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# Automated Targeting for Resource Conservation Network with Interception Placement

Denny Kok Sum Ng*, Dominic Chwan Yee Foo
Department of Chemical & Environmetal Engineering
University of Nottingham Malaysia,
Broga Road, 43500 Semenyih, Selangor, Malaysia.
Corresponding email: Denny. Ng@nottingham.edu.my

Raymond R. Tan
Chemical Engineering Department, De La Salle University-Manila,
2401 Taft Avenue, 1004 Manila, Philippines.

After the opportunities for maximum material recovery are exhausted through direct reuse/recycle, fresh resources consumption may be further reduced with the use of interception/regeneration processes. This paper presents an optimisation-based procedure known as *automated targeting* to locate the minimum resource consumption targets for a resource conservation network (RCN) with interception placement. The automated targeting was originally developed for mass integration by El-Halwagi and Manousiothakis (1990). Based on the concept of insight-based targeting approach, the automated targeting technique is formulated as a linear programming (LP) model for which the global optimum is guaranteed if a solution exists. A literature example is solved to illustrate the proposed approach.

## 1. Introduction

In the past decades, process industries have been focusing on conventional end-of-pipe waste treatment in order to comply with environmental legislation. However, recent trends show that the industries are now diverging towards the reduction of the generated waste and the search for better alternatives in securing sustainable manufacturing processes. This is mainly due to the increase of public awareness towards environmental sustainability, the rise of manufacturing costs (i.e. raw material, utilities, waste treatment, etc.) as well as more stringent environmental legislation. One of the active areas for cost reduction and sustainable process development is resource conservation activities, where process integration techniques have been well recognised as a promising tool.

Over the past decade, numerous research works have been performed to systematically address in-plant water reuse/recycle (Wang and Smith, 1994; El-Halwagi et al., 2003; Manan et al., 2004; Foo et al., 2006). In order to further reduce fresh water demand of a water network after maximum water recovery potential has been exhausted via

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reuse/recycle, partial treatment of water sources, or more generally termed as *water regeneration* or *interception*, can be considered (Wang and Smith, 1994; Kuo and Smith, 1998; Ng et al., 2007). In this work, an automated targeting approach that was originally developed for mass exchange network synthesis (El-Halwagi and Manousiothakis, 1990) is extended to locate the minimum flowrate/cost targets for a RCN with interception placement. A literature example is utilised for illustration.

## 2. Problem Statement

In this work, the problem definition of a RCN with single contaminant may be stated as follows:

- A set of process sources: SOURCES = $\{i \mid i = 1,2, \ldots, N_{\text{sources}}\}$ consist of process streams that may be recycled or discharged. Each source has a flowrate, $F_i$ and is characterised by a constant concentration of a single impurity, $C_i$.
- A set of process sinks (units): SINKS = $\{j \mid j = 1,2, \ldots, N_{\text{sinks}}\}$, that are process units that can accept sources. Each sink requires a flowrate, $F_j$ and may accept an average inlet contaminant concentration from the source that is lower than its maximum allowable impurity concentration, $C_j^{\max}$.

The objective of this work is to locate the minimum resource flowrate(s)/cost of the network prior to the detailed design of a RCN with interception placement.

## 3. Automated Targeting

The automated targeting technique was originally developed for mass exchange network synthesis (El-Halwagi and Manousiothakis, 1990). It was extended by Ng et al. (2008) for resource conservation network (RCN) based on water cascade analysis (Manan et al., 2004). However, the previous work did not consider interception/regeneration. This aspect is now included in this work.

First step of the automated targeting technique calls for the construction of a revised *concentration interval diagram* (El-Halwagi and Manousiothakis, 1990), where the impurity concentrations ($C_k$) of the material sinks and sources being arranged in an ascending order, from the lowest concentration level $k = 1$ to the highest level $k = n$ (see Figure 1). Additional concentration levels for fresh resource(s) and zero concentration level (e.g. 0 ppm, 0%) are added, if they do not exist among the process sinks and sources. In addition, a final concentration level (e.g. $10^6$ ppm, 100%) is added to allow the calculation of residue impurity load. Next the flowrate and impurity load cascades are performed across all concentration levels based on Equations 1 and 2 respectively.

$$\delta_k = \delta_{k\text{-}1} + (\, \Sigma_i\, F_{\text{SR}i} - \Sigma_j\, F_{\text{SK}j}\, )_k \tag{1}$$

$$\varepsilon_k = \varepsilon_{k-1} + \delta_k\,(C_{k+1} - C_k) \tag{2}$$

As shown in Equation 1, the sum of the *net material flowrate* cascaded from the earlier concentration level $k - 1$ ($C_{k\text{-}1}$) with the flowrate balance ($\Sigma_i F_{\text{SR}i} - \Sigma_j F_{\text{SK}j}$) at concentration level $k$ form the net material flowrate of each $k$-th level ($C_k$). Meanwhile, the impurity load at each concentration interval is given by the product of the net material flowrate from level $k$ ($\delta_k$) and the difference between two adjacent concentration levels ($C_{k+1} - C_k$). The residue of the impurity load of each concentration level $k$ ($\varepsilon_k$) is to be cascaded down to the next concentration level. The residual impurity load, $\varepsilon$ must take a positive value:

$$\varepsilon_k \geq 0 \tag{3}$$

When the residue impurity load is determined as zero in the model solution, a pinch concentration is observed. Note that the above formulation is a linear programming (LP) problem, which can be solved easily to achieve global optimal solution.

## 4. Waste Interception (Regeneration/Treatment)

According to Wang and Smith (1994), regeneration systems are broadly categorised as *fixed outlet concentration* ($C_{\text{out}}$) and *fixed removal ratio* (RR) types. In this work, RCN with fixed $C_{\text{out}}$ treatment system is analysed. To incorporate a fixed $C_{\text{out}}$ regeneration unit in the automated targeting procedure, $C_{\text{out}}$ of the regeneration unit is added in the RCCD, as shown in Figure 1. However, note that this step may be omitted when $C_{\text{out}}$ coincides with any of the sink or source concentrations.

As shown in the generic RCCD in Figure 1, the regeneration unit draws water from sources at concentration levels $C_3$ and $C_4$ (treated as sinks) and sends the better quality water (as source) to the $C_{\text{out}}$ level. The assumption of no flowrate loss is observed for the regeneration system, and hence the regeneration system has constant inlet and outlet flowrates ($F_{\text{Reg1}} + F_{\text{Reg2}}$ as given in Figure 1). As the regeneration process removes impurity load from the water source(s) to improve its quality, better water recovery is expected. This corresponds to reduced fresh water and wastewater flowrates. In practise, any source within the water network may be regenerated for further reuse/recycle, so the regeneration unit should draw water from all concentration levels with the present of water source(s). To illustrate the proposed approach, an example that involves simultaneous synthesis of water and mass exchange networks is presented.

## 5. Illustrative Example

A pyrolysis process that converts scrap tires into fuel taken from Noureldin and El-Halwagi (1999) is used for illustration. As reported, two primary wastewater sources are observed, i.e. 0.20 kg/s from the decanter and 0.15 kg/s from the seal pot (for a fresh water flowrate of 0.15 kg/s), with impurity (heavy organic) concentration of 500 ppm and 200 ppm respectively. These sources may be reused/recycled within the process in order to reduce fresh water consumption. Two process sinks that may accept these water sources are also identified, i.e. seal pot and water-jet compression station. The following constraints on flowrate and impurity content (heavy organic) should be satisfied when water reuse/recycle scheme is considered:

Seal pot:
$0.10 \leq$ Flowrate of feed water (kg/s) $\leq 0.20$
$0 \leq$ Impurity concentration of feed water (ppm) $\leq 500$

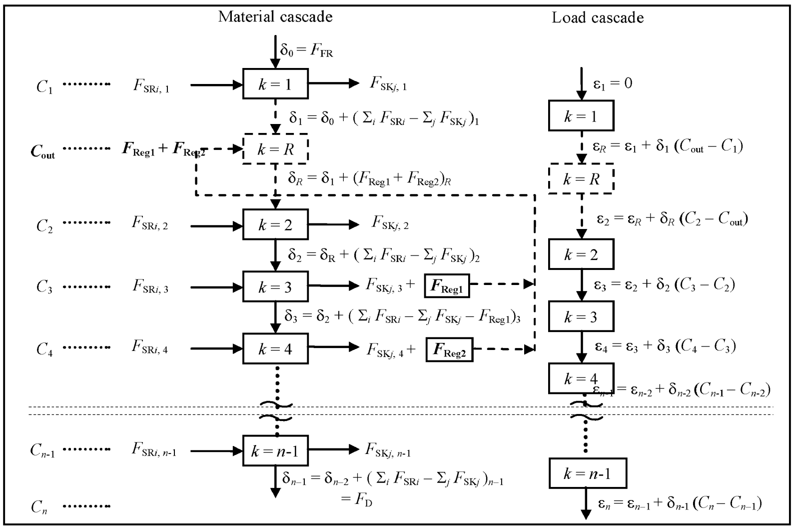


*Figure 1 Generic RCCD for Water Network with Regeneration System of Fixed $C_{out}$.*

Makeup to water-jet compression station:
0.18 ≤ Flowrate of feed water (kg/s) ≤ 0.20
0 ≤ Impurity concentration of makeup water (ppm) ≤ 50

In this case, various mass separating agents (MSA) may be used in a mass exchange network to reduce the heavy hydrocarbon content in the water sources (Noureldin and El-Halwagi, 1999). The selection of the appropriate MSA depends on its technical feasibility as well as its treatment cost. According to Noureldin and El-Halwagi (1999), the flare gas from the finishing section may be used as a process MSA ($S_1$) to strip away the impurity content from the water sources. Furthermore, the stripping operation may be carried out in the seal pot. Hence, priority is given to the use of this process MSA, since it is available free of charge. Apart from the flare gas, three external MSAs may also be considered for heavy organic removal, i.e. solvent extractant ($S_2$), adsorbent ($S_3$) and stripping agent ($S_4$). For the $p$-th rich stream with an impurity concentration of $y_p$, the linearised equilibrium relation governing its impurity transfer to the $q$-th MSA is given by Equation 1:

$$y_p = m_q\left(x_q^{\max} + \varepsilon_q\right) + b_q \tag{4}$$

where $x_q^{\max}$ is the maximum practical achievable concentration of MSA $q$; $m_q$ and $b_q$ are the slope and intercept of the linearised equilibrium relation respectively; $\varepsilon_q$ is the minimum allowable concentration difference for each MSA. Equilibrium and operating data for the MSAs, along with their respective annualised cost are given in Table 1.

*Table 1 Data for Various MSA in Example (Noureldin and El-Halwagi, 1999).*

| **MSA, $S_q$** | **Flowrate, $L_q$ (kg/s)** | **Supply concentration (ppm), $x^s_q$** | **Target concentration (ppm), $x_q^{max}$** | $m_q$ | $\varepsilon_q$ **(ppm)** | **Annualised Cost$_q$ (\$/kg MSA)** |
|---|---|---|---|---|---|---|
| $S_1$ | 0.15 | 200 | 900 | 0.5 | 200 | - |
| $S_2$ | $\infty$ | 300 | 1000 | 1.0 | 100 | 0.001 |
| $S_3$ | $\infty$ | 10 | 200 | 0.8 | 50 | 0.020 |
| $S_4$ | $\infty$ | 20 | 600 | 0.2 | 50 | 0.040 |

As shown in Equation 4, the impurity load is removed from the water source(s) by the MSA to upgrade the water quality for further recovery. Therefore, the cost of water regeneration is set by the minimum flowrate of the external $q$-th MSA ($L_q$) that is used to remove impurity load from the water source. From Equation 4, the minimum outlet concentration of the regenerated water source is determined as 200 ppm, 400 ppm, 48 ppm and 14 ppm, for the associated MSA of $S_1$, $S_2$, $S_3$ and $S_4$ respectively.

In this example, the objective function is set to minimise the annualised cost (AC) which includes fresh water cost, annualised costs of water regeneration (which includes the capital cost of the equipment as well as operating cost incurred during regeneration), and wastewater treatment cost which likewise includes the capital and operating costs. The cost of pure fresh water (0 ppm), $\mathrm{COST}^{\mathrm{FW}}$ and wastewater treatment for discharge, $\mathrm{COST}^{\mathrm{WW}}$ are assumed as \$1/kg and \$0.10/kg respectively (Noureldin and El-Halwagi, 1999). Equation 5 shows the annualised cost for the water network with regeneration:

$$\mathrm{AC} = \mathrm{COST}^{\mathrm{FW}} \times F_{\mathrm{FW}} + \sum_q (\mathrm{Cost}_q \times L_q) + \mathrm{COST}^{\mathrm{WW}} \times F_{\mathrm{WW}} \tag{5}$$

where $\mathrm{Cost}_q$ refers to the annualised cost of $q$-th MSA (Table 1).

Solving Equation 5 subject to the constraints in Equations 1 – 3 yield the RCCD in Figure 2. As shown, a zero discharge network without fresh water feed is achieved ($F_{\mathrm{FW}} = F_{\mathrm{WW}} = 0$). It is also observed that 0.20 kg/s ($F_{\mathrm{Reg2}}$) of water from the decanter (500 ppm) is purified in the seal pot (as a stripping column) by process MSA of fuel gas ($S_1$). This results in a reduced heavy hydrocarbon concentration of 200 ppm. Next, 0.1613 kg/s ($F_{\mathrm{Reg1}}$) of the water source from the seal pot is regenerated by the stripper where its heavy hydrocarbon content is stripped away by the external MSA ($S_4$). The objective function of the automated targeting corresponds to the minimum annual cost of the external MSA, i.e. \$ 65,250 (365 annual working days). This result is consistent with what was originally reported (Noureldin and El-Halwagi, 1999).

## 6. Conclusion

A novel automated targeting approach for single-component RCN that has the advantage of both pinch analysis and mathematical optimisation approaches is presented. The flexibility in changing the objective function is one of the advantages of the automated targeting approach over the conventional insight-based techniques. In addition, the technique locates network targets prior to detailed design.

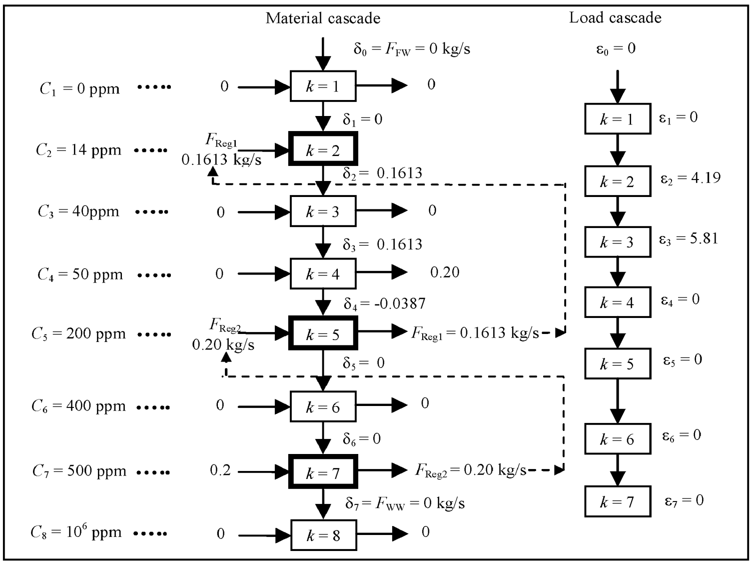


*Figure 2 RCCD for Example.*

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