navarro et al., 2000; Santana and Machado, 2008; Oliveira et al., 2013

Introduction – Economic Problems

- In Brazil, fertirrigation frequently becomes an economic problem when the area to apply vinasse in the appropriate dosage is not available.
- This might happen when the crop belongs to the suppliers or it is located far away from the industrial plant.
- Moreover, Brazilian environmental legislation recently established procedures for vinasse application in the soil (technical standard P4.231).

Introduction – Economic Problems

P4.231 (CETESB, 2006) defines the maximum dosage of vinasse to be used in the fertirrigation, which causes problems of surplus vinasse for storage in open lagoons, worsening the aforementioned problems.



Problem Statement

- The distillery is required to reduce its vinasse production in order comply with the recent environmental technical standard, which in turn will meet RenovaBio objective.
- RenovaBio is an initiative of the Brazilian government whose objective is guarantee the expansion of biofuel production in the country, based on environmental, economic, and financial sustainability, in harmony with the Brazilian commitment at COP 21 (MME, 2016).

Problem Statement

- Although, many authors have been proposing new design of the ethanol plant in order to increase its sustainability, usually, the capital investment costs are not feasible for the sugarcane Brazilian plants, reducing the likelihood of putting these improvement projects into practice.

- Therefore, the goal of this analysis is to purpose modifications with low investment costs that lead to significant reductions in economic and environmental impacts.

Objective and Contribution

- The objective of this study is simulate, analyze, and compare a full-scale industrial system of an ethanol distillery operating with direct and indirect heating using Aspen Hysys process simulator.

- No prior work reported in the open literature took into account the use of reboilers in order to decrease the quantity of vinasse produced, analyzing its environmental and economic advantages for distilleries and sugar mills in Brazil.

Objective and Contribution

- The models mimic the distillery of the *Cooperativa Agrícola de Astorga Ltda* (COCAFE), which is located in the Northwest of Parana State, (South of Brazil).

Methodology

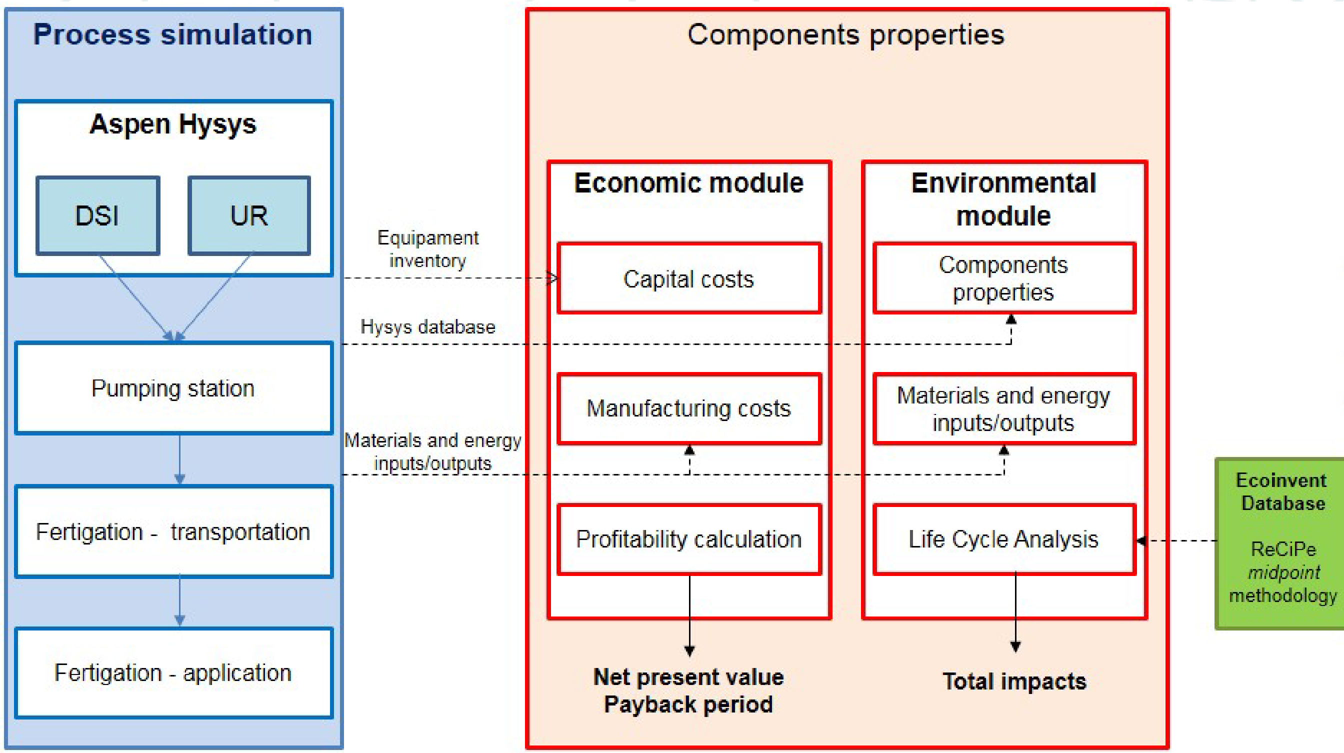
In this work, we compare the use of reboiler (UR) with direct steam injection (DSI) to provide heat to the first distillation column of the COCAFE distillery.

1. The simulation is developed on Aspen Hysys v8.6 in order to compare the production of ethanol, flegma, and vinasse.
2. The information in the simulator is used to perform an economic and environmental evaluation programmed in Matlab R2016a.

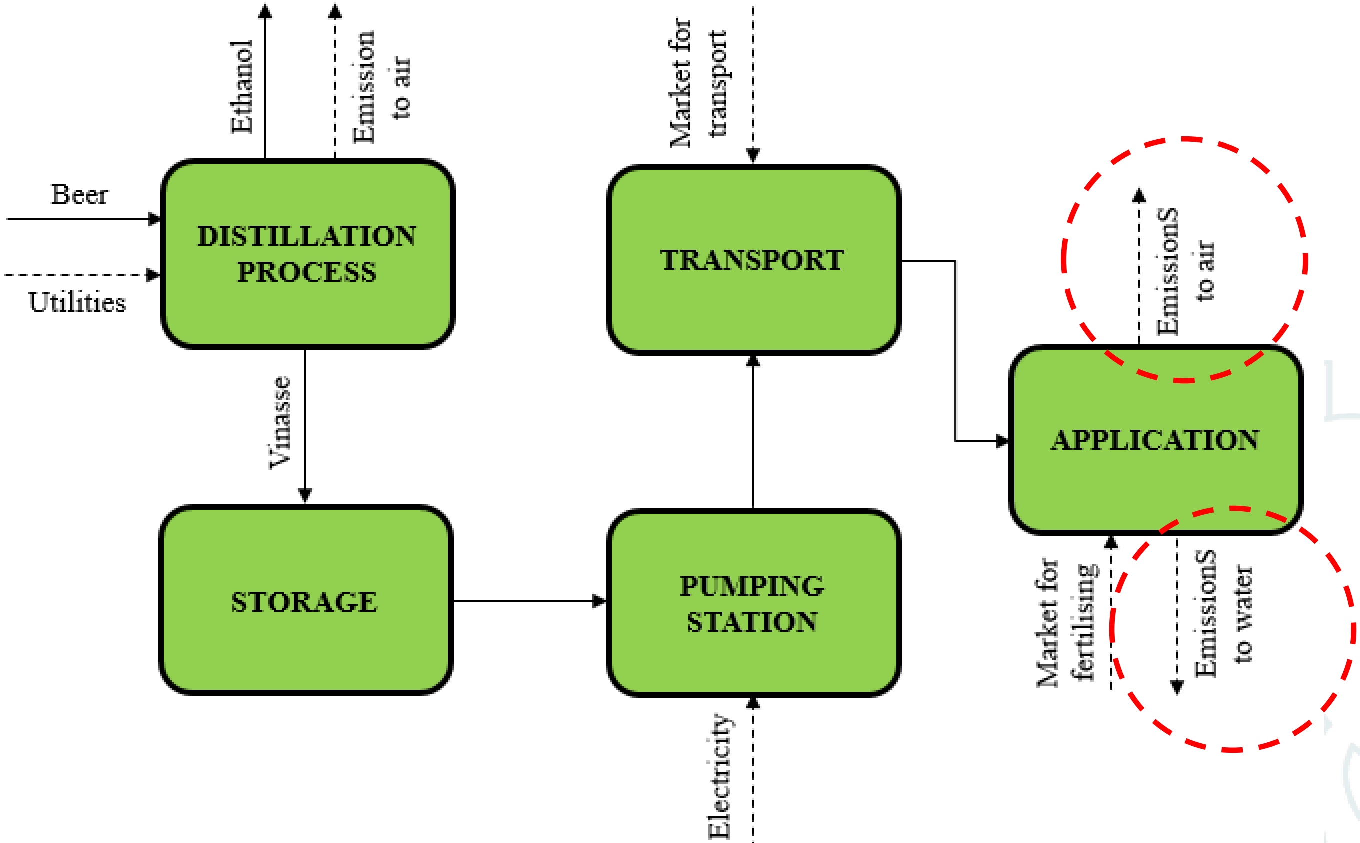
It is important to highlight that as the rest of the activities are common for DSI and UR, all the economic and environmental evaluations are executed only within the boundary system, which covers the distillation and fertirrigation processes.

Methodology – Comparison of alternatives

Flow diagram of the automated procedure for the environmental and economic evaluation based on process modeling. Detailed information can be found in Torres et al. (2011).



Methodology – Life Cycle Inventory



Emission from vinasse treated as elementary flows

Methodology – Life Cycle Inventory

Emission factors resulting from mineral fertilization.

Released substances	Ratio	Emission	Reference
CO_2	3.64 kg CO_2/kg N	air	IPCC (2006)
N_2O	0.05 kg N_2O/kg N	air	Crutzen et al. (2008)
NO_x	0.053 kg NOx/kg N	air	Renouf et al. (2008)
NH_3	0.026 kg NH_3/kg N	air	Renouf et al. (2008)
NO_3^-	0.065 kg NO_3^- /kg N	water	Renouf et al. (2008)
PO_4^{3-}	0.128 kg PO_4^{-3}/kg N	water	Bloesch et al. (1997)
C_2H_6O	-	air	Retrieved from Aspen Hysys

Methodology – Multi-objective Optimization

- The synthesis of chemical processes is treated as a multi-objective optimization that accounts for the simultaneous minimization of the total cost and environmental impact.

$$
\begin{aligned}
(M)\ \min_{x_D}\quad & z = \alpha . f_1(x,u,x_D) + \beta . f_2(x,u,x_D) + \prod (s_1 + s_2 + s_3) \\
s.t.\quad & \alpha = 1 - \beta \\
& h_I(x,u,x_D) = 0 \\
& h_E(x,u,x_D) + s_1 - s_2 = 0 \\
& g_E(x,u,x_D) \leq s_3 \\
& s_1 \geq 0;\ s_2 \geq 0;\ s_3 \geq 0
\end{aligned}
$$

- The multi-objective optimization methodology is performed only for the configuration that presented the best results for the process after the comparative study.

Methodology – Multi-objective Optimization

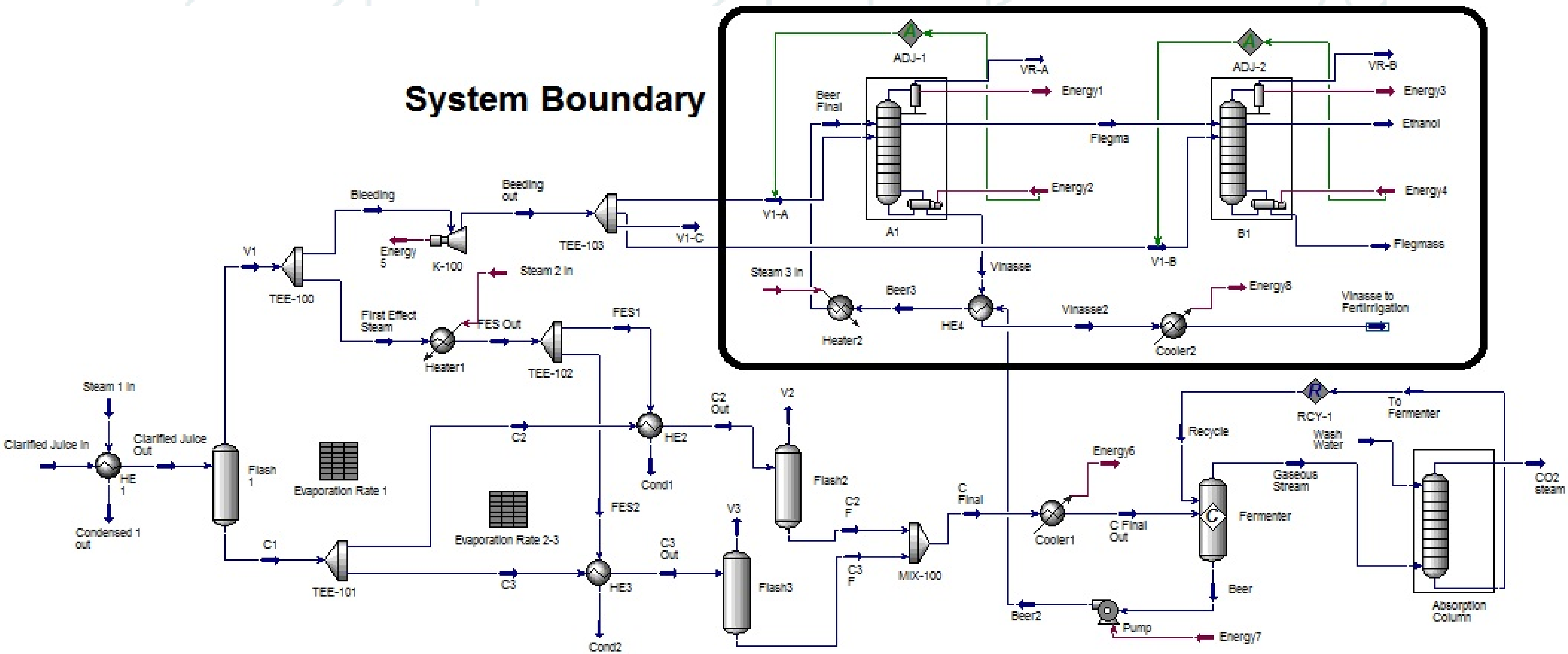
- The optimization is performed in terms of climate change (one of the midpoint impact categories present in the ReCiPe methodology), similar to the work of Zhang et al. (2014).

- The methodology followed provides as output a set of Pareto optimal solutions that trade-off the economic and environmental performance.

- We use the weighted sum method to obtain the Pareto frontier, providing a practical and easy-to-use approach for multi-objective optimization and is useful as such (Marler and Arora, 2010).

Results – Process Simulation

COCAFE industrial Hysys model



Results – Comparative Study

Comparison between direct steam injection (DSI) and the use of reboiler (UR)

	DSI	UR	Variation (%)	
Vinasse ($kg{\cdot}h^{-1}$)	1.86E+05	1.57E+05	-15.59	Reduction of vinasse
Flegma ($kg{\cdot}h^{-1}$)	3.17E+04	3.18E+04	0.32	No effect on the productivity
Ethanol ($kg{\cdot}h^{-1}$)	1.62E+04	1.62E+04	0	
Cooling energy ($kJ{\cdot}h^{-1}$)	3.29E+7	2.49E+7	-24.32	
Reboiler energy ($kJ{\cdot}h^{-1}$)	0	6.55E+7	-	
V1-A energy ($kJ{\cdot}h^{-1}$)	3.90E+8	0	-	

Results – Economic Evaluation

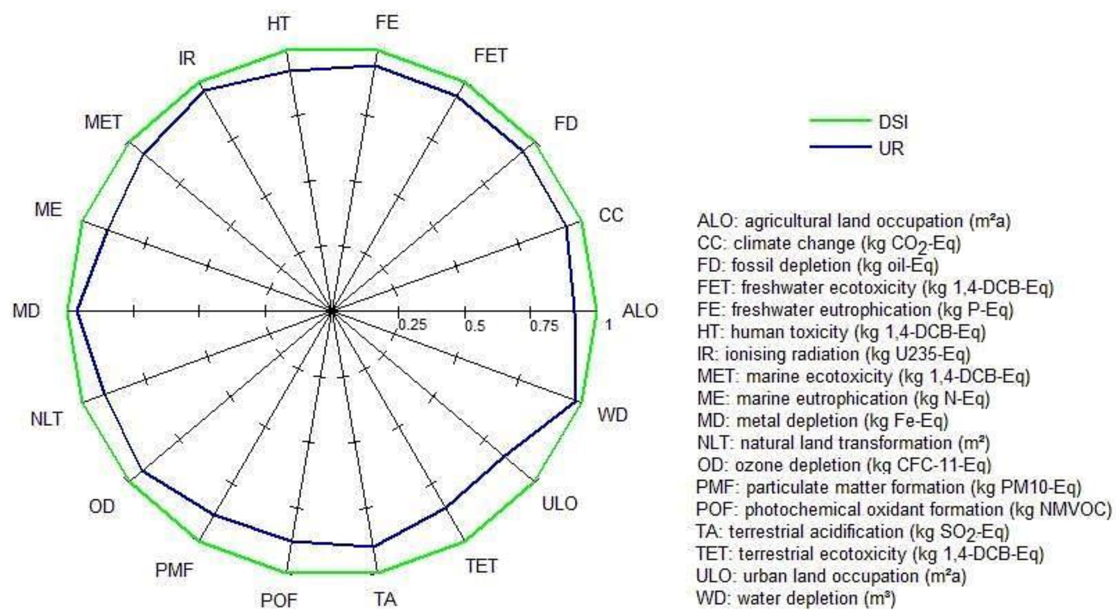
Capital costs and operating costs producing ethanol and fertirrigation process alternatives for direct and indirect heating.

	Direct Steam Injection ($)	Use of Reboiler ($)	Variation (%)
Capital investment costs			
Reboilers	274,749	350,636	27.62
Manufacturing cost (yearly)			
Waste treatment	1,261,237	1,170,296	-7.21
Utilities			
Electricity	151,880	151,880	0
Steam (LP/MP/HP)	158,863	41,050	-74.16
Cooling water	198,915	178,829	-10.10
Operating labor	331,695	331,690	0
Other manufacturing costs[a]	538,631	739,660	37.32
Total	2,641,221	2,613,405	-1.05

- Annual interest rate = 12.65% (BCB, 2015)
- NPV = $77,184
- Payback of 3.57 years

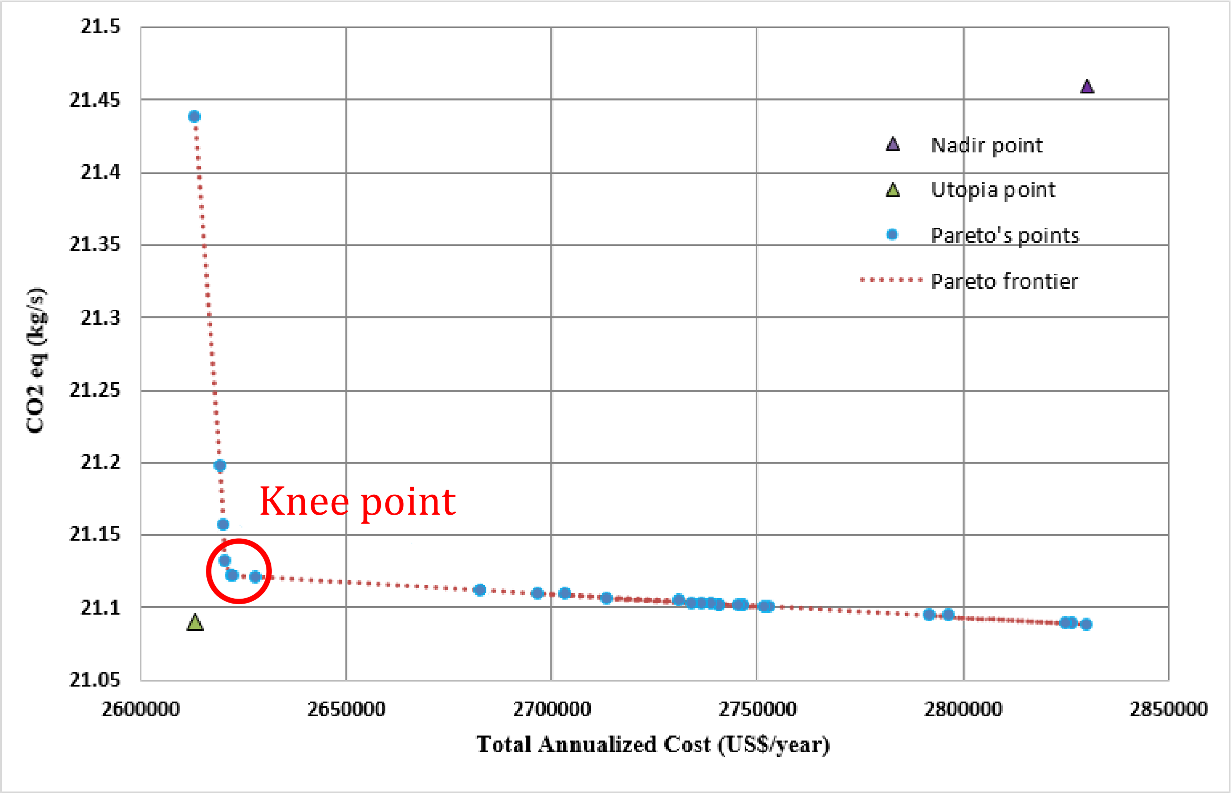
Results – Environmental Assessment

Comparison of the normalized impacts for the DSI and UR process alternatives following the ReCiPe methodology.



Results – Multi-objective Optimization

Pareto set of solutions for the climate change versus total cost.



Conclusions

- ✓ A validated process simulation automatically integrated to a mathematical programming is a powerful tool to evaluate the performance of a wide range of industrial processes.
- ✓ The economic assessment presents a high profitability, the environmental evaluation revealed that all the impacts of the proposed configuration are lower when compared to the actual one.
- ✓ In the multi-objective optimization, considering simultaneously the cost and the environmental impacts. The profile of the curves indicates that the environmental impact can be further reduced with a marginal effect in the cost.

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