Computers and Chemical Engineering 34 (2010) 825–845

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

# Automated targeting technique for concentration- and property-based total resource conservation network

Denny Kok Sum NG[a], Dominic Chwan Yee Foo[a,*], Raymond R. Tan[b], Mahmoud El-Halwagi[c]

[a] Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
[b] Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
[c] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA

ARTICLE INFO

*Article history:*
Received 29 July 2009
Received in revised form
29 December 2009
Accepted 21 January 2010
Available online 4 February 2010

*Keywords:*
Process integration
Resource conservation
Automated targeting
Waste minimisation
Optimisation
Property integration

ABSTRACT

Resource conservation networks (RCNs) are among the most effective systems for reducing the consumption of fresh materials and the discharge of waste streams. A typical RCN involves multiple elements of resource pre-treatment, material reuse/recycle, regeneration/interception, and waste treatment for final discharge. Due to the close interactions among these individual elements, simultaneous synthesis of a total RCN is necessary. This paper presents an optimisation-based procedure known as automated targeting technique to locate the minimum resource usage or total cost of a concentration- or property-based total RCNs. This optimisation-based approach provides the same benefits as conventional pinch analysis techniques in yielding various network targets prior to detailed design. Additionally, this approach offers more advantages than the conventional pinch-based techniques through its flexibility in setting an objective function and the ability to handle different impurities/properties for reuse/recycle and waste treatment networks. Furthermore, the concentration-based RCN is treated as the special case of property integration, and solved by the same model. Literature examples are solved to illustrate the proposed approach.

## 1. Introduction

The process industries have traditionally focused on conventional end-of-pipe waste treatment in order to comply with environmental legislation. This approach has been gradually replaced by the use of pollution prevention strategies. This is mainly due to the increase of public awareness of environmental sustainability, the rising cost of raw material, and the increasingly stringent environmental legislation. One of the cost effective solutions is resource conservation, wherein materials are reused/recycled within processes without adversely affecting the process performance. *Process integration* has been commonly accepted as an effective tool in developing and evaluating various resource conservation alternatives.

El-Halwagi (1997, 2006) defined process integration as *a holistic approach to process design, retrofitting and operation which emphasises the unity of the process*. Within the framework of process integration, *pinch analysis* technique has emerged as a promising tool in identifying various network targets prior to detailed design. Over the past decades, extensive pinch analysis works have been reported for the synthesis of water (e.g., Almutlaq, Kazantzi, & El-Halwagi, 2005; Bandyopadhyay, Ghanekar, & Pillai, 2006; El-Halwagi, Gabriel, & Harell, 2003; Foo, Manan, & Tan, 2006; Manan, Tan, & Foo, 2004; Ng, Foo, & Tan, 2009a; Wang & Smith, 1994a) and utility gas networks (e.g., Agrawal & Shenoy, 2006; Alves & Towler, 2002; Bandyopadhyay, 2006; El-Halwagi et al., 2003; Foo & Manan, 2006). The net result of resource conservation activities is the simultaneous reduction of both fresh resource consumption and waste discharge.

After the opportunities for maximum material recovery are exhausted through direct reuse/recycle, fresh resource flowrate may be further reduced with interception or regeneration processes (e.g., Agrawal & Shenoy, 2006; Bai, Feng, & Deng, 2007; Bandyopadhyay & Cormos, 2008; Feng, Bai, & Zheng, 2007; Foo, Manan, & Tan, 2006; Kuo & Smith, 1998a; Ng, Foo, & Tan, 2009b; Ng, Foo, Tan, & Tan, 2007, 2008; Wang & Smith, 1994a). In addition, before waste is discharged to the environment, it needs to be treated to meet the requirements given in the emission legislation. Various works have also been dedicated to this area (e.g., Bandyopadhyay et al., 2006; Bandyopadhyay & Cormos, 2008; Kuo & Smith, 1997; Ng, Foo, & Tan, 2007a, 2007b; Wang & Smith, 1994b).

As pointed out by Kuo and Smith (1998b), there are close interactions between water reuse/recycle, regeneration system, and effluent treatment system. Hence, an overall framework that inte-

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* Corresponding author. Tel.: +60 3 8924 8130; fax: +60 3 8924 8017.
*E-mail addresses:* Denny.Ng@nottingham.edu.my (D.K.S. NG), Dominic.Foo@nottingham.edu.my (D.C.Y. Foo), raymond.tan@dlsu.edu.ph (R.R. Tan), el-halwagi@tamu.edu (M. El-Halwagi).

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doi:10.1016/j.compchemeng.2010.01.018

## Nomenclature

*Indices and sets*

| | |
|---|---|
| $i$ | index for source |
| $I$ | sets of source |
| $j$ | index for sink |
| $J$ | sets of sink |
| $k$ | index for property level |
| $K$ | sets of property level |
| $u$ | index for regeneration |
| $U$ | sets of regeneration |
| $v$ | index for treatment system |
| $V$ | sets of treatment system |

*Parameter/acronyms*

| | |
|---|---|
| $AC^{AS}$ | annualised cost of air stripping |
| $AC^{Bio}$ | annualised cost of biotreatment |
| AOT | annual operating time |
| $C_D$ | maximum allowable discharge concentration |
| $COST_{Clay}$ | unit cost of clay |
| $COST_{FW}$ | unit cost of fresh water |
| $COST_R$ | unit cost of regeneration |
| $COST_{UPW}$ | unit cost of ultra pure water |
| $COST_{TR}$ | unit cost of wastewater treatment |
| DI | deionising unit |
| $m$ | fractional interest rate per year |
| $n$ | number of property levels |
| $OC^{AS}$ | operating cost of air stripping |
| $OC^{Bio}$ | operating cost of biotreatment |
| $p^{LBE}$ | lower bound of property discharge limit |
| $p^{UBE}$ | upper bound of property discharge limit |
| RCCD | resource conservation cascade diagram |
| RCN | resource conservation network |
| RO | reverse osmosis |
| RP | purified stream of filtration unit |
| RR | reject stream of filtration unit |
| RRN | reuse/recycle network |
| RRT | fixed removal ratio |
| SR$i$ | source $i$ |
| SK$j$ | sink $j$ |
| TAC | total annualised cost |
| TOC | total operating cost |
| UF | ultrafiltration |
| UPW | ultra pure water |
| WTN | waste treatment network |
| $y$ | number of years |
| $\psi$ | property operator |
| $\psi_k$ | property operator level $k$ |
| $\psi_D$ | outlet property operator for final discharge |

*Variables*

| | |
|---|---|
| $C$ | concentration |
| $C_R$ | outlet concentration of regeneration/interception unit |
| $C_{Ru}$ | concentration of the individual regeneration streams feeding to regeneration unit $u$ |
| $C_{TR}$ | outlet concentration of treatment system |
| $C_{Tv}$ | concentration of the individual waste streams feeding to treatment unit $v$ |
| $F_{Clay}$ | flowrate of clay |
| $F_D$ | waste discharge flowrate |
| $F_{FW}$ | flowrate of the fresh water |
| $F_{Ru}$ | flowrate from regeneration $u$ |
| $F_{Ru,k}$ | flowrate from regeneration $u$ at level $k$ |
| $F_{REGu}$ | total flowrate of regeneration $u$ |
| $F_{RP}$ | flowrate of purified stream |
| $F_{RR}$ | flowrate of reject stream |
| $F_{SRi}$ | flowrate of SR$i$ |
| $F_{SKj}$ | flowrate of SK$j$ |
| $F_{TRDv}$ | flowrate of treated source $v$ |
| $F_{TRv}$ | flowrate of individual treatment source $v$ |
| $F_{TRv,k}$ | flowrate of individual treatment source $v$ at level $k$ |
| $F_{TR,RR}$ | treatment flowrate from reject stream |
| $F_{UPW}$ | flowrate of UPW |
| $F_{Wi}$ | flowrate of waste from SR$i$ |
| $F_{WRP}$ | flowrate of wastewater generated from purified stream |
| $F_{WRR}$ | flowrate of wastewater generated from reject stream |
| $F_{In}^{UF}$ | inlet flowrate to UF system |
| $F_P^{UF}$ | permeate flowrate for UF system |
| $F_R^{UF}$ | reject flowrate for UF system |
| $F_P^{RO}$ | permeate flowrate for RO system |
| $F_R^{RO}$ | reject flowrate for RO system |
| $L$ | mass flowrate of air |
| $\bar{\rho}$ | mean property |
| $p^{discharge}$ | property discharge limit |
| $p_{Ru}$ | property of regenerated source $u$ |
| $p_{RP}$ | property of purified stream |
| $p_{RR}$ | property of reject stream |
| $p_{SRi}$ | property of source $i$ |
| $p_{SKj}$ | admissible property of sink $j$ |
| $p_{SKj}^{min}$ | lower bound of admissible property of sink $j$ |
| $p_{SKj}^{max}$ | upper bound of admissible property of sink $j$ |
| $R_{SRi}$ | resistivity of source SR$i$ |
| $\bar{R}$ | mean resistivity |
| $x$ | mass concentration of methanol in air |
| $z_{SRi}$ | fractional contribution of SR$i$ in the total mixture flowrate |
| $\delta_k$ | net material flowrate from level $k$ |
| $\delta_n$ | net material flowrate at final level $n$ |
| $\varepsilon_k$ | residue of the property load from property operator level $k$ |
| $\psi(p_D)$ | linearly-additive operator on the final discharge stream |
| $\psi(p_{Ru})$ | linearly-additive operator on the property of regenerated source $u$ |
| $\psi(p_{RP})$ | linearly-additive operator on the property of purified stream |
| $\psi(p_{RR})$ | linearly-additive operator on the property of reject stream |
| $\psi(p_{SRi})$ | linearly-additive operator on the property of SR$i$ |
| $\psi(\bar{p})$ | linearly-additive operator on the mean property |
| $\psi(p_{TR})$ | linearly-additive operator on the waste treatment effluent |
| $\psi_R$ | outlet property operator for regeneration |
| $\psi_{TR}$ | outlet property operator for waste treatment |
| $\rho_{SRi}$ | density of SR$i$ |
| $\bar{\rho}$ | mean density |
| $\zeta_k$ | net waste flowrate at level $k$ |
| $\zeta_n$ | net waste flowrate at final level $n$ |
| $\xi$ | minimum allowable concentration difference of mass exchanger |
| $\lambda_k$ | residual waste load at level $k$ |