Design of a water reuse network for industrial symbiosis - A global optimization strategy

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Design of a water reuse network for industrial symbiosis - A global optimization strategy

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Abstract: The study presents a global optimization strategy in designing a water reuse network for industrial symbiosis. Two optimization approaches, stochastic and deterministic, are compared based on the level of complexity of the network such as the number of contaminants, treatment unit selection, flow variation. Preliminary results on a general superstructure formulated as a mixed integer nonlinear programing shows promising performance of a stochastic model using a non-dominated sorting genetic algorithm. The developed optimization methodology will be extended to perform uncertainty and flexibility assessments of water reuse networks.

Keywords: Water reuse network, industrial wastewater, global optimization, decentralized treatment

Introduction

Sustainable growth of industries especially in fast developing and water-scarce countries can only be achieved by optimizing water usage and reducing wastewater discharge. By regenerating water for reuse through partial treatment of their wastewater streams, industries can greatly reduce their freshwater intake. They can opt for recycling the used water internally, or for exchanging it with neighbouring industries and create symbiosis relations. It is not a trivial task to design a water reuse network for an existing industrial site to minimize the economic and environmental factors. Each industry consists of multiple unit processes that require specific water quality, and the network becomes more complex as the number of process units increases.

Previous studies have performed optimization for designing a network of water exchange streams in industrial parks by applying a model-based global multi-objective optimization approach (Boix et al., 2012; Khor et al., 2014). However, only a few have considered the complexity of used water streams in terms of flow rate variation (Montastruc et al., 2013) and number of significant pollutants (Rubio-Castro et al. , 2011). Regarding the optimization method, most of the studies either applied a deterministic approach, by making simplifications of the network formulation to achieve a Linear Programing model, or have attempted to solve a more comprehensive mixed integer nonlinear programming (MINLP) formulation of the problem by applying linearization or relaxation methods. However, these assumptions may compromise the optimization results or create convergence issues. A stochastic (or metaheuristic) approach in solving a MINLP model, on the other hand, is sufficiently flexible to include a wider complexity of the problem as compared to a deterministic (or heuristic) approach, however, at the expense of finding a near-optimal solution and requiring high computational time.

The present study aims at comparing the performance of stochastic and deterministic model-based approaches for solving a MINLP model of a water reuse network considering different levels of complexity. The evaluation criteria are robustness and convergence to an optimal or near optimal solution with an increase in the level of complexity.

Materials and Methods

The general formulation of the water reuse network is shown in the superstructure (an example for three processes) in Figure 1 using a series of multiple treatment units prior to reuse. A selection of different decentralized fit-for-purpose treatment units is formulated as mixed-integer discrete variables in the network model:

$$Q_j = \sum_{i=1}^{N} x_{ij} Q_i + Q_{f,j}$$

$$C_{jk} Q_j = \sum_{i=1}^{N} x_{ij} Q_i C_{out,i,k} (1 - T_{ij}) + C_{f,jk}\, Q_{f,j}\,, \quad j = 1{:}n \quad k = 1{:}K$$

where:

C_{jk}	Concentration of contaminant k in the inlet of process unit *j*
$C_{out,ik}$	Concentration of contaminant k in the outlet of process unit *i*
$C_{f,jk}$	Concentration of contaminant k in the freshwater to process unit *i*
x_{ij}	Fraction of flow from unit process *i* to *j*
Q_i	Total flow rate of water from/to unit *i*
$Q_{f,i}$	Flow rate of fresh water to unit *i*
T_{ij}	Treatment unit for flow fraction from unit *i* to *j*
n,*K*	Number of unit operations and contaminants, respectively

Constraints are put on the influent and discharge concentration limits of the contaminants. The objective function is to minimize fresh water consumption and total network cost (capital and operational cost of piping and treatment). For the stochastic approach, the multi-objective Non-dominated Sorting Genetic Algorithm NSGA II (Deb et al., 2000) was applied. The deterministic approach includes solving the MINLP problem using the high-level language GAMS (General Algebraic Modelling System). The two approaches are tested for the following levels of complexity, (i) multi-contaminants, (ii) multiple treatment units, (iii) flow variation.

Results and Discussion

The stochastic-based NSGA II algorithm has been tested on a case of five manufacturers including 7 process units (see Table 1). The source of fresh water in this case study is ground water abstraction with an average unit cost of ca. 0.3 $/m^3. Figure 2 shows the Pareto front provided by NSGA II. It is a set of optimal solutions based on a trade-off between fresh water consumption and cost of unit water. The unit cost includes annualized capital cost and yearly operating cost of equipment (pipes, pumps, treatment units) and yearly maintenance cost (5% of capital cost) for fresh water abstraction and water reuse network. The optimum network based on the 50%-50% trade-off between two objectives is shown in Figure 3. The optimum water-reuse network indicates significant potential in reducing the fresh water consumption. However, reduction of about 50% fresh water consumption results in 25% increase in unit price of water to ca. 0.4 $/m^3. In order to make the water reuse network more economically viable, an extended network with resource recovery units is required, where besides water, energy and material is recovered.

This on-going work includes applying the deterministic optimization methodology to the case study and comparing the performance to the obtained stochastic optimization approach. After finding the suitable optimization strategy, the network will be expanded to up to 20 process units and recovery units. The developed optimization methodology can also be used to perform uncertainty and flexibility assessments of water reuse networks.

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Figures and Tables

Table 1 A case study of 5 companies with 7 units in an existing industrial part

Company	**Unit**	**Water use** (m^3/day)
A	Cooling Boiler	1000 500
B	Washing	126
C	Boiler	150
D	Process	550
E	Process Boiler	420 200

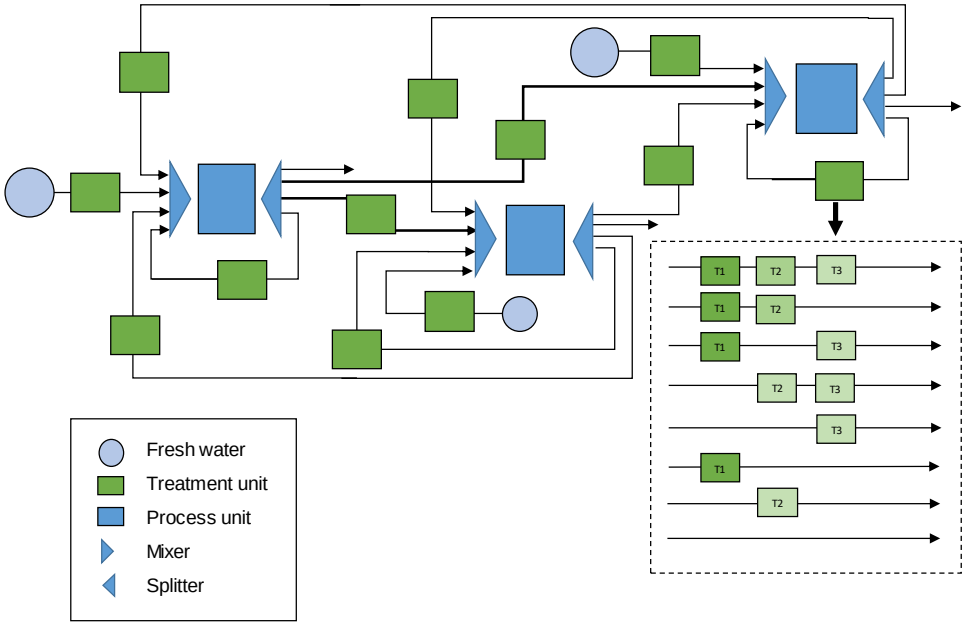

Figure 1 Superstructure of water reuse network among multiple processes (in this case, three) including multiple treatment options. T1-4 denote different wastewater treatment steps in different configurations

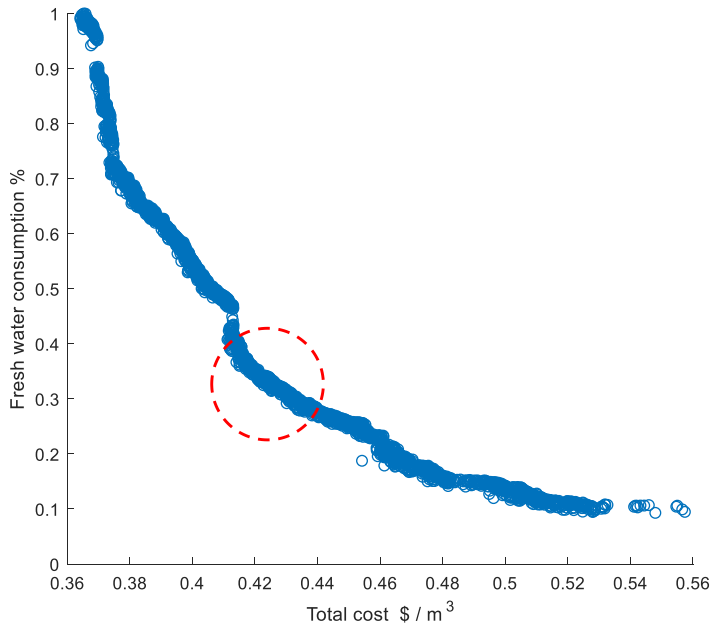

Figure 2 Pareto front result of applying NSGA II optimization to a case study of a network consisting of 7 units

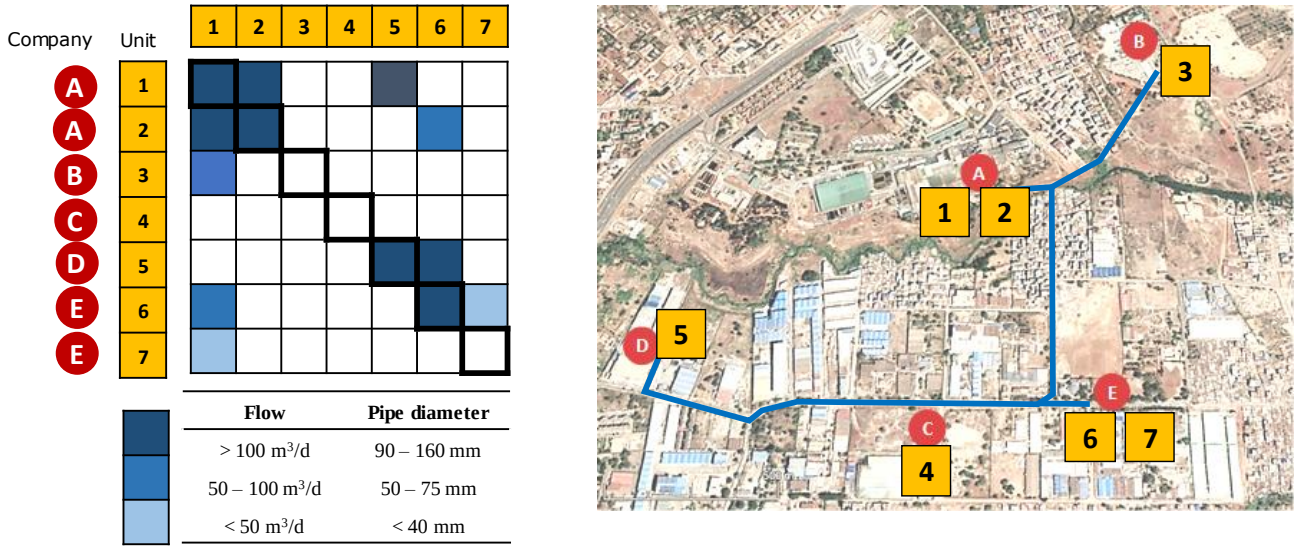

Figure 3 Preliminary results of finding an optimum water reuse network including 7 water using process units (see Table 1).