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Simultaneously targeting for the minimum water requirement and the maximum production in a batch process

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ABSTRACT

This work proposes a multiple objective formulation to simultaneously target the minimization of fresh water requirement and the maximization of production in a batch process. The proposed mixed integer linear programming formulation includes scheduling (such as allocation constraints, time constraints, capacity constraints, mass balances, etc.) as well as fresh water minimization constraints (such as concentration, flow requirements, etc.) and illustrated through an example. The trade-offs between the production and the fresh water requirement is captured through the Pareto optimal front. The Pareto optimal front consists of discrete points and facilitates decision maker to select an appropriate operating point based on other process constraints. Furthermore, it has been demonstrated that due to non-convexity of the model, weighted objective method fails to identify all the Pareto optimal points.

1. Introduction

Water is one of the major resources in process industries. Efficient use of fresh water and thereby reduction in waste water, is one of the important aspects for cleaner production processes. Reduction in water footprint leads to higher profitability and lesser environmental impact. Furthermore, water utilization has a direct impact to water security and climate change. Techniques of Process integration have been applied successfully to identify conservation opportunities of various resources in process industries, including water management (Klemeš et al., 2013).

Batch processing is common in process industries especially when specialized productions are needed (e.g. food, pharmaceuticals, fine chemicals, bio-chemicals and agrochemicals, etc.). The major difference between water minimization in batch and continuous processes lies mainly in the discreteness of tasks in the batch process. Therefore, units are not always active during the time horizon of interest. This means that water is not always required or produced during a time period. In a continuous process, the main constraint for waste water recovery is the impurity concentration. Significant research efforts have been observed for water minimization in continuous processes (Foo, 2009). Wang and Smith (1994) presented a graphical method to calculate minimum water requirement for continuous process. Gomes et al. (2007) proposed a heuristic based algorithm to synthesize water networks for the following different situations of water re-use recycle and regeneration. Statyukha et al. (2008) proposed a hybrid approach involving insight-based techniques and mathematical programming for designing of waste water treatment network. Chew et al. (2009) proposed a game theory-based approach for water conservation using inter-plant water integration. Abd El-Salam and El-Naggar (2010) showed the potential of in-plant control measures for water conservation via a case study. Sotelo-Pichardo et al. (2011) presented a mathematical model for the optimal retrofit of WANs considering recycle, reuse and regeneration of water. Su et al. (2012) proposed a design methodology for the WANs with single internal water main and multiple contaminants.

It may be noted that in a batch process there is an additional time constraint other than impurity concentration and both these

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constraints are to be simultaneously satisfied. In recent years, various techniques based on physical-insight as well as mathematical optimization have been reported in literature to minimize the fresh water requirement in a batch process. These approaches can be classified in two categories: fixed schedule and variable schedule. In fixed schedule approaches time is treated as a parameter. Wang and Smith (1995) proposed a graphical technique to determine the minimum fresh water target for semi-continuous processes. A similar methodology to conserve fresh water in pure batch processes was presented by Majozi et al. (2006). These methodologies are applicable only to mass transfer based operations. Foo et al. (2005) extended applicability of water cascade analysis to cyclic batch process to include non-mass transfer based operations. Liu et al. (2007) developed a time-dependent concentration interval analysis method to solve the batch water-using system involving both mass and non-mass transfer based operations. Chen et al. (2010) proposed a graphical technique to deal with hybrid system comprising of both truly batch and semi-continuous operations. Kim (2011) proposed a methodology for semi-continuous batch processes with fixed load operations. In this work, the lower as well as the upper bounds on fresh water requirement are set prior to the actual design of the allocation networks (Kim, 2011). Recently, Chaturvedi and Bandyopadhyay (2012) proved algebraically that for a single batch operation, targeting via sequential transfer of waste water from one time interval to the next time interval leads to the overall minimum fresh water requirement and for cyclic batch all the time intervals may be collapsed as a single interval and the minimum fresh water requirement can be targeted directly. It may be noted that all these physical insight based techniques are applicable to fixed scheduled batch process only.

Almato et al. (1999) developed non-linear programming (NLP) models to optimize water reuse network with systematic rationalizing of water reuse in batch process. Kim and Smith (2004) proposed a method for discontinuous water systems considering time constraints and the network designs which the results in mixed integer non-linear programming (MINLP) model. Chen et al. (2008) analysed the impact of central storage facilities on fresh water reduction and introduced a model to synthesize water allocation networks (WANs) with the minimum fresh water consumption. Shoaib et al. (2008) proposed a three stage approach for the synthesis of cost-efficient batch water allocation networks, where all water reuse/recycle between water sources and sinks are conducted between two consecutive batches of operation via water storage to avoid scheduling problems. In this model, all water-using processes are connected to their respective intermediate storage tanks for water recovery (Shoaib et al., 2008). An important limitation of this work is that water recovery is possible only through storage vessels. Tokos and Pintarič (2009) developed MINLP models for the fresh water and waste-water contaminant load minimization for discontinuous processes, involving re-use and regeneration. The major drawback of these mathematical optimization based works is that they are restricted to fixed schedule operations.

For variable schedule approaches, fresh water minimization is carried out by determining an optimal schedule of operations. Majozi (2005) presented a framework to insert waste water minimization within an established scheduling framework such that starting and finishing times become optimization variables. Gouws and Majozi (2007) extended the model to include multiple contaminants along with multiple storage vessels in an MINLP formulation. Cheng and Chang (2007) developed a procedure to incorporate batch production, water reuse, and waste water treatment into a single comprehensive model. However, all possible network configurations were not included in the superstructure, resulting sub-optimal solution. Oliver et al. (2008) used hybrid method that combines use of the insight based and the mathematical optimization based techniques to synthesize a batch water network. Zhou et al. (2009) presented a nonconvex MINLP formulation to address similar problem. Gouws et al. (2010) presented a review of all the techniques for water minimization in batch process. Recently, Nonyane and Majozi (2012) presented a methodology for waste water minimization which can be applied for longer horizon time with lesser complexity.

Various methodologies proposed in the literature are restricted to minimizing fresh water requirement without considering the effect of production in a given time horizon or focused on the overall operating cost optimization. However, the effects of varying production on the minimum fresh water requirement can be effectively studied through multi-objective optimization of the overall batch processes.

Addressing multi-objectives simultaneously provides a crucial input for decision maker to decide optimum production policy. Erol and Thöming (2005) proposed multi-objective optimization approach to study trade-off between cost and environmental impacts. Mariano-Romero et al. (2007) proposed a multiple-objective optimization model for minimization of fresh water consumption along with infrastructure cost required to construct the network. Arbiza et al. (2008) presented a multi-objective framework for scheduling batch process in order to deal with environmental impact along with makespan and/or financial performance. Faria et al. (2009) presented a NLP model for minimising fresh water consumption and operating cost with and without regeneration of water. Kim et al. (2009) proposed a MINLP formulation for designing WAN and HEN for process industries simultaneously based on cost. Tudor and Lavric (2011) proposed a dual-objective optimization approach for simultaneous minimization of fresh water consumption and operating costs of water piping and pumping for WANs. Boix et al. (2012) developed a multi-objective optimization formulation to minimize fresh water, regenerated water flow rates and number of network connections for a water network. The formulation is also extended to design an eco-industrial park involving three plants. Halim et al. (2012) proposed a multi-objective genetic algorithm for synthesis of WANs with objective of minimizing fresh water and treatment costs. Shadiya et al. (2012) developed a methodology using multi-objective optimization to enhance a chemical process in order to increase overall profit and reduce waste generation. Tokos et al. (2013) paper proposed a bi-objective optimization method for evaluation of the environmental and economic impacts to retrofit WAN. Tokos et al. (2013) have used benchmarking of environmental indicators to calculate environmental impact. Zhou et al. (2013) presented an inexact fuzzy multi-objective programming model to deal with industrial structure optimization problems under uncertainty. Vázquez-Castillo et al. (2013) adopted a multi-objective approach, considering cost and storage as objectives, for synthesis of batch WANs. The solution to this problem facilitates decision maker to select the solutions that makes the proper balance between storage and cost. Similarly, Adekola et al. (2013) presented a mathematical formulation for simultaneous energy and water minimization for batch process with variable schedule. However, Adekola et al. (2013) considers profit (i.e., difference between the product revenue and the sum of fresh water, effluent treatment, cooling water and steam) in their single objective function. A review by Klemeš (2012) covers various water minimisation methodologies including multi-objective approaches.

In this paper, a multi-objective approach of simultaneous minimization of fresh water requirement and maximization of