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Extension of the water sources diagram method to systems with simultaneous fixed flowrate and fixed load processes

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ABSTRACT

In this article, the water source diagram (WSD) (Gomes et al., 2007) is extended to the design of water networks involving both fixed flowrate and fixed contaminant load, as well as water loss/gain operations. The algorithm targets minimum external water consumption while simultaneously synthesizing the corresponding water system structure. In addition, it is shown that the WSD can be applied to water allocation problems (WAP) based only on water sources and sinks, maintaining its good performance. To illustrate the methodology, case studies handling hybrid water system are presented, including a zero wastewater discharge discussion and data from a Brazilian pulp mill.

NomenclatureΔm_{ji} contaminant mass load transferred in operation j in interval $i$$C_{fj}$ outlet concentration in j operationC_{ij} inlet concentration in j operationC_{fi} concentration upper limit in interval $i$$C_{ii}$ concentration lower limit in the interval iETS effluent treatment systemEW external waterf_j flowrate in j operation$f_{ava}^{ew,j}$ flowrate available in the source from j original operation$f_{f,j}$ outlet flowrate from j original operation$f_{i,j}$ inlet flowrate from j original operation$m$ contaminant mass loadN_{op} number of operationsN_{int} number of concentration intervals in the WSDJ operation$i$ concentration interval

1. Introduction

Chemical and petrochemical plants use a large quantity of water. Water scarcity, restricting environmental laws, as well as rising costs of energy and effluent treatment suggests adopting strategies of water management. In this context, reuse, recycle, regeneration with recycle, and regeneration with reuse of water have been extensively studied aiming at reducing water consumption.

Several procedures have been proposed to design the water allocation problems (WAPs). In general, these procedures can be divided into three majors groups: conceptual engineering (i.e. pinch analysis, water pinch), algorithmic, and mathematical optimization-based procedures. Comprehensive descriptions of these procedures can be found in Bagajewicz (2000), El-Halwagi (2012, 2006), Foo (2012, 2009), Jeżowski (2010) and Klemeš (2012). These methodologies are part of process integration, an area of process system engineering. In particular, these methodologies are aimed at systematically reducing impacts on the environment through the reduction of the consumption of resources or harmful emissions (Klemeš et al., 2013).

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Water using operations in chemical processes can be divided into two groups: (1) quality controlled and (2) quantity controlled (Dhole et al., 1995; Polley and Polley, 2000; Hallale, 2002; Manan et al., 2004). Quality-controlled operations are represented by fixed load (FL) operations and the main feature is that the water using units are modeled as mass transfer process with a fixed amount of contaminant that is transferred from a process stream to water (e.g. extraction, absorption and scrubbing). The inlet and outlet stream flowrates are typically equal and hence in this kind of operations there are no water losses or gains.

Quantity-controlled operations are represented by fixed flow (FF) operations where the focus is the flowrate through the operation (e.g. cooling towers, boilers, chemical reaction with water as reagent or product), and these water using units are usually not modeled as mass transfer process

The principal characteristic for the FF operations is that water loss or gain may takes place in the operation. This kind of problems also can be characterized as water source and sinks that consumes or generates a fix quantity of water. The inlet stream are bounded by permissible upper values of concentration while the outlet stream must leave the operation at the given maximum value of concentration and are thus independent on the inlet concentrations (Fan et al., 2012; Teles et al., 2009). Aiming fresh water consumption minimization, Prakash and Shenoy (2005) stated that the outlet stream should leave the operation at the given maximum value of concentration, while the inlet stream must have the maximum specified value, in both types of problems (FL or FF).

As reported by Foo (2009) a growing emphasis to synthesize water network with FF problem was lately observed. However, as described above, a limited number of works to design systems with FF using a conceptual approach have been reported in the literature. We now focus on reviewing the work on water systems with fixed flowrate (FF) operations: originally, Wang and Smith (1995) suggested the use of splitting and local recycling of water to meet the flowrate constraints in FF problems with multiple sources of water of varying quality. To account for water loss/gain the authors neglecting changes in water flowrate and then accounted the changes in the freshwater line. Next, Dhole et al. (1995) presented a targeting methodology for WAPs with FF operations based on a graphical approach. In their graphical representation of the problem, every inlet stream is treated as a demand and every outlet stream as a source. They also suggested that stream mixing and bypassing could be proposed to reduce the fresh water consumption. Polley and Polley (2000) noted a problem in Dhole et al. (1995) method: an incorrect stream mixing option could change the composite curve and lead to an apparent target higher than the true minimum fresh water consumption. In addition, Hallale (2002) also showed that the targeting procedure of Dhole et al. (1995) does not give correct targets because it relies on one chosen mixing option and therefore they could be wrong. In the same article, Hallale (2002) suggested a graphical procedure to find the absolute targets in water systems with FF operations based on a water surplus diagram (a diagram equivalent to the source and sink composite curve). However, the plotting procedure of the water surplus diagram is iterative and turns this task in a tedious and cumbersome work of trial-and-error steps. In addition, it has limitations when generating accurate targets because of its graphical nature. In addition, the methodology cannot handle multiple water supply sources. To overcome and eliminate the iterative steps of water surplus diagram, El-Halwagi et al. (2003) proposed a rigorous targeting approach applied to FF and FL problems based on source and sink composite curves. A numerical version of source and sink composite curves was developed by Almutlaq et al. (2005), called algebraic targeting approach. This approach uses the load interval diagram (LID) (Almutlaq and El-Halwagi, 2007). Another work based on LID was published by Aly et al. (2005) who presented a systematic procedure for water minimization based on two steps. In the first step, the water target is obtained using the load problem table (LPT), which is an adapted form from the LID. The second step, the design step, uses the pinch location and some guidelines to generate the water network through a special strategy of mixing the water sources in order to satisfy the respective water demands. This approach needs the construction of a table where the cascade analysis is performed, first finding the infeasible target and lately the true target. For the network design step, it is required to make the correct link between the source and demands in each concentration interval. This approach is time consuming because it involves a trial-and-error solution to link the sources and demands.

Simultaneously, Manan et al. (2004) proposed the water cascade analysis (WCA) technique, a numerical targeting tool that can be applied to obtain the minimum freshwater and wastewater targets for both FL and FF problems with single contaminant. This procedure is a numerical version of the water surplus diagram (Hallale, 2002), but without the iterative step; it also requires the construction of two diagrams, the water cascade and the pure water surplus cascade diagrams. These two diagrams are integrated by the interval water balance table. Foo (2007) extended the WCA to handle FF problems with multiple water supply sources. The proposed extension is based on the addition of three new steps to locate the minimum consumption of pure and impure fresh water sources. Finally, Foo et al. (2006) illustrated a process involving a zero liquid discharge network in a paper mill using the WCA. Parand et al. (2013a) proposed some adjustments in WCA to allow the correct identification of infeasible targets, which are the major iterative issues of the method.

Prakash and Shenoy (2005) developed the near neighbor algorithm (NNA). This algorithm is based in the use of the nearest source streams available in the neighborhood to satisfy a specific water demand in terms of concentration. In others words, the method creates a mix source that is just above and a source that is just below the specific demand to meet the demand value for FF problems. To be applied in FL problems it is necessary to first convert it into a FF problem in terms of sources and demands. This method cannot be used in problems with multiple water supply sources and with regeneration processes. In addition, it uses a graphical approach, the material recovery pinch diagram (MRPD), to determine the minimum freshwater consumption. An extension of NNA, the enhanced NNA (Shenoy, 2012), increased the applicability of the algorithm to FL problem giving priority to local-recycle matches. Later, Agrawal and Shenoy (2006) analyzed the capability of the NNA to target the minimum freshwater consumption in FF problems for a single contaminant. They extended the composite curve concept to create the composite table algorithm (CTA) to determine the minimum fresh water consumption, which is a hybrid graphical and numerical targeting technique. Parand et al. (2013a) demonstrated the applicability of the CTA for various water network synthesis problems (e.g. FL, mixed FL and FF, multiple pinch, and threshold problems) considering reuse/recycle schemes. Nevertheless, in integrated water