Computers and Chemical Engineering 93 (2016) 221–233

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Shared and practical approach to conserve utilities in eco-industrial parks

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ARTICLE INFO

Article history:
Received 17 March 2016
Received in revised form 4 May 2016
Accepted 6 May 2016
Available online 16 June 2016

Keywords:
EIP
Heat exchanger network synthesis
Inter-plant integration
Mixed integer non-linear programming
Optimization

ABSTRACT

Conserving utilities in an eco-industrial park (EIP) by exploiting the synergistic heating/cooling needs of its inhabitants can have significant economic and environmental benefits. However, a successful implementation of an EIP-wide heat integration involves much more than the simple minimization of utility usage. Like any collaborative endeavour involving independent and diverse profit-making enterprises, an EIP-wide heat integration faces several real and practical challenges such as exchanger locations, stream transports over long distances, etc. In this work, we propose a mixed-integer nonlinear programming model (MINLP) for configuring an EIP-wide multi-enterprise heat exchanger network (HEN). We propose a practical and rational strategy that (1) considers all the major capital and operating costs, and utility savings, (2) selects an optimum HEN location with the highest net present value, (3) uses a third-party logistics provider for managing and operating the HEN, and (4) ensures an identical rate of return on investment for all participating enterprises.

1. Introduction

The chemical process industry needs much energy in the form of many hot/cold utilities with significant economic and environmental impacts. Hence, it is important to conserve energy by exchanging heat between its hot and cold process streams. Since Linnhoff and Flower (1978) first introduced heat integration in 1978, more than four hundred works (Furman and Sahinidis, 2002) have addressed heat integration and heat exchanger network synthesis (HENS). However, most have focused on intra-plant versus inter-plant integration.

Eco-industrial park (EIP) is an integrated complex of symbiotic manufacturing and service facilities in close proximity, which collaborate with each other for improved environmental, social, and economic performance, and thus sustainability (Boix et al., 2015; Côté and Cohen-Rosenthal, 1998; Lowe et al., 1996). Jurong Island (Singapore), Kalundborg (Denmark), Rotterdam (Netherlands), and Uimaharju (Finland) are some examples of successful industrial symbioses (Ehrenfeld and Gertler, 1997; Kastner et al., 2015; Saikku, 2006), where companies utilize each other's by-products, form wastewater cascading, and share utilities and logistics facilities. Inter-plant energy integration and optimization is possible in such clusters and is of much research interest (Boix et al., 2015; Chen and Wang, 2012; Côté and Cohen-Rosenthal, 1998). In fact, some EIPs such as Jurong Island in Singapore wish to assess the possibility of and potential for inter-plant heat integration.

Ahmad and Hui (1991) first adapted the pinch analysis to find minimum energy usage for separate, but sparsely connected, process regions inside a plant. Hui and Ahmad (1994) further extended this to a 9-step procedure to identify a network considering the costs of interconnections and exchangers. Rodera and Bagajewicz (1999) developed a pinch-based method to achieve maximum energy savings for direct and indirect heat integration across multiple plants with the help of fluid circuits. They also developed an MILP model to identify the optimal number of connections and circuit locations (Bagajewicz and Rodera, 2000, 2002; Rodera and Bagajewicz, 1999). Rodera and Bagajewicz (2001) extended this transshipment model to multipurpose heat exchangers that enabled the plants to operate in standalone or integrated modes. Kralj et al. (2002, 2005) analyzed various alternatives for heat integration among retrofitted and non-retrofitted processes. Stijepovic and Linke (2011) noted the limitations in recovering heat from distant plants. They proposed an approach to target waste heat reuse potentials in industrial zones, and developed concrete integration options based on economic goals. Stijepovic et al. (2012) later extended this approach to combined heat and power

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http://dx.doi.org/10.1016/j.compchemeng.2016.05.003
0098-1354/

Nomenclature

Subscripts

e	Enterprise in the EIP
i	Hot process stream
j	Cold process stream
k	Stage in the HEN superstructure
l	Location of the central HEN
s	Process stream

Superscripts

L	Lower limit
U	Upper limit

Parameters

E	Number of enterprises
F	Heat-content flow (mass flow × heat capacity or kW/K) of hot stream
FC	Fixed component of the purchase cost of a heat exchanger ($)
G	Heat-content flow (mass flow × heat capacity or kW/K) of cold stream
I	Number of hot process streams
J	Number of cold process streams
K	Number of stages in the superstructure excluding the first and last stage
L	Number of potential locations for the central HEN
N	Number of years
r	Interest rate for NPV computation
S	Number of process streams
TC	Cost ($/a) of transporting a stream to and from the HEN
TIN	Initial temperature of stream (K)
$TOUT$	Final (target) temperature of stream (K)
$UTIN$	Entry temperature of utility (K)
$UTOUT$	Exit temperature of utility (K)
U	Overall heat transfer coefficient (kW/m^2-K)
UC	Unit utility cost ($/kW-a)
VC	Coefficient in the variable component of the purchase cost of a heat exchanger
α	Installed cost-purchased cost multiplier for an exchanger
β	Exponent in the cost correlation for an exchanger

Continuous variables

A	Area of an exchanger (m^2)
$CAPEX$	Total capital expense ($)
CTA	Temperature approach at the cold end of an exchanger (K)
D	Temperature change for hot substream in an exchanger (K)
f	Fractional heat-content flow of hot substream in an exchanger
g	Fractional heat-content flow of cold substream in an exchanger
HEC	Heat exchanger cost ($)
HTA	Temperature approach at the hot end of an exchanger (K)
$LMTD$	Logarithmic mean temperature difference (K)
MTA	Minimum allowable temperature approach in an exchanger (K)
NPV	Net present value ($)
$OPEX$	Operating expense ($/a)
Q	Heat duty (kW)
R	Temperature change for cold substream in an exchanger (K)
T	Temperature of a stream (K)
UEC	New in-plant utility heater/cooler cost ($)
γ	Annuity factor for annual operating expense
δ	Fractional contribution to CAPEX or OPEX

Binary variables

v	Comparison of area for the two utility heat exchangers
w	Number of utility heaters/coolers for a stream
x	Existence of a heat exchanger
y	Entry of stream in the stage
Y	Existence of stage
z	Entry of stream into the HEN

Acronyms

EIP	Eco-industrial park
HE	Heat exchanger
HEN	Heat exchange network
HENS	Heat exchange network synthesis
MILP	Mixed-integer linear programming
MINLP	mixed-integer non-linear programming
NPV	Net present value

(CHP) generation. Hipólito-Valencia et al. (2014a) incorporated organic Rankine cycles (ORCs) inside their HEN superstructure, and achieved reductions in utilities and external power. To address the environmental and social objectives in addition to the economics, Hipólito-Valencia et al. (2014b) then developed an HEN design considering greenhouse gas emissions and job creation for an industrial trigeneration system comprising an ORC, a steam Rankine cycle (SRC), and an absorption refrigeration cycle (ARC). Chae et al. (2010) proposed a framework that includes energy data collection, information analysis, optimization of waste heat utilization, and total energy cost minimization in an EIP. Their model showed reduction in total waste heat and energy costs for an existing petrochemical complex in Yeosu, South Korea. Kim et al. (2010) used the same case study to optimize utility network using an MILP model that considers raw material costs, piping investments, and operating expenses. Bade and Bandyopadhyay (2014) optimized the thermal oil flow rates to reduce the piping and pumping costs for indirect integration among multiple plants. Recently, Wang et al. (2015) studied a combined scheme of direct and indirect heat integration, primarily meant for two plants. They considered piping costs, but assumed isothermal mixing.

While the aim of an EIP-wide HENS to exploit the synergistic heating/cooling needs of its plant inhabitants and reduce total utility costs is sound, the implementation, construction, and operation of such a network entails several costs and challenges (Chew et al., 2013) in practice. In contrast to intra-plant heat integration, EIP-wide integration poses several unique economic, design, logistics, operations, and safety challenges.

First, an EIP-wide HEN requires willing collaboration among multiple, independent, diverse, profit-making entities. It must offer a sufficiently attractive economic incentive to each party along with an equitable cost-benefit sharing arrangement. This has largely been addressed using game theory and fuzzy optimization techniques (Tan et al., 2016). Cheng et al. (2014) proposed the idea of plants trading their streams (process or utility) to others based on a game theory. However, as we discuss later, their approach has real issues. It advocates shifting the savings of one company to make up the costs of others. Although this avoids losses by one company, the