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A two-stage approach for the synthesis of inter-plant water networks involving continuous and batch units

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ABSTRACT

This paper presents a mathematical optimization model for inter-plant water network (IPWN) synthesis, where process units operate in mixed continuous and batch modes. The current developed model consists of a two-stage approach, and is dedicated to the special case where there are more continuous than batch units. In the first stage, all batch units are treated as continuous units by using auxiliary water storage tanks, and a continuously operated IPWN is synthesized to minimize the fresh water consumption. Subject to the determined IPWN flow rates, the water storage policy for the batch units is determined in the second stage to minimize the total storage capacity. Alternatively, the formulations of both stages can be combined and solved simultaneously to minimize the IPWN cost. Two modified literature examples are used to illustrate the proposed approach.

Keywords: Continuous process; Batch process; Inter-plant water integration; Process integration; Water network synthesis; Mathematical optimization

1. Introduction

Water is an important utility being intensively used in the process industry. Some of the common uses of water include thermal purposes, steam stripping, liquid–liquid extraction and various washing operations. Rapid industrial growth has led to serious water pollution in the world, and therefore the environmental regulations for wastewater disposal are increasingly stringent. Concurrently, the scarcity of industrial water (partly due to climate change) has also led to the rise of fresh water and effluent treatment costs. The economic considerations, along with the increased public awareness of environmental sustainability, have stimulated the recent development of systematic design tools for efficient and responsible use of water in industry. Particularly, systematic design of in-plant water recovery systems through *process integration* techniques (also known as *water network synthesis*) has been commonly accepted as an effective means in this regard, with *reuse*, *recycle* and *regeneration* as options for reduction of industrial fresh water intake and wastewater discharge (Wang and Smith, 1994).

Over the past decades, various process integration techniques for water network synthesis have been developed for continuous and batch processes (Bagajewicz, 2000; Foo, 2009; Jeżowski, 2010; Gouws et al., 2010). These techniques can be broadly classified into *insight-based pinch analysis* and *mathematical optimization* approaches. The former is generally a two-step methodology consisting of targeting and network design steps (Foo, 2012). It offers good insights into the synthesis problem and thus assists in the identification of bottleneck operations. Although the mathematical techniques do not provide such insights, they are very useful in dealing with complex cases, such as multiple contaminant systems, cost considerations, forbidden or compulsory matches and limited piping connections (Takama et al., 1980; Alva-Argáez et al., 1999; Bagajewicz and Savelski, 2001).

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Nomenclature

Indices and sets

$c \in \mathcal{C}$	contaminants
$d \in \mathcal{D}$	wastewater disposal systems
$i \in \mathcal{I}$	water-using units
$i \in \mathcal{I}^b \subset \mathcal{I}$	batch water-using units
$i \in \mathcal{I}^c \subset \mathcal{I}$	continuous water-using units
$i \in \mathcal{I}_p \subset \mathcal{I}$	water-using units in plant p
$m \in \mathcal{M}$	water mains
$m \in \mathcal{M}_p \subset \mathcal{M}$	water mains in plant p (local mains)
$m \in \mathcal{M}^{cen} \subset \mathcal{M}$	centralized water mains
$p \in \mathcal{P}$	process plants
$t \in \mathcal{T}$	time intervals
$w \in \mathcal{W}$	fresh water sources

Parameters

AF	annualization factor
AOH	annual operating hours
$C_{ic}^{in,max}$	maximum inlet concentration of contaminant c for unit i
$C_{ic}^{out,max}$	maximum outlet concentration of contaminant c for unit i
C_{wc}	concentration of contaminant c in fresh water source w
CFW_w	unit cost of fresh water from source w
CM_m^{fix}	fixed cost for main m
CM_m^{var}	variable cost for main m
$CP_\dagger^{fix}$	fixed cost for pipe connection $\dagger \in \{id, im, md, mi, mm', wi\}$
$CP_\dagger^{var}$	variable cost for pipe connection $\dagger \in \{id, im, md, mi, mm', wi\}$
CST_i^{fix}	fixed cost for the storage tanks of batch unit i
CST_i^{var}	variable cost for the storage tanks of batch unit i
CWD_d	unit cost of wastewater disposal through system d
Δ_t	length of time interval t
$F_\dagger^L$	lower bound for the flow rate in connection $\dagger \in \{id, im, md, mi, mm', wi\}$
$F_\dagger^U$	upper bound for the flow rate in connection $\dagger \in \{id, im, md, mi, mm', wi\}$
$\bar{F}_i^{s1}$	upper bound for the inlet/outlet flow rate of tank 1 of batch unit i
$\bar{F}_i^{s2}$	upper bound for the inlet/outlet flow rate of tank 2 of batch unit i
F_m^L	lower bound for the inlet flow rate of main m
F_m^U	upper bound for the inlet flow rate of main m
M_{ic}	mass load of contaminant c in unit i
T^{cyc}	batch cycle time
T_i^{op}	total operating time of batch unit i in a cycle
Z_{it}^{op}	binary parameter indicating whether batch unit i operates in time interval t

Variables

c_{ic}^{in}	inlet concentration of contaminant c to unit i
c_{ic}^{out}	outlet concentration of contaminant c from unit i
c_{mc}	concentration of contaminant c in main m
f_i^{in}	inlet water flow rate of unit i
f_i^{out}	outlet water flow rate of unit i
f_{it}^{in}	inlet water flow rate of batch unit i in time interval t
f_{it}^{out}	outlet water flow rate of batch unit i in time interval t
$f_{it}^{s1,in}$	inlet water flow rate to tank 1 of batch unit i in time interval t
$f_{it}^{s1,out}$	outlet water flow rate from tank 1 of batch unit i in time interval t
$f_{it}^{s2,in}$	inlet water flow rate to tank 2 of batch unit i in time interval t
$f_{it}^{s2,out}$	outlet water flow rate from tank 2 of batch unit i in time interval t
f_{id}	water flow rate from unit i to wastewater disposal system d
f_{im}	water flow rate from unit i to main m
f_m^{in}	inlet water flow rate of main m
f_m^{out}	outlet water flow rate of main m
f_{md}	water flow rate from main m to wastewater disposal system d
f_{mi}	water flow rate from main m to unit i
$f_{mm'}$	water flow rate from main m to main m'
f_{wi}	water flow rate from fresh water source w to unit i
q_{it}^{s1}	amount of water stored in tank 1 of batch unit i at the end of time interval t
q_{it}^{s2}	amount of water stored in tank 2 of batch unit i at the end of time interval t
$\bar{q}_i^{s1}$	storage capacity of tank 1 of batch unit i
$\bar{q}_i^{s2}$	storage capacity of tank 2 of batch unit i
$y_\dagger$	binary variable indicating the existence of connection $\dagger \in \{id, im, md, mi, mm', wi\}$
y_m	binary variable indicating the existence of main m

Apart from in-plant water recovery, opportunities for *inter-plant water integration* (IPWI) may be explored to achieve further recovery when considering an industrial complex with multiple plants or processes, i.e. *inter-plant water network* (IPWN) synthesis. The first process integration work addressing this issue was reported by Olesen and Polley (1996) using the conventional fixed-load model (Wang and Smith, 1994). Foo (2008) later addressed the problem from the fixed-flow-rate perspective.

In addition to the earlier works based on pinch analysis approaches, several other works on the use of mathematical techniques were later reported for IPWI. This includes the early work of Keckler and Allen (1998), in which each process plant is treated as a single unit. Lovelady et al. (2007) later devised a more detailed optimization model for IPWI in pulp and paper plants. Liao et al. (2008) developed a two-step approach to deal with the multi-period problem in IPWNs. The model developed by Chew et al. (2008) handles two different schemes of IPWI, i.e. *direct* and *indirect* integration. In the former, water from different plants is integrated directly via cross-plant pipelines; in the latter, integration of water from different plants is carried out indirectly via a centralized utility hub. Note that the utility hub can be seen as an internal water main (reservoir) in a water network to improve operational flexibility and controllability (Kuo and Smith, 1998; Feng and Seider, 2001). The model of Chew et al. (2008) was then extended for eco-industrial park (EIP) design with the concept of property integration (Lovelady et al., 2009). Another optimization model for IPWN synthesis was proposed by Chew