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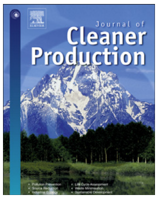

Fuzzy analytic hierarchy process and targeting for inter-plant chilled and cooling water network synthesis

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ABSTRACT

In recent years, the concept of industrial symbiosis (IS) has led to improvements in resource efficiency that may not be possible with individual industrial plants acting independently. One specific aspect is to achieve economies of scale by having multiple companies located in close proximity in order to share common utilities, such as chilled and cooling water. Together, these industrial plants may form an inter-plant chilled and cooling water network (IPCCWN) to achieve greater overall cost savings. Some issues faced by an IPCCWN include network reliability problems due to the consistency of sources' availability, and cost savings allocations for IPCCWN synthesis due to the subjectivity of human preference on decision making. Thus, there exists a need for a decision-making tool to determine a feasible solution that will satisfy all industrial plants in the IPCCWN. In this work, a multi-objective linear programming model is developed to synthesize IPCCWN that achieves maximum cost savings. Next, a Pareto optimal solution is selected using fuzzy analytic hierarchy process (FAHP) approach. This solution gives the best balance of performance for a set of pre-defined qualitative and quantitative criteria, which is able to account for subjectivity that cannot be addressed from a purely mathematical programming standpoint.

1. Introduction

Due to an expanding world population and strong economic growth, world energy demand is increasing rapidly. According to Energy Information Administration (EIA, 2013), world energy consumption will grow by 56% between 2010 and 2040, while fossil fuels will continue to serve as the main supply for energy production through 2040. Following the trend of consistently increasing energy price, energy conservation remains the primary concern for many process industries. As of today, the global challenge currently facing researchers, industrial practitioners as well as policy makers is to apply systematic techniques in sustainable process design to reduce energy consumption, greenhouse gas emissions and waste production.

Process integration (PI) is one of the key methods identified for sustainable process design. The earliest successful application of PI was heat integration (Hohmann, 1971; Linnhoff and Flower, 1978). Subsequently, the analogy between heat and mass transfer led to the evolution of mass integration (El-Halwagi and Manousiouthakis, 1989), from which water network synthesis has become a widely studied area (Kuo and Smith, 1998; Foo, 2009). As heat and water utilities are often associated with each other in process industry operations, the optimum synthesis of chilled and cooling water network is gaining much attention from researchers to achieve simultaneous water and energy savings (Ponce-Ortega et al., 2007; Lee et al., 2013; Chew et al., 2013).

Chilled and cooling water networks consist of process operations which use chilled water and/or cooling water as utilities to remove excess heat. Chilled water has a typical temperature range of 2–7 °C, while cooling water streams range from 20 °C to 30 °C. Typically, vapour compression chillers are used to generate chilled water using mechanical energy as input, although vapour absorption systems that use thermal energy instead are also available (Smith, 2005; Hundy et al., 2008). On the other hand, cooling towers use evaporative cooling mechanisms to remove heat and produce cooling water near wet bulb air temperature. Fig. 1 shows the typical chilled water and cooling water system as mentioned above.

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Nomenclature

Sets

$C = \{c_1, \ldots, c_{N_{\text{criteria}}}\}$ is set of criteria
$D = \{d_1, \ldots, d_{N_{\text{designs}}}\}$ is set of alternative IPCCWN
$I = \{i_1, \ldots, i_{N_{\text{sources}}}\}$ is set of process sources
$I_k = \{i \in I | i \text{ is located in plant } k\}$ is set of process sources located in plant k
$J = \{j_1, \ldots, j_{N_{\text{sinks}}}\}$ is set of process sinks
$J_k = \{j \in J | j \text{ is located in plant } k\}$ is set of process sinks located in plant k
$K = \{k_1, \ldots, k_{N_{\text{plants}}}\}$ is set of participating plants

Parameter

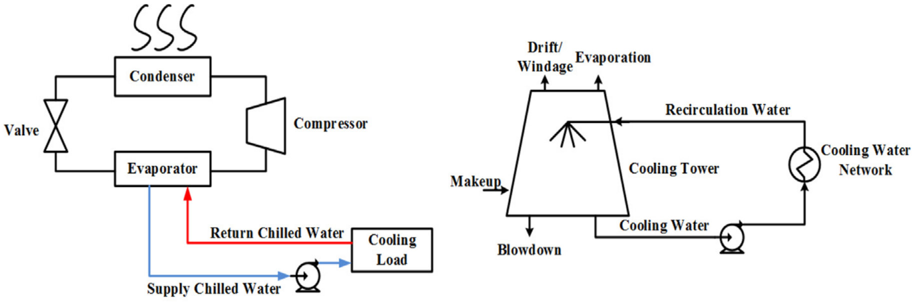
α	index of optimism
ρ	water density
AF	annualized factor
$L_{k,k'}$	distance for all pipelines between two participating plants
Fd_j	water flow rate requirement of sink j
Fs_i	available water flow rate of source i
F_{LB}	lower limit of the cross-plant stream flow rate
F_{UB}	upper limit of the cross-plant stream flow rate
Hy	yearly operating time
p	incremental cost parameter based on the cross-sectional area of pipeline
q	fixed cost parameter for building one pipeline
TAC_k^{L}	lower limit of total annualized cost for plant k (desired costs) in the IPCCWN
TAC_k^{U}	upper limit of total annualized cost for plant k in the IPCCWN
$Tchw$	temperature of fresh chilled water
Tcw	temperature of fresh cooling water
Tin_j	temperature requirement of sink j
$Tout_i$	temperature of source i
$Uchw$	unit cost of fresh chilled water
Ucw	unit cost of fresh cooling water
Uw	unit cost of return stream
Ur	unit cost of reused water
v	stream velocity

Variables

λ	overall satisfaction level
λ_k	satisfaction level of plant k
A	fuzzy relative importance of each pair criteria
a	lower values of fuzzy synthetic values
b	medium values of fuzzy synthetic values
c	upper values of fuzzy synthetic values
DC_k	fresh chilled and cooling water cost in plant k
$FC_{k,k'}$	cost associated with reused water in plant k
$Fchw_j$	flow rate of fresh chilled water entering sink j
Fcw_j	flow rate of fresh cooling water entering sink j
FS_d	final score of alternative IPCCWN d
$F_{i,j}$	reuse/recycle water flow rate from source i to sink j
I_c	integral value of R_c
l	lower value of TFN
m	modal value of TFN
$M_{c,c'}$	triangular fuzzy number of criteria c over criteria c'
OC_k	cost associated with return stream in plant k
$PCE_{k,k'}$	annualized inter-plant piping cost of plant k as exporter
$PCR_{k,k'}$	annualized inter-plant piping cost of plant k as receiver
$s_{c,d}$	criteria score of alternative IPCCWN d
R_c	fuzzy synthetic values with respect to criteria c
TAC_k	total annualized cost of plant k
TFC_k	overall cost associated with reused streams
TPC_k	overall inter-plant piping cost of plant k
u	upper value of TFN
W_i	flow rate of return stream from source i
w_c	final average weight of criterion
$x_{i,j}$	binary variables for cross-plant pipelines

Kim and Smith (2001) presented a systematic method for cooling water system design that accounts for the interaction between cooling water network and cooling tower efficiency. In their work, design of the cooling water network using the proposed method can avoid investment in a new cooling tower. Several works dealing with the optimization of chilled and cooling network were done using pinch analysis (Leong et al., 2008; Shenoy and Shenoy, 2013; Foo et al., 2014) and superstructural mathematical optimization (Panjeshahi et al., 2009; Ponce-Ortega et al., 2010; Rubio-Castro et al., 2010, 2013; Lee et al., 2013). From their works, significant cost savings are achieved through the reduction of utilities consumption and waste production.

All the above mentioned works have been successful in achieving resource conservation through in-plant chilled/cooling water process integration and optimization. On the other hand, the concept of industrial ecology (IE) which promotes cooperation



(a) (b)

Fig. 1. (a) Vapour compression chilled water and (b) evaporative cooling water systems.