Computers and Chemical Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Synthesis of water networks for industrial parks considering inter-plant allocation

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form 14 March 2016
Accepted 18 March 2016
Available online xxx

Keywords:
Inter-plant
Allocation
Water network
Industrial park
Superstructure

ABSTRACT

Since an industrial park is a cluster of multiple company individuals, there is requirement to develop specific reuse strategies so as to improve the utilization of resources across plants. This article presents a ‘plant-based’ mode respecting to the water allocation problem within industrial parks. In the mode, mixers and splitters are involved to present the mixing, conveying and splitting operations for reusing streams across plants. Such that, the mixing possibilities can also be investigated and many redundant solutions can be avoided by considering the number limit of inter-plant stream connections at the building stage of network superstructures. On base of this mode, both direct and mixed (direct–indirect) integration scenarios are studied in this study. Superstructures are established and mathematically formulated aiming to minimum fresh water consumption as well as the total annualized cost. At last, three integration cases are explored based on an example from literature for illustration.

1. Introduction

Nowadays, the shortage and pollution problems of water have become serious barriers to the development of human society. As a promising way of cooperating among individual plants, industrial parks can provide more opportunities for resources saving and sharing, as well as the centralized treatment of waste. So exploring the reusing possibility in industrial parks, especially investigating the allocation, using and regeneration by breaking process or plant boundary limits would be very meaningful for the global saving and pollution reduction of water in process industries.

Since the earliest introduction of water integration issue by Wang and Smith (1994), lots of efforts have been made to develop methodologies and strategies toward this topic. Among which, Doyle and Smith (1997) proposed a sequential optimization approach to seek the maximum water reuse for multiple contaminants systems. Alva-Argáez et al. (1998) combined water pinch technology with mathematical programming method. Based on decomposition scheme, they optimized the multi-contaminant network with considering waste water treatment operation. The wastewater treatment network then was extracted and studied by Galan and Grossmann (1999) via using a non-convex nonlinear programming. Savelski and Bagajewicz (2000, 2001, 2003) proposed the optimality conditions for the design of single-contaminant and multi-contaminant water network, based on which they presented rules for the maximum water reuse. Feng and Seider (2001) introduced internal water mains to carry out single-contaminant water network design, and used this methodology to simplify the network structure and reduce fresh water consumption. El-Halwagi et al. (2003) developed recycle pinch technique to design recycle networks for various species including water. Tan and Cruz (2004) proposed a systematic fuzzy linear programming and applied it to retrofit single-contaminant water reuse networks. Ng et al. (2009), Faria and Bagajewicz (2010) considered the pre-treatment problem in the design of water network. And in recent reports, Wang et al. (2012), Shenoy (2012), Soo et al. (2013), Jimenez-Gutierrez et al. (2014) and Ahmetovic et al. (2014) extended the application of heuristic and mathematical methods to address the complex water integration problems referring recycle, waste treatment, multi-system-integration (including heat, energy, mass and properties) and also algorithm. The mentioned approaches are all effective tools for solving water allocation problems, however, they only focus upon a single plant. The design involving interaction across plants was not considered in these studies.

Considering the booming of industrial parks and new problems caused thereby, the researches on water integration respecting with industrial parks were gradually enriched in recent years.

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http://dx.doi.org/10.1016/j.compchemeng.2016.03.013

Please cite this article in press as: Liu L, et al. Synthesis of water networks for industrial parks considering inter-plant allocation. Computers and Chemical Engineering (2016), http://dx.doi.org/10.1016/j.compchemeng.2016.03.013

Nomenclature

Indices

c	contaminant
i	water source
j	water sink
p	plant
p'	plant

Sets

CN	set of contaminants
P	set of plants
$SINK_p$	set of water sinks in plant p
$SOURCE_p$	set of water sources in plant p

Parameters

AF	annualized factor
AWH	annual working hour
$C_{\text{sink}}(c,j,p)$	maximum permissible composition of pollutant c in sink j, plant p
$C_{\text{source}}(c,i,p)$	composition of pollutant c in source i, plant p
$C_{\text{f}}(c)$	composition of pollutant c in fresh water
D	inter-plant pipelines distance
E_{cost}	unit cost for waste treatment
f_{loss}	water loss
$F_{\text{sink}}(j,p)$	required flowrate of sink j in plant p
$F_{\text{source}}(i,p)$	provided flowrate of source i in plant p
k	pipeline cost parameter
LB	lower bound for stream
m	fractional interest rate per year
n	number of working years
N_{inter}	maximum allowed number of inter-plant streams
q	pipeline cost parameter
R	removal ratio of pollutant c in central regeneration
R_{cost}	unit cost for regeneration
UB	upper bound for stream
W_{cost}	unit cost for fresh water
ρ	water density
v	flowrate velocity

Variables

$C_{\text{in-mix}}(c,p)$	concentration of contaminant c in the total inter-plant stream that to be used in plant p
$C_{\text{out-mix}}(c,p)$	concentration of contaminant c in inter-plant stream formed in plant p
$C_{\text{reg}}(c)$	concentration of contaminant c at the outlet of regenerator
$f_{\text{f-s}}(j,p)$	flowrate of fresh water to sink j in plant p
$f_{\text{s-s}}(i,j,p)$	flowrate of inner-plant stream from source i to sink j in plant p
$f_{\text{s-w}}(i,p)$	flowrate of inner-plant stream from source i to wastewater sink in plant p
$f_{\text{s-i}}(i,p)$	flowrate of inter-plant stream from source i in plant p
$f_{\text{i-s}}(j,p)$	flowrate of inter-plant stream to sink j in plant p
$f_{\text{in-inter}}(p)$	total flowrate of inter-plant stream into plant p
$f_{\text{out-inter}}(p)$	total flowrate of inter-plant stream out of plant p
$f_{\text{dir}}(p,p')$	flowrate of direct inter-plant stream from plant p to plant p'
$f_{\text{in-ind}}(p)$	flowrate of indirect inter-plant stream from regenerator to plant p
$f_{\text{out-ind}}(p)$	flowrate of indirect inter-plant stream from plant p to regenerator
M_{reg}	total contaminant mass load removed by regenerator
N	inter-plant stream number in a network
obj_{cost}	total annualized cost
obj_{fresh}	fresh water consumption
obj_{inter}	total inter-plant flowrate
P_{cost}	annualized capital cost for pipelines
$x(p)$	binary variable to indicate the existence of indirect inter-plant stream from plant p to regenerator
$y(p)$	binary variable to indicate the existence of indirect inter-plant stream from regenerator to plant p
$z(p,p')$	binary variable for direct inter-plant stream from plan p to plant p'

Olesen and Polley (1996) carried out the earliest water integration study for inter-plant problem in 1996 by dividing the overall site into several geographical zones. Then, Spriggs et al. (2004) proposed the material recovery pinch diagram to determine the minimum fresh water consumption of inter-plant water allocation problem. However, an extensive discussion about this issue was mainly concentrated in last eight years. Wherein, Lovelady et al. (2007) proposed an optimization approach so as to reduce the water consumption and discharge in pulp and paper plants. Foo (2008) utilized the numerical tool of water cascade analysis (WCA) for inter-plant water network synthesis. Chew and Foo (2009) introduced an automated targeting technique based on pinch technology.

The aforementioned methods can be categorized into the heuristic methods. These methods can give designers good insights during the design, however, they are hard to be used in the large-scale, multi-contaminant and multi-objective problems which are often the cases for industrial park water allocation problems. Mathematical programming approaches are more suitable for these more complex problems, and have been developing fast in recent years based on the study on superstructure.

Liao et al. (2007) developed a stagewise methodology for multi-period plant-wide water network synthesis, but without taking account the regeneration and reallocation of water. Chew et al. (2008) proposed that inter-plant water integration can be classified into direct integration and indirect integration, wherein the former can be directly implemented through the pipelines between plants, and the latter requires the water from plants being sent to a utility hub and then reallocated. But they did not include the water reuse inside each plant, and the direct and indirect integration were utilized separately. Lovelady and El-Halwagi (2009) introduced interception theory into the optimal design of inter-plant water network, the direct and indirect integration were simultaneously executed in this study. Bandyopadhyay et al. (2010) proposed a universal decomposing method when dealing with the optimal utilization of resources in segregated targeting problem, and applied it to inter-plant water integration. Lim and Park (2010) presented an optimization model and simultaneously studied the life circle assessment (LCA) and life circle cost (LCC) to make economic and environmental analysis for their obtained water systems. Later, source-interception-sink representation was used by Rubio-Castro et al. (2012) to retrofit existing networks for eco-industrial parks. In order to improve the practicability of system, Chen et al. (2010) presented a mathematical model for integration by placing centralized and decentralized water mains within and between individual plants. Boix et al. (2012) studied a multi-objective optimization problem, in which the fresh water flow rate, regenerated water flow rate as well as the inter-plant stream number were simultaneously minimized, then Montastruc et al. (2013) extended this study to a flexibility analysis. Rubio-Castro et al. (2013) proposed a

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