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Process integration of a multiperiod sugarcane biorefinery

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HIGHLIGHTS

- A Multiperiod Heat Exchanger Network is proposed for a sugarcane biorefinery.
- The energy integration is able to increase energy security.
- More bagasse becomes available to produce second generation ethanol or electricity.
- The solution scheme is based on an efficient meta-heuristic method.
- Total Annualized Cost and energy demand reduction are obtained.

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ABSTRACT

Process integration in sugarcane biorefineries allows reducing steam consumption. As a consequence, the bagasse surplus can be diverted to second generation ethanol production. Furthermore, sugarcane plants can vary the production of ethanol and electricity, depending on the demand. For those reasons, equipment present in the plant might be required to operate under different conditions. This study presents the energy integration of a sugarcane biorefinery. A Mixed Integer Nonlinear Programming (MINLP) optimization model is proposed to solve the problem of synthesizing a Heat Exchanger Network (HEN) able to periodically operate under the distinct conditions required in the biorefinery, *i.e.*, a multiperiod HEN. For solving the MINLP problem, a hybrid metaheuristic approach was used, which combines Simulated Annealing and Rocket Fireworks Optimization. The proposed strategy achieved lower HEN total annualized cost (TAC) when compared with the project energy integration that is commonly found in Brazilian plants. This reduction in TAC, in particular in utilities demand, allows the surplus bagasse to be available for the most suitable application: produce 2G ethanol or more electricity.

1. Introduction

Sugarcane mills present economic importance not only in ethanol and sugar production, but also in the generation of electricity from sugarcane biomass. Sugarcane bagasse is burned in the boiler and the steam produced moves the turbines and generates energy. Cogeneration process reduces energy costs in the plant, supplies internal energy demand and, in many cases, allows selling the surplus.

A sugarcane biorefinery can be defined as an industrial process able to produce different products and by-products (sugar, 1G/2G ethanol and electricity) from the main raw material (sugarcane). The current efforts to turn 2G ethanol production process viable aim, among other goals, at increasing energy security and decreasing environmental resources consumption, since 2G ethanol turns possible the increase of production of this biofuel without the increase of cultivated land area. However, 2G ethanol technology is still not consolidated and requires studies to allow the integrated first and second generation ethanol production process to be more sustainable and economic.

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Nomenclature

Variables

A	heat exchanger area [m^2]
Acu	cooler area [m^2]
Ahu	heater area [m^2]
C_{total}	annualized total cost [USD/year]
Fc	fraction of cold stream [–]
Fh	fraction of hot stream [–]
$LMTD$	logarithmic mean temperature difference [K]
Q	heat load in a heat exchanger [kW]
Qcu	heat load in a cooler [kW]
Qhu	heat load in a heater [kW]
$Qmax$	maximum heat load [kW]
TAC	total annualized cost [USD/year]
$Tchuin$	inlet temperature of the cold stream in a heater [K]
$Thcuin$	inlet temperature of the hot stream in a cooler [K]
$Tcin$	inlet temperature of the cold stream in a heat exchanger [K]
$Thin$	inlet temperature of the hot stream in a heat exchanger [K]
$Tcout$	outlet temperature of the cold stream in a heat exchanger [K]
$Thout$	outlet temperature of the hot stream in a heat exchanger [K]
$Tcmix$	mixture temperature of the cold stream after mixer [K]
$Thmix$	mixture temperature of the hot stream after mixer [K]
U	overall coefficient of heat transfer [kW/(m^2 K)]
z	binary variable representing existence of a heat exchanger [–]
zcu	binary variable representing existence of a cooler [–]
zhu	binary variable representing existence of a heater [–]
$\theta^{(1)}$	temperature approximation at the hot end of a heat exchanger [K]
$\theta^{(2)}$	temperature approximation at the cold end of a heat exchanger [K]
ΔT	temperature difference [K]

Parameters

a	annual fixed cost coefficient for heat exchangers [USD/year]
a'	fixed cost coefficient for heat exchangers [USD]
a_F	fuel cost per unit of energy [USD/kJ]
b	annual variable cost coefficient for heat exchangers [USD/(m^2 year)]
b'	variable cost coefficient for heat exchangers [USD/m^2]
c	area cost exponent [–]
c'	area cost exponent [–]
C_B	cost of bagasse [USD/tonne]
ccu	cost of cold utility [USD/(kW year)]
C_F	fuel cost for steam generation [USD/kg]
C_G	total cost for steam generation [USD/kg]
chu	cost of hot utility [USD/(kW year)]
CPc	heat capacity of the cold stream [kW/K]
CPh	heat capacity of the hot stream [kW/K]
C_W	cost of cooling water [USD/m^3]
$EMAT$	minimum temperature approximation in the heat exchanger [K]
hc	heat transfer convective coefficient of the cold stream [kW/(m^2 K)]
hh	heat transfer convective coefficient of the hot stream [kW/(m^2 K)]
h_{IN}	enthalpy of cooling water at inlet cooler [kJ/kg]
h_{OUT}	enthalpy of cooling water at outlet cooler [kJ/kg]
h_{COND}	enthalpy of condensation [kJ/kg]
H_S	enthalpy of steam [kJ/kg]
h_W	enthalpy of boiler feedwater [kJ/kg]
k	number of the stage [–]
LHV	lower heating value [kJ/kg]
t	plant life [h/year]
Tc^0	initial temperature of the cold stream [K]
Tc^{final}	final (target) temperature of the cold stream [K]
Th^0	initial temperature of the hot stream [K]
Th^{final}	final (target) temperature of the hot stream [K]
u	annual capital interest [–]
$\hat{v}$	specific volume [m^3/kg]
η	boiler efficiency in relation to LHV [%]
θ	annualization factor [1/year]
τ	operation time [h/year]

Data set

N_C	cold streams [–]
N_H	hot streams [–]
N_S	stages [–]

Subscripts

i	cold streams
j	hot streams
k	stage superstructure

Text

CSA	Continuous Simulated Annealing
GA	Genetic Algorithm
HS	Harmonic Search
HEN	Heat Exchanger Network
HENs	Heat Exchanger Networks
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NL	Non-Linear Programming
NIM-SWS	Nonisothermal Mixing Stage-wise Superstructure
SA	Simulated Annealing
SQP	Sequential Quadratic Programming
SWS	Stage-wise Superstructure
PSO	Particle Swarm Optimization
RFO	Rocket Fireworks Optimization
TS	Tabu Search

Some important computational studies in sugarcane biorefineries were published, considering the simulation of first and second ethanol generation process [1], the evaluation of technical configurations for bioenergy production with sugarcane bagasse [2], the process flexibility in second generation ethanol and electricity production [3], an economic perspective of ethanol production costs in Brazil [4], and the optimization and comparison of processes for 1G/2G ethanol and electricity production [5]. Recently, studies applied to biorefineries include the process optimization involving process and environmental criteria [6], the evaluation of potential of CO_2 as a carbon source for