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Fixed-flowrate total water network synthesis under uncertainty with risk management

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ABSTRACT

This work addresses the problem of integrated water network synthesis under uncertainty with risk management. We consider a superstructure consisting of water sources, regenerators, and sinks that leads to a mixed-integer quadratically-constrained quadratic program (MIQCQP) for a fixed-flowrate total water network synthesis problem. Uncertainty in the problem is accounted for via a recourse-based two-stage stochastic programming formulation with discrete scenarios that gives rise to a multiscenario MIQCQP comprising network design in the first stage and its operation in the second stage acting as recourse. In addition, we extend the model to address risk management using the Conditional Value-at-Risk (CVaR) metric. Because a large number of scenarios is often required to capture the underlying uncertainty of the problem, causing the model to suffer from the curse of dimensionality, we propose a stepwise solution strategy to reduce the computational load. We illustrate this methodology on a case study inspired from the water network of a petroleum refinery in Malaysia. The presence of nonconvex bilinear terms necessitates the use of global optimization techniques for which we employ a new global MIQCQP solver, GAMS/GloMIQO and verify the solutions with BARON. Our computational results show that total water network synthesis under uncertainty with risk management problems can be solved to global optimality in reasonable time.

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1. Introduction

The optimal synthesis of water network presents a significant challenge for the design of process systems particularly in the face of scarcity of freshwater resources and increasingly stringent environmental regulations on effluent discharge. A specific class of the problem termed as total water network synthesis involves a simultaneous consideration of both water-using units and water (or wastewater) treatment operations (Foo, 2009). Water-using units represent water sources or sinks, including freshwater sources, with their corresponding contaminant concentrations. Water treatment or regeneration operations act as intermediate processes to reduce contaminant levels as necessary before the sources can be subject to reuse/recycle in the sinks. The goal is to synthesize a network that integrates these water-using and water-regeneration operations by optimizing a certain objective, which is typically "environomic" in nature, i.e., as based on economics in maximizing profit or minimizing cost as well as meeting certain environmental sustainability criteria, while complying with constraints on the water users and/or final discharge limits to the environment.

In our earlier work (Khor et al., 2012b), a deterministic fixed-flowrate formulation of the water network synthesis problem is presented that assumes fixed values of all model parameters. However, in actual operating conditions, there are often significant variations or stochastics in the parameter values. Indeed, literature data on effluent quality in process plants typically indicates significant variability in the water source flowrates and contaminant concentrations as well as in the regenerator efficiency for contaminant removals (Tchobanoglous et al., 2004). Fig. 1 displays a representative trend of such removal efficiencies for six contaminants over a duration of one month as sampled to compare the influent and effluent of a reverse osmosis skid at a petroleum refinery in Malaysia (Khor et al., 2009). As evidenced from the plot, there are substantial variations in the removal ratio parameter of such a membrane regenerator unit, thus it is imperative to account for uncertainty in this parameter in a model formulation. In general, physical reasons contributing to uncertain contaminant removals are mainly due to fluctuations in operating condition as a result of fouling and leaks (resulting from aging) in pipelines. For a

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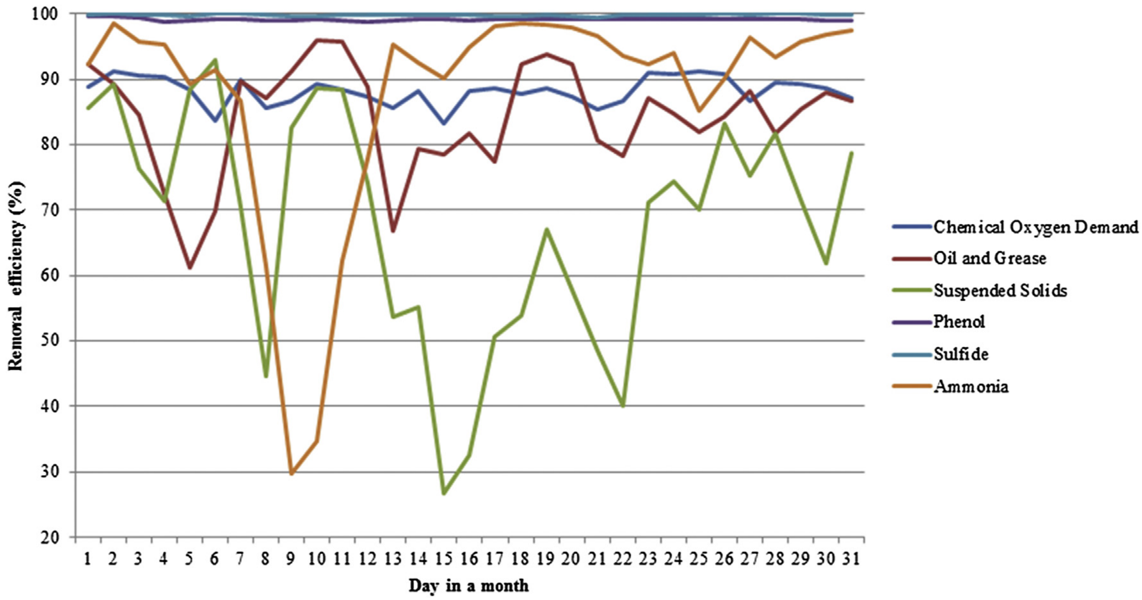

Fig. 1. Typical trends in fluctuations of contaminant removal efficiencies as measured at a plant over a duration of one month (source: Khor et al., 2009).

membrane regenerator unit, such physical phenomena may lead to frictional pressure loss in the membrane channel and pressure drop in the module manifolds with consequential varying operating conditions (Maskan et al., 2000). Note that these sources of uncertainty are externally imposed, i.e., they are exogenous (as opposed to endogenous) uncertainty.

Nonetheless, only a small fraction of work in the literature to date considers the arguably more practical problem of water network synthesis under uncertainty. The work by Koppol and Bagajewicz (2003) represents a novel attempt at addressing uncertainty in water network synthesis. A mixed-integer linear program (MILP) is proposed that adopts a discrete scenario generation approach using bounded uniform distribution to represent uncertainty in contaminant mass load of water-using units and coupled with a scenario reduction technique. Additionally, the model considers financial risk management on the total network cost. The authors advocate that it is not possible to mitigate risk when the operating cost is much larger than the capital cost because a design with minimum expected operating cost usually poses minimum risk, but when capital cost is comparable to operating cost, reuse of wastewater is amenable to reducing risk.

Al-Redhwan et al. (2005) employs two-stage stochastic programming to formulate a fixed-load water network model with uncertain mass load parameter. Karuppiah and Grossmann (2008) also utilizes a similar framework with consideration for an additional uncertain parameter in the contaminant removal ratio. A major contribution of this work is to globally optimize the nonconvex mixed-integer nonlinear program (MINLP) by using relaxation via McCormick's (1976) convex and concave envelopes for the bilinear terms and linear overestimators constructed from secants for concave terms in the objective function. The authors propose a spatial branch-and-cut scheme with a Lagrangian decomposition approach to solve the multiscenario model.

Tan et al. (2007) utilizes a Monte Carlo-simulation approach to investigate the sensitivity of solutions obtained from water pinch analysis by accounting for uncertainty in the mass load parameter. It is found that fluctuations in processing conditions can lead to process disruptions and affect product quality and process stability. In another work considering mass load uncertainty, Zhang et al. (2009) attempts to develop a resilient water network by aiming for a low value of a metric introduced as the tolerance amount of a water-using unit, which measures the difference between the limiting and actual mass load of a network. Feng et al. (2011) addresses the design of a multicontaminant water-using network with consideration for mass load uncertainty. The proposed NLP-based approach adjusts stream flows through a combination of optimization and heuristics while preserving the optimal water network structure obtained under nominal condition for minimum freshwater use.

In a series of paper, Chang et al. (2009) employs a flexibility analysis approach to cater for a water network operation under uncertainty in freshwater quality, mass load, removal ratios, and maximum inlet and outlet concentrations of both water-using and treatment units. A MINLP model is used to assess the feasibility of a nominal design and to improve its flexibility index by relaxing the maximum freshwater capacity and installing new and/or removing existing pipelines. An initialization procedure is developed to help convergence to a global optimum. This line of work is continued by Riyanto and Chang (2010) that adopts a MINLP with heuristics based on active constraints to improve the operational flexibility of a water network design. Later, Li and Chang (2011) proposes a simplified NLP for an efficient computation of the flexibility index that obviates a need for elaborate initialization and the high computational expense entailed with use of a MINLP.

Hung and Kim (2011) considers uncertain inlet flowrate and mass load of water-using units. The uncertain parameters are represented as average values via a multiperiod MINLP formulation. The model addresses uncertainty by incorporating buffer tanks to handle sudden contaminant level rise and supplementary pipelines to supply freshwater to ensure feasibility. An insights-based decomposition strategy that involves iteratively solving a sequence of MILP and LP relaxations by fixing the concentration and flowrate of water-using units is proposed to initialize the solution.

Synthesis of water-regeneration systems particularly within the context of a total water network system investigates options for regeneration–reuse besides direct reuse or recycle. Tan et al. (2009) considers the use of partitioning regenerators specifically

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