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Multi-objective synthesis of work and heat exchange networks: Optimal balance between economic and environmental performance

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ABSTRACT

Sustainable and efficient energy use is crucial for lessening carbon dioxide emissions in industrial plants. This paper introduces a new multi-objective optimization model for the synthesis of work and heat exchange networks (WHENs), aiming to obtain the optimal balance between economic and environmental performance. The proposed multistage superstructure allows power and thermal integration of process gaseous streams, through the simultaneous minimization of total annualized cost (TAC) and environmental impacts (EI). The latter objective is determined by environmental indicators that follow the life cycle assessment (LCA) principles. The WHEN superstructure is optimized as a multi-objective mixed-integer nonlinear programming (moMINLP) model and solved with the GAMS software. Results show a decrease of ~79% in the heat transfer area and ~32% in the capital cost between the solutions found for single problem optimizations. These results represent a diminution of ~23.5% in the TAC, while EI is increased in ~99.2%. As these solutions can be impractical for economic or environmental reasons, we present a set of alternative Pareto-optimal solutions to support decision-makers towards the implementation of more environment-friendly and cost-effective WHENs.

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1. Introduction

Environmental impact caused by increasing carbon gaseous emissions and the rapid depletion of fossil fuels reserves is a major global concern. Due to the rising interest in the development of more sustainable and efficient energy processes, multi-objective optimization (MOO) has arisen as a useful design and planning tool [1–4]. In fact, MOO is able to simultaneously deal with conflicting goals (*e.g.*, environmental and economic), allowing to identify the best alternatives that balance the bi-criteria problem [5,6].

Pressure manipulation is an energy-intensive process particularly important in synthetic methanol and ammonia synthesis, oil refineries and cryogenic production of liquefied natural gas (LNG) or air (N_2, O_2 or Ar). In such plants, the integration between work and heat can be critical for achieving significant savings in energy and processing costs [7–12]. The recognized importance of heat integration, and more recently, power integration, in process synthesis is stressed by the increasing literature about these aspects during the last few years. An important contribution to this area is addressed to Huang and Fan [13]. In their work, the authors have introduced the first insights about work exchange networks (WENs), defining the main operational principles for the process.

In Aspelund et al. [14], a heuristic graphical-based approach is used for energy requirements minimization in heat exchanger networks (HENs), considering pressure levels adjustment of process streams at sub-ambient conditions. Inspired on this previous work, Wechsung et al. [15] have developed a model for HENs synthesis with integrated pressure manipulation, combining mathematical programming, pinch and exergy analyses. The authors have successfully applied the model to LNG production, showing that process total irreversibility can be decreased through a specific compression and expansion route of streams based on the "plus–minus" principle (*i.e.*, cold streams: heating, expansion, heating, compression, cooling, expansion and heating; hot streams: cooling, compression, cooling, expansion, heating, compression and cooling) [16].

Afterwards, Onishi et al. [9] have utilized this pressure manipulation route to formulate a superstructure for simultaneous HENs synthesis, aiming to enhance heat integration by power recovery. The mathematical model is formulated using generalized disjunctive programming (GDP), and optimized via mixed-integer nonlinear programming (MINLP) by minimizing the total annualized cost. The authors have demonstrated that optimal integration between

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Nomenclature

Roman letters

Cp	heat capacity
C_{PO}	unitary cost
CR_{max}	maximum compression ratio
$CAPEX$	capital cost
fac	annualization factor for the capital cost
f_{EI}	annualization factor for the environmental impact
EI	environmental impact
F	streams flowrate
Fb	bypass flowrate
F_{BM}	correction factor for capital cost
Fe	SSTC equipment flowrate
Fv	valve flowrate
Fu	stand-alone equipment flowrate
M	big-M reformulation parameter
$OPEX$	operational expenses
P	streams pressure
P_{IN}	network inlet pressure
Pin	stage inlet pressure
P_{OUT}	network outlet pressure
$Pout$	stage outlet pressure
Q	heat flow
T	streams temperature
TAC	total annualized cost
T_{IN}	network inlet temperature
Tin	stage inlet temperature
T_{OUT}	network outlet temperature
$Tout$	stage outlet temperature
$Tturb$	outlet temperature of turbines
$Tval$	outlet temperature of valves
We	work of SSTC equipment
Wg	work of generators
Wm	work of helper motors
Wu	work of utility equipment
y	binary variable to define the existence of SSTC equipment
y^a	binary variable auxiliary
y^B	binary variable to define the existence of a bypass
y^U	binary variable to define the existence of utility equipment
y^V	binary variable to define the existence of valves

Acronyms

CEPCI	Chemical Engineering Plant Cost Index
GAMS	General Algebraic Modeling System
GDP	Generalized Disjunctive Programming
HEN	Heat Exchanger Network
HP	High-Pressure
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
LP	Low-Pressure
MINLP	Mixed-Integer Nonlinear Programming
MOO	Multi-Objective Optimization
moMINLP	Multi-Objective Mixed-Integer Nonlinear Programming
SSTC	Single-Shaft-Turbine-Compressor
PSE	Process Systems Engineering
WEN	Work Exchange Network
WHEN	Work and Heat Exchange Network

Greek letters

α_{de}	process burdens for energy utilities
β_{de}	damage factor produced by each damage category
δ	damage category
γ	heat capacity ratio
η	isentropic efficiency
μ	Joule-Thompson coefficient
ϖ	weighting factor for the damage category
θ	normalization factor

Subscripts

e	SSTC axes
i	LP streams
ic	impact category
j	HP streams
k	streams splits
m	heating utility
n	cooling utility
s	stages in the WEN

work and heat significantly improves the process energy efficiency, reducing capital and operational costs related to the LNG process. The mathematical formulation has been extended by Onishi et al. [11] for the retrofit of existing HENs.

Razib et al. [7] have proposed an optimization model for preliminary WEN synthesis. In their work, the problem is formulated using mathematical programming techniques with the objective of minimizing the total annual cost. However, these authors have not considered heat integration of process streams. To address this issue, Onishi et al. [10] have developed a MINLP model for WENs optimization, allowing streams thermal integration. Their results emphasize that simultaneous heat integration between pressure manipulation stages is essential for improving the WEN cost-effectiveness.

Fu and Gundersen [17] have studied the correct placement of pressure manipulation equipment coupled to HENs at above ambient conditions. A graphical approach is developed for HENs design containing compressors and expanders, for minimization of exergy consumption. Later, Fu and Gundersen [18] have proposed new thermodynamic insights based on pinch analysis for the application of work and heat integration to CO_2 capture processes. The authors have shown that optimal integration between work and heat can lead to considerable energy savings in oxy-combustion and post-combustion membrane-based separation processes.

Although the above-mentioned works can represent important contributions for the process systems engineering (PSE) field, none of them has considered environmental concerns during the network design task. To surpass this limitation, we introduce a new multi-objective model for the synthesis of work and heat exchange networks (WHENs), aiming to obtain the optimal balance between economic and environmental performance. To the best of our knowledge, this is the first study to carry out the WHEN design through the simultaneous optimization of both objectives. Hence, the main novelty of this work relies in the assessment of the environmental impacts associated to energy services consumption during the WHEN synthesis, while accounting for the total annualized cost of the network. The life cycle assessment (LCA)-based Eco-indicator 99 is used to evaluate the environmental criteria. The proposed model is formulated via multi-objective mixed-integer nonlinear programming (moMINLP), and solved by the standard ε-constraint method. A case study is performed to obtain a set of optimal alternative Pareto solutions. As each of these solutions

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