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Synthesis of robust water reuse networks for single-component retrofit problems using symmetric fuzzy linear programming

Raymond R. Tan[a,*], Dennis E. Cruz[b]

[a] *Chemical Engineering Department, De La Salle University-Manila, 2401 Taft Avenue, 1004 Manila, Philippines*
[b] *Industrial Engineering Department, De La Salle University-Manila, 2401 Taft Avenue, 1004 Manila, Philippines*

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Abstract

Water integration techniques can be used to minimize the utility water consumption and effluent generation of process plants through the implementation of reuse or recycle networks. There are a number of graphical and mathematical programming techniques available for the synthesis of such water reuse networks. However, effective use of these methods requires the availability of reliable process data, which in reality might be difficult to acquire. This paper describes a procedure for the synthesis of robust water reuse networks from imprecise data using symmetric fuzzy linear programming (SFLP). Two model variants, one based on mass exchange units and the other on source/sink allocation, are presented. Each variant is illustrated with a numerical example.

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Keywords: Process integration; Water reuse network; Fuzzy linear programming; Water pollution

1. Introduction

Water is used heavily in the process industries for washing or rinsing of raw materials and process equipment. Environmental concerns pertaining to fresh water supply sustainability and effluent discharge impacts have resulted in the increased use of process integration to concurrently reduce both plant water requirements and wastewater volume. Early developments in water integration emerged from analogies with thermal pinch technology. A graphical method based on mass exchange units with water as solvent was developed by Wang and Smith (1994). This targeting method identifies the minimum water flow rate for a given set of processes. Mathematical programming techniques have also been used for water integration problems. For single-component systems the mathematical approach simultaneously yields the water target and the water reuse network configuration needed to achieve this target. Alva-Argaez, Vallianatos, and Kokossis (1999), Yang, Lou, and Huang (2000) and Bagajewicz and Savelski (2001) give examples of formulations based on the mass transfer model. A comprehensive review can be found in Bagajewicz (2000).

Subsequent work has shifted to the use of source/sink models. The graphical method developed by Dhole, Ramchandani, Tainsh, and Wasilewski (1996) is simple to use, but cannot be guaranteed to locate the global pinch point. Hallale's water surplus diagram (2002) and Foo's water cascade table (2003) overcome these difficulties. More recently, a simple but effective graphical technique was developed by El-Halwagi, Gabriel, and Harrel (2003) for solving source/sink problems. Formulation of the source/sink problem as a linear program is much simpler than for mass transfer-based systems (El-Halwagi et al., 2003) and results in a modified transportation problem. Compared to models based on mass exchange units, the source/sink formulation has the advantage of being able to account for non-mass transfer processes that may have water inputs with no output (e.g.,

* Corresponding author. Tel.: +632 536 0257; fax: +632 524 0563.
E-mail address: tanr_a@dlsu.edu.ph (R.R. Tan).

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boilers) or water outputs with no inputs (e.g., reactors where water is generated as a reaction byproduct).

Robustness of water reuse networks designed using imprecise data is a critical issue in the use of process integration techniques in real process plants. The principal weakness of current methods is that they assume that design data are well-defined. In practice, however, acquisition of the data needed for the use of these techniques is not a trivial task. The difficulty of obtaining process data has been cited as one of the major obstacles to the widespread use of process integration (Wenzel, Dunn, Gottrup, & Kringelum, 2002). Some process parameters such as flowrates and discharge stream concentrations can be derived from historical data or direct physical measurements, and can thus be estimated with some precision. Key sources of uncertainty differ for mass exchange unit and source/sink models:

- For mass exchange unit models, the principal source of uncertainty is the mass load, or the quantity of contaminant transferred from the product stream into the water or solvent. Typically the mass load is not directly measurable but has to be deduced from historical flowrate and concentration data (Bagajewicz, 2000).
- For source/sink problems, estimating the maximum inlet stream concentration that can be tolerated by a water-using sink without disrupting process or product quality is the main difficulty; some amount of educated guesswork is likely to be involved in arriving at a suitable value (Bagajewicz, 2000; Wenzel et al., 2002).

Fuzzy mathematical programming offers a computationally efficient alternative to stochastic models for design problems in uncertain environments (Sahinidis, 2004; Zimmermann, 1992).

2. Symmetric fuzzy linear programming (SFLP)

Early work on fuzzy sets in the 1960s quickly led to applications in the field of mathematical optimization (Bellmann and Zadeh, 1970). The symmetric fuzzy LP method is one such application (Zimmermann, 1992). Its key features are:

- Crisp constraints are converted into fuzzy constraints by introducing tolerances. This change introduces the concept of degree of satisfaction of a constraint, bounded in the interval [0,1].
- An aspiration level is identified for the objective function. Hence, optimization becomes equivalent to maximizing the degree to which the target level is achieved. This degree of satisfaction is also bounded by the interval [0,1]. This task is simplified for single-component WRN synthesis since the objective function is automatically bounded by the maximum water flowrate (without reuse) and the theoretical minimum as determined by any graphical targeting technique (Foo, Manan, & Aziz, 2003; Hallale, 2002). A new variable, α, is added to the LP model. This variable assumes values in the interval [0,1] and serves to concurrently modulate the original objective function and constraints. The new objective of the SFLP model is to maximize the global degree of satisfaction, α, which applies simultaneously to the objective function and constraints.

In SFLP the objective function and constraints are treated identically, hence the use of the term "symmetric." If the degrees of satisfaction (i.e., membership functions) are assumed to be linear, the SFLP model is very compact, involving only one additional variable and one new (global) objective function to the original problem; at the same time the linearity of the original model is preserved. Since the SFLP model is just a specially structured LP, it can be solved using the ubiquitous simplex algorithm available in many software packages such as Microsoft Excel Solver. It is also not necessary for all constraints to be fuzzy.

Two models are presented in this paper. Both are fuzzy extensions of previous mathematical formulations based on mass exchange units and source/sink problems. Implementation of fuzzy constraints improves the models by increasing robustness and allowing uncertainty margins to be incorporated into the network design process. Both models are for single-component retrofit problems. They assume:

- That water quality can be described by a single quantity. Multiple contaminants that can be grouped into a single heading (e.g., BOD) are considered as single component.
- That there is a fixed number of existing processes, and that the design problem is to determine the appropriate reuse streams among the units that make up the network.

3. Fuzzy Model I: mass exchange unit problem

Yang et al. (2000) described a nonlinear model based on a multicomponent mass exchange unit system. The model can be linearized for single-component problems (Bagajewicz, 2000; Bagajewicz and Savelski, 2001).

If the mass load of each mass exchange unit or process is imprecise, the following SFLP model results:

$$\max\ \alpha \tag{1}$$

subject to:

$$\Sigma_i f_i \leq F_{\max} - \alpha(F_{\max} - F_{\text{target}}) \tag{2}$$

$$w_i(C_{\text{out},i} - C_{\text{in},i}) \geq M_i + \alpha(\Delta M_i) \quad \forall_i \tag{3}$$

$$w_i = f_i + \Sigma_j r_{ji} \quad i \neq j, \forall_i \tag{4}$$

$$C_{\text{in},i} w_i = \Sigma_j C_{\text{out},j} r_{ji} \quad i \neq j, \forall_i \tag{5}$$

$$w_i = e_i + \Sigma_j r_{ij} \quad i \neq j, \forall_i \tag{6}$$

$$\alpha \leq 1 \tag{7}$$

$$\alpha, f_i, w_i, r_{ij}, e_i \geq 0 \tag{8}$$