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Methodology for the optimal design of an integrated first and second generation ethanol production plant combined with power cogeneration

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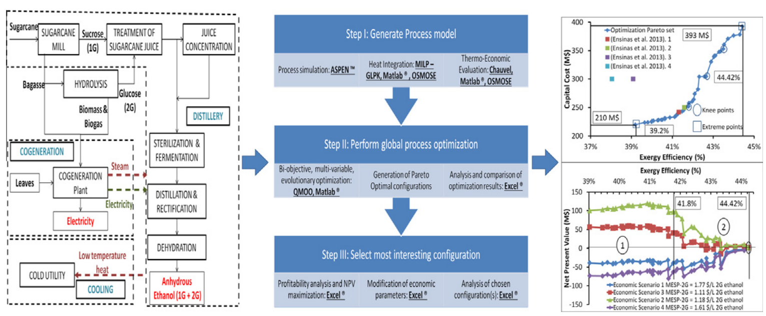
HIGHLIGHTS

- Method for optimal design of 1st and 2nd generation ethanol and power plant.
- Process simulation, integration and evaluation model.
- Bi-objective multi-variable evolutionary optimization run.
- Profitability analysis for choosing point under different economic scenarios.
- Analysis of Pareto curve and characterization of optimal point.

GRAPHICAL ABSTRACT



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ABSTRACT

The application of methodologies for the optimal design of integrated processes has seen increased interest in literature. This article builds on previous works and applies a systematic methodology to an integrated first and second generation ethanol production plant with power cogeneration. The methodology breaks into process simulation, heat integration, thermo-economic evaluation, exergy efficiency vs. capital costs, multi-variable, evolutionary optimization, and process selection via profitability maximization. Optimization generated Pareto solutions with exergy efficiency ranging between 39.2% and 44.4% and capital costs from 210 M$ to 390 M$. The Net Present Value was positive for only two scenarios and for low efficiency, low hydrolysis points. The minimum cellulosic ethanol selling price was sought to obtain a maximum NPV of zero for high efficiency, high hydrolysis alternatives. The obtained optimal configuration presented maximum exergy efficiency, hydrolyzed bagasse fraction, capital costs and ethanol production rate, and minimum cooling water consumption and power production rate.

1. Introduction

The application of systematic methodologies for the optimal design of integrated processes has seen increased interest in literature. Morandin et al. (2010) applied a systematic methodology to the optimization of a combined sugar and ethanol production process integrated with a CHP system with the objective of maximizing power production. Bechara et al. (2014) on the other hand applied a similar methodology for the minimization of the utility consumption of a stand-alone second generation ethanol production process. Finally, Albarelli et al. (2015) used such a methodology for the optimization of the joint production of ethanol and methanol from sugarcane with energy efficiency and capital costs as chosen objective functions.

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List of abbreviations

ex_{eff}	exergy efficiency (%)
$Ex_{Elec_{net}}$	exergy of net electricity produced (MW)
Ex_{leaves}	exergy of leaves (MW)
$ex^0_{ethanol}$	specific chemical exergy of ethanol (MWh/t)
$\dot{m}_{cane}$	mass flow rate of sugarcane (t/h)
$\dot{m}_{leaves}$	mass flow rate of leaves (t/h)
$\dot{m}_{enz}$	mass flow rate of enzymes (t/h)
C_{Fixed}	fixed capital cost (M$)
sd_{load}	solids loading in hydrolysis reactor (wt.%)
$C_{gluc,hyd}$	glucose concentration in hydrolysates (g/l)
MESP-2G	minimum selling price for second generation ethanol ($/l 2G ethanol)
$Ex_{ethanol}$	exergy of produced ethanol (MW)
Ex_{cane}	exergy of sugarcane (MW)
Ex_{enz}	exergy of enzymes (MW)
ex_{Elec}	specific electricity exergy content (MW/MW)
ex^0_{cane}	specific chemical exergy of cane (MWh/t)
ex^0_{leaves}	specific chemical exergy of leaves (MWh/t)
ex^0_{enz}	specific chemical exergy of enzymes (MWh/t)
NPV	Net Present Value (M$)
res_{hyd}	residence time in hydrolysis reactor (h)
a, b, c, d, $res_{hyd,0}$	kinetic parameters for calculating $C_{gluc,hyd}$ as a function of hydrolysis parameters

In the context of biomass valorization and renewable bioenergy production, the integrated first and second generation ethanol from sugarcane production process combined with power cogeneration has seen increased interest in literature. Dias et al. (2012b) investigated the improvement of the integrated process by modifying the operating conditions of the biomass combustion section, namely the boiler pressure and superheating temperature. Macrelli et al. (2012) performed a thermo-economic evaluation of several process configurations integrating different second generation ethanol producing technologies with various first generation schemes. Dias et al. (2013) on the other hand studied the impact of varying hydrolysis solids loading and conversion yield on process specific steam consumption (kg steam/ton sugarcane), specific ethanol production (l ethanol/ton sugarcane) and specific power production (kWh/ton sugarcane). Furlan et al. (2012) went a step further by coupling process simulation with a global optimization algorithm with the goal of determining the optimal fraction of bagasse to be diverted to second generation ethanol production with regards to revenue maximization. Moreover, Ensinas et al. (2013) made use of a similar tool, but with a bi-objective optimization: maximizing electricity production versus maximizing ethanol production. Furthermore, this work incorporated heat integration into the optimization problem. Likewise, Costa et al. (2015) performed multiple bi-objective optimization runs to a variant of the study process, with the possibility of distillation waste, vinasse, concentration. All these works stressed the importance of using a systematic methodology for optimal process design, and highlighted the predicament posed by diverting large quantities of bagasse to hydrolysis. Finally, Macrelli et al. (2014) studied the additional effect of varying market factors on the choice of process alternatives, which are also a key factor in profitability and minimum selling price.

Considering the previous, this present article expands on these works and applies a systematic process design methodology for an integrated first and second generation ethanol production plant coupled with electricity cogeneration. This article starts by describing and applying the chosen methodology and its constitutive steps to the studied process. It is then followed by a visualization, assessment and discussion of the obtained results, before finishing off with conclusions.

2. Materials and methods

The used methodology, highlighted and employed in Gassner and Maréchal (2012), can be broken down into three main steps as depicted in Fig. 1. The first step consists in generating the process model with the ultimate goal of enabling thermo-economic evaluation. Its key sub-steps are: process simulation, heat integration and ultimately thermo-economic evaluation. The second step consists in global process optimization. The chosen technique is multi-variable, bi-objective optimization using evolutionary algorithms as highlighted in Leyland (2002). This step leads to the generation of a Pareto Optimal Frontier (POF) for the optimization problem. This frontier highlights the optimal compromise between the chosen objective functions. Considering this, the last step consists in the selection of the most interesting process configuration from the previously obtained Pareto Optimal Frontier. This selection step makes use of decision making techniques which guide the decision maker towards the most interesting solutions.

The application of this methodology and its constitutive components for the optimal design of an integrated first and second generation ethanol production plant combined with power cogeneration is highlighted in this section.

2.1. Step I: generate process model

As indicated in Fig. 1, the process model breaks down into simulation, heat integration and thermo-economic evaluation. The application of each component to the studied process will be detailed herein.

2.1.1. Process simulation model

The process simulation model is described for the studied process in this section where process capacity and block flow diagram are indicated.

2.1.1.1. Process capacity. Process capacity was set to 500 tons of sugarcane (TC)/h, and to 33 tons of leaves/h (70 kg leaves /TC). Input sugarcane is composed of: water (71.57 wt.%), sugars (13.92 wt.%), dirt (0.6 wt.%), impurities (1.99 wt.%) and bagasse fibers (11.92 wt.%). This bagasse is composed of: cellulose (43 wt.%), hemicellulose (26 wt.%), lignin (24 wt.%) and ashes (7 wt.%). Input leaves is on the other composed of: water (15 wt.%), ash (2 wt.%), and biomass fibers (83 wt.%). The process has moreover a third input material, enzymes, whose mass flow rate is set to 0.1 g/g hydrolyzed bagasse cellulose. It is thus directly dependent on the problem's optimization variables. Finally, The NREL database was chosen for modeling the various components. These information are in line with (Dias et al., 2009; Ensinas et al., 2013).

2.1.1.2. Process block flow diagram. The studied process consists in an integrated first and second generation ethanol production distillery, combined with a heat and power production plant, and a cold utility system. The block flow diagram for this process, as inspired from previous literature works (Ensinas et al., 2013; Macrelli et al., 2012), is provided in Fig. 2. Three important sections