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A two-stage optimization approach for the synthesis of resource conservation networks involving interception units

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ABSTRACT

This study presents a mathematical optimization model for resource conservation network (RCN) synthesis that includes interception units within the structure of the network. RCNs are the one of the most efficient designs for minimizing fresh water consumption, wastewater generation, and operation cost. Interception units (single pass and partitioning units) are widely accepted industrial application techniques used to reduce network complexity and flow rate targets in RCN. Cost equations relating to the piping and operating costs are added when interception units are designed in an RCN. Then, the problem is formulated as a two-stage optimization model whose objective functions are to minimize freshwater consumption and total annualized cost (TAC). The applicability of the developed model is demonstrated with two case studies. Single pass interception units with a fixed outlet concentration (C_{Rout}) reduced freshwater consumption by 23.16% and 46.3%, while partitioning units reduced consumption by 21.69% and 29% respectively, when compared to base systems.

1. Introduction

Water has become a major source of supply in many process industries; for example paper and pulp and chemical industries rely completely on freshwater. Optimization of freshwater consumption is one of the most important objectives of modern process industries. Increases in resource prices and operating costs lead process industries to optimize freshwater consumption while maintaining profitability. As result of improvements in material conservation and recycling/reuse, mass/heat exchange network-based process integration has seen major efficiency gains over the past decades. Process integration technique has emerged as an effective tool in identifying various retrofit alternatives and is defined as a holistic approach to design, modernize, and unify processes (El-Halwagi, 1997, 2006). This approach serves as a more aggressive strategy for pollution prevention than conventional end-of-pipe waste treatment activities (Chen et al., 2011). Process industries are also in search of efficient and less expensive technologies to sustainably design manufacturing processes. Within the framework of process integration, resource conservation network (RCN) activities are cost-effective solutions where materials are recycled/reused within processes without adversely affecting the process performance (Ng et al., 2009b).

Compared to an end-of-pipe wastewater treatment system, process integration approaches involving RCNs are well suited to address various resource conservation alternatives. In most cases, fresh material consumption and waste generation are reduced simultaneously through resource conservation

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Nomenclature

Sets

i	$\{i = 1, 2, 3, 4\ldots$ sources$\mid$ i is a set of process sources$\}$
j	$\{j = 1, 2, 3, 4\ldots$ sinks$\mid$ j is a set of process sinks$\}$

Variables

W_{RE}	flow rate of a single pass interception inlet stream
W_{REG}	regenerated (purified) flow rate of single pass interception
W_{FW}	total freshwater flow rate
$W_{FW,SKj}$	required fresh water flow rate for sink j
$W_{REG,SKj}$	regenerated (purified) flow rate required by sink j
$W_{SRi,SKj}$	reuse/recycle flow rate from source i to sink j
$W_{SRi,RE}$	regenerated flow rate from source i
$W_{SRi,WW}$	wastewater flow rate from source i
W_{Rin}	inlet flow rate of partitioning interception unit
W_p	purified stream flow rate of partitioning interception unit
W_{RJ}	reject flow rate of partitioning interception unit
C_{Rin}	inlet stream concentration of partitioning interception unit
C_P	purified stream concentration of partitioning interception unit
C_{RJ}	reject stream concentration of partitioning interception unit
$W_{RJ,SKj}$	reject flow rate of partitioning interception unit from sinks j
TAC	total annual cost
OC	operating cost
PC	piping cost
$B_{SRi,SKj}$	binary variable indicating the existence of connection between sinks and sources

Parameters

$W_{SR,i}$	limiting flow rate of source i
$C_{SR,i}$	limiting concentration of source i
$W_{SK,j}$	limiting flow rate of sink j
$C_{SK,j}$	limiting concentration of sink j
C_{SKj}^{min}	maximum admissible concentration of sink j
C_{SKj}^{max}	minimum admissible concentration of sink j
C_{Rout}	outlet concentration of regenerated stream
α	liquid recovery factor
RR	removal ratio
AWT	annual working time
L	unit cost of waste water
M	unit cost of freshwater
N	unit cost of regenerated water
U	upper bound of reuse/recycle flow rate for both the interception units
D	individual distance between sinks and sources
v	stream flow rate velocity
ρ	water density
AF	annualizing factor
p	fractional interest rate
q	number of years

activities (Dunn and El-Halwagi, 2003; Smith, 2005). To establish network alternatives, recent trends have minimized water consumption through process integration, recycling, reuse, and regeneration (Saif et al., 2008). Implementing material reuse/recycling in RCN synthesis can reduce water consumption and waste generation while embedding various process elements within the structure of the RCN.

Wang and Smith (1994) developed a model which involves all possible configurations for water regeneration–recycling and regeneration-reuse. Yang et al. (2000) proposed a wastewater reuse network in the form of a mathematical program, such that the model was aimed at minimizing wastewater when multiple pollutants are contained in the water stream. Apart from the reuse network, systematic methods have been developed to reduce water usage and effluent generation simultaneously based on pinch analysis (Bai et al., 2007; El-Halwagi et al., 2003; Feng and Seider, 2001; Foo et al., 2006; Hallale, 2002; Prakash and Shenoy, 2005) and mathematical modeling (Savelski and Bagajewicz, 2001; Jeżowski et al., 2003; Tan and Cruz, 2004; Tan et al., 2007a; Tsai and Chang, 2001). However, mathematical modeling offers significant advantages over graphical techniques in handling cost equations, limited piping considerations, forbidden or compulsory matches between certain processes, and process uncertainty (Chen et al., 2011; Tan et al., 2008).

When the detailed synthesis of an RCN is achieved, process sources are partially treated by interception units or regeneration processes in order to further reduce target flowrates after the potential for water recovery through direct reuse/recycling is exhausted (Chen et al., 2011; Ng et al., 2009a). Interception units are a viable technology in process industries. Interception units are classified into two general categories: single pass and partitioning units. Both interception units are classified as fixed outlet quality (C_{Rout}) and removal ratio (RR) type (Foo and Manan, 2006; Hallale and Liu, 2001; Ng et al., 2009a). In the single pass unit, the inlet stream and outlet streams have same flow rates ($F_{Rin} = F_{Rout}$). On the other hand, partitioning units accept a feed water stream and produce two outlet streams of different quality: the purified stream and the reject stream. The purified stream is of higher quality than the feed water stream, while the reject stream is of lower quality than the feed. Partitioning units encompass membrane-based processes (e.g. reverse osmosis), flotation processes, and gravity settling systems (Tan et al., 2010).

Several reports have studied the incorporation of interception units in RCNs (Bai et al., 2007; Bandyopadhyay and Cormos, 2008; Kuo and Smith, 1998; Ng et al., 2008). Takama et al. (1980) suggested water regeneration-based mathematical optimization, which involves the development of a superstructure accounting for all possible configurations of reuse and regeneration. Bagajewicz and Savelski (2001) considered linear programming (LP) and mixed integer linear programming (MILP) models to synthesize optimal water superstructure. This heuristic approach was suggested to guide the placement of regeneration units. Ng et al. (2007) proposed a numerical targeting procedure to locate the minimum regeneration flow rate for both fixed flow rate and fixed load problems. Tan et al. (2010) employed a graphical pinch analysis approach to target the minimum flow rate of a partitioning water pretreatment system. However, they did not address the total annual cost (TAC) of pretreatment units in the water network. Ng et al. (2009a) proposed an automated targeting technique to determine RCN targets involving interception