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# Synthesis of Inter-Plant Water Networks Involving Batch and Continuous Processes

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This work presents a mathematical technique for the synthesis of inter-plant water networks, where some of the plants involve batch and continuous processes. To integrate both kinds of process units, a two-phase approach is proposed. First, all batch units are treated as operating in continuous mode, and the inter-plant water network is synthesized for minimum fresh water consumption. Policy of water storage for the batch units is then determined, on which they can behave as continuous units. The objective of the second phase is to minimize the capacity of storage tanks subject to the determined water flow rates. An example is solved to illustrate the proposed approach.

## 1. Introduction

The water shortages and increasingly stringent environmental legislation have resulted in the rising costs of fresh water and effluent treatment. This is the main stimulus for the recent development of systematic approaches to water minimization. Over the past decades, many research works on water network synthesis were reported, where the methodologies used may be broadly categorized as pinch analysis and mathematical optimization techniques (Bagajewicz, 2000; Foo, 2009; Gouws et al., 2010; Halim and Srinivasan, 2010; Jeżowski, 2010; Matijašević et al., 2010). While most of the previous works are restricted to single water network, it is recognized as a further means of water recovery to carry out inter-plant water integration. The first work on water integration across plants was reported by Olesen and Polley (1996) using the load table that is based on pinch analysis. A few works on the use of mathematical methods were later reported (Lovelady et al., 2007; Chew et al., 2008; Lovelady and El-Halwagi, 2009; Chen et al., 2010). This work aims to introduce a mathematical model for the synthesis of inter-plant water networks involving batch and continuous units. The inter-plant integration scheme proposed by Chen et al. (2010) is adopted, where central (among different plants) and decentralized water mains (within individual plants) are placed to serve as buffers between the water-using units. For batch units, auxiliary storage tanks are used to manage their inlet and outlet flow rates and adapt them to be pseudo-continuous units. The synthesis task involves solving a two-phase problem. An example is solved for illustration.

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## 2. Problem Statement

Given is an industrial park that comprises a set of process plants $p \in \mathcal{P}$. Each plant has a set of water-using units $i \in \mathcal{I}$ to remove a set of contaminants $c \in \mathcal{C}$ with fixed mass loads from the process materials. Some of the units $i \in \mathcal{I}^{b}$ are operated in batch mode. Available for service are a set of fresh water sources $w \in \mathcal{W}$ supplying water of different purity levels. In addition, a set of water mains $m \in \mathcal{M}$ are used to increase network practicability, and a set of receiving tanks $r \in \mathcal{R}$ are used to collect wastewater streams before discharge. The objective is to synthesize the optimum inter-plant water network with minimum fresh water consumption, while satisfying all process constraints.

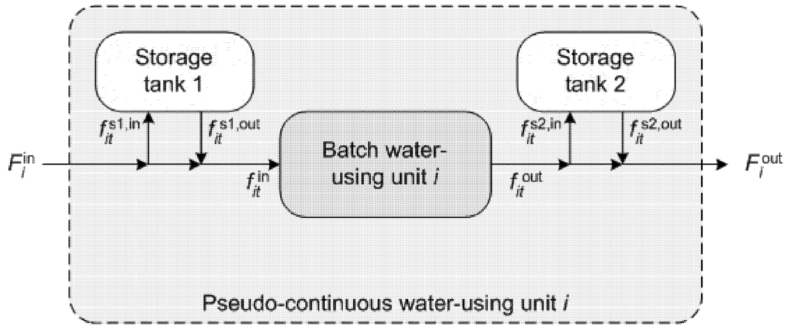


*Figure 1: Schematic diagram of a batch water-using unit with storage tanks*

## 3. Model Formulation

In this work, the synthesis of inter-plant water networks involving continuous and batch units is formulated as a two-phase problem. For each of the batch units, it is proposed to use a pair of storage tanks so that they can behave as continuous units.

### 3.1 Phase 1: Synthesis of continuous inter-plant water network

In the first phase, all water-using units are treated as operating in continuous mode and a continuous inter-plant water network is synthesized. The model is formulated based on a superstructure including all feasible reuse/recycle options. This superstructure consists of diagrams of water-using unit, water main, and receiving tank. The resultant mathematical formulation consisting mainly of mass balance equations and logical constraints is omitted for brevity. Readers who are interested in the details may refer to our previous work (Chen et al., 2010).

The objective of Phase 1 is to minimize the fresh water consumption, i.e.

$$\min \sum_{w \in \mathcal{W}} \sum_{i \in \mathcal{I}} f_{wi} \tag{1}$$

where $f_{wi}$ is the flow rate from water source $w$ to unit $i$. Because of the bilinear terms (in the mass balance equations) and binary variables to indicate the existence of flow connections, the model of Phase 1 is a mixed-integer nonlinear program (MINLP).

**3.2 Phase 2: Determination of storage policy for batch units**

Figure 1 shows a schematic diagram of a batch water-using unit with two auxiliary storage tanks. As shown, one tank is placed ahead of the unit to handle its inlet flow, while the other tank behind the unit handles its outlet flow. The formulation of a batch water-using unit is presented as follows.

Inlet and outlet flow rates of unit $i$ in time interval $t$:

$$f_{it}^{\text{in}} = F_i^{\text{in}} - f_{it}^{\text{s1,in}} + f_{it}^{\text{s1,out}} \qquad \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{2}$$

$$f_{it}^{\text{out}} = F_i^{\text{out}} - f_{it}^{\text{s2,in}} + f_{it}^{\text{s2,out}} \qquad \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{3}$$

Optional constraint to forbid the inlet and outlet flows of a storage tank from occurring in the same time interval:

$$f_{it}^{*,\text{in}} \le F_i^{\max} z_{it}^{*,\text{in}} \qquad * \in \{\text{s1},\text{s2}\}, \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{4}$$

$$f_{it}^{*,\text{out}} \le F_i^{\max} \left(1 - z_{it}^{*,\text{in}}\right) \qquad * \in \{\text{s1},\text{s2}\}, \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{5}$$

Flow balance around a storage tank:

$$q_{it}^{*} = q_{i,T}^{*}\Big|_{t=1} + q_{i,t-1}^{*}\Big|_{t>1} + \left(f_{it}^{*,\text{in}} - f_{it}^{*,\text{out}}\right)\Delta_t \qquad * \in \{\text{s1},\text{s2}\}, \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{6}$$

where the amount of water stored ( $q_{it}^{*}$ ) is limited to the storage capacity ( $\hat{q}_i^{*}$ ):

$$q_{it}^{*} \le \hat{q}_i^{*} \qquad * \in \{\text{s1},\text{s2}\}, \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{7}$$

Connection between the actual ( $f_{it}^{\text{in}}$ ) and pseudo inlet flow rates ( $F_i^{\text{in}}$ ) of unit $i$:

$$f_{it}^{\text{in}} = Z_{it}^{\text{op}} F_i^{\text{in}} T^{\text{cyc}} / T_i^{\text{op}} \qquad \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{8}$$

$$T_i^{\text{op}} = \sum_{t \in \mathcal{T}} Z_{it}^{\text{op}} \Delta_t \qquad \forall i \in \mathcal{I}^{\text{b}} \tag{9}$$

Flow rate balance around unit $i$ in time interval $t$ (assuming no water loss or gain):

$$f_{it}^{\text{in}} = f_{it}^{\text{out}} \qquad \forall i \in \mathcal{I}^{\text{b}}, t \in \mathcal{T} \tag{10}$$

The objective of Phase 2 is to minimize the capacity of storage tanks, i.e.

$$\min \sum_{i \in \mathcal{I}^{\text{b}}} \left(\hat{q}_i^{\text{s1}} + \hat{q}_i^{\text{s2}}\right) \tag{11}$$

Note that the model of Phase 2 is a mixed-integer linear program (MILP).

## 4. Illustrative Example

An example that consists of three process plants is solved to illustrate the proposed approach. The operating data for the water-using units are shown in Tables 1-3 (Chen et al., 2010). A single, contaminant-free fresh water source is available. The optimization

is implemented in the General Algebraic Modeling System (GAMS), with DICOPT and CPLEX as the solvers for MINLP and MILP.
A central main is placed among the three plants and each plant has a decentralized main. The overall fresh water consumption is determined as 362 ton/h after solving the model of Phase 1. Figure 2 shows the resultant inter-plant network configuration. The model of Phase 2 is then solved and the resulting storage policy is shown in Fig. 3.

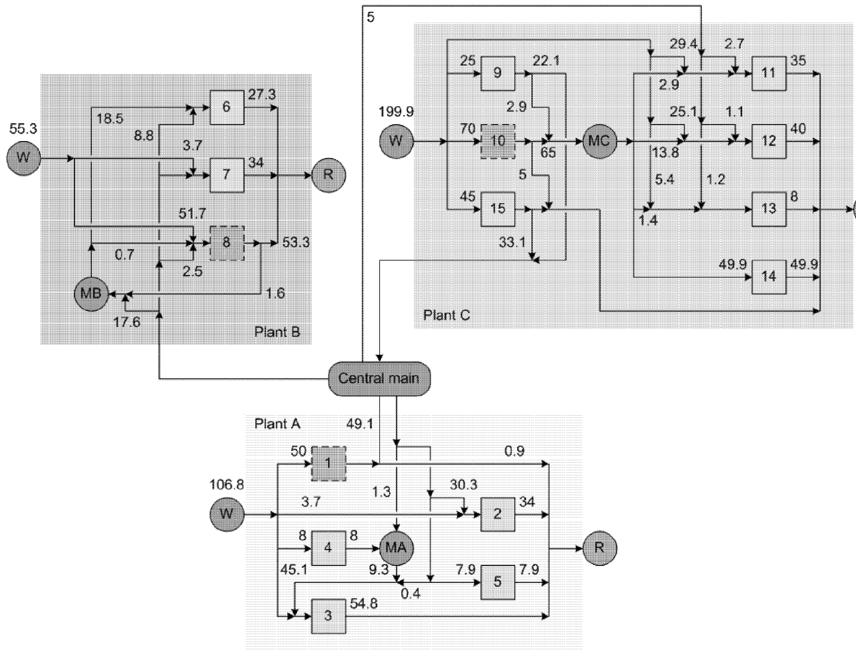


*Figure 2: Resultant network configuration*

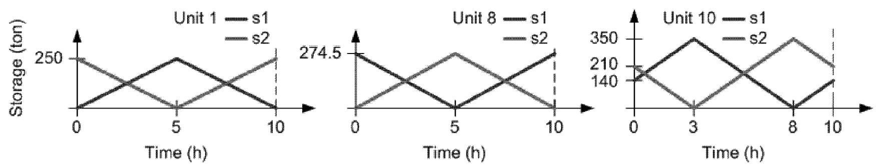


*Figure 3: Storage profiles of tank pairs*

## 5. Concluding Remarks

A mathematical technique was developed for the synthesis of inter-plant water networks involving batch and continuous units. The network configuration is first determined by treating all batch units as continuously operated. Subject to the targeted water flow rates, the storage policy for the batch units is next determined. An example was solved to illustrate the proposed approach.

*Table 1: Operating data for water-using units in plant A*

| unit | operating mode | operating period (h; $T^{cyc}$ = 10 h) | contaminant | $C_{ic}^{max,in}$ (ppm) | $C_{ic}^{max,out}$ (ppm) | $M_{ic}^{load}$ (g/h) |
|---|---|---|---|---|---|---|
| 1 | batch | 5-10 | c1 | 0 | 15 | 750 |
| | | | c2 | 0 | 400 | 20000 |
| | | | c3 | 0 | 35 | 1750 |
| 2 | continuous | – | c1 | 20 | 120 | 3400 |
| | | | c2 | 300 | 12500 | 414800 |
| | | | c3 | 45 | 180 | 4590 |
| 3 | continuous | – | c1 | 120 | 220 | 5600 |
| | | | c2 | 20 | 45 | 1400 |
| | | | c3 | 200 | 9500 | 520800 |
| 4 | continuous | – | c1 | 0 | 20 | 160 |
| | | | c2 | 0 | 60 | 480 |
| | | | c3 | 0 | 20 | 160 |
| 5 | continuous | – | c1 | 50 | 150 | 800 |
| | | | c2 | 400 | 8000 | 60800 |
| | | | c3 | 60 | 120 | 480 |

*Table 2: Operating data for water-using units in plant B*

| unit | operating mode | operating period (h; $T^{cyc}$ = 10 h) | contaminant | $C_{ic}^{max,in}$ (ppm) | $C_{ic}^{max,out}$ (ppm) | $M_{ic}^{load}$ (g/h) |
|---|---|---|---|---|---|---|
| 6 | continuous | – | c1 | 150 | 900 | 22500 |
| | | | c2 | 700 | 4500 | 114000 |
| | | | c3 | 800 | 3000 | 66000 |
| 7 | continuous | – | c1 | 20 | 120 | 3400 |
| | | | c2 | 300 | 12500 | 414800 |
| | | | c3 | 45 | 180 | 4590 |
| 8 | batch | 0-5 | c1 | 120 | 220 | 5600 |
| | | | c2 | 20 | 45 | 1400 |
| | | | c3 | 200 | 9500 | 520800 |

*Table 3: Operating data for water-using units in plant C*

| unit | operating mode | operating period (h; $T^{cyc}$ = 10 h) | contaminant | $C_{ic}^{max,in}$ (ppm) | $C_{ic}^{max,out}$ (ppm) | $M_{ic}^{load}$ (g/h) |
|---|---|---|---|---|---|---|
| 9 | continuous | – | c1 | 0 | 50 | 1250 |
| | | | c2 | 0 | 100 | 2500 |
| | | | c3 | 0 | 50 | 1250 |
| 10 | batch | 3-8 | c1 | 0 | 100 | 7000 |
| | | | c2 | 0 | 300 | 21000 |
| | | | c3 | 0 | 600 | 42000 |

*Table 3: Operating data for water-using units in plant C (continued)*

| unit | operating mode | operating period (h; $T^{cyc}$ = 10 h) | contaminant | $C_{ic}^{max,in}$ (ppm) | $C_{ic}^{max,out}$ (ppm) | $M_{ic}^{load}$ (g/h) |
|---|---|---|---|---|---|---|
| 11 | continuous | – | c1 | 20 | 150 | 4550 |
| | | | c2 | 50 | 400 | 12250 |
| | | | c3 | 50 | 800 | 26250 |
| 12 | continuous | – | c1 | 50 | 600 | 22000 |
| | | | c2 | 110 | 450 | 13600 |
| | | | c3 | 200 | 700 | 20000 |
| 13 | continuous | – | c1 | 20 | 500 | 3840 |
| | | | c2 | 100 | 650 | 4400 |
| | | | c3 | 200 | 400 | 1600 |
| 14 | continuous | – | c1 | 500 | 1100 | 30000 |
| | | | c2 | 300 | 3500 | 160000 |
| | | | c3 | 600 | 2500 | 95000 |
| 15 | continuous | – | c1 | 0 | 15 | 675 |
| | | | c2 | 0 | 400 | 18000 |
| | | | c3 | 0 | 35 | 1575 |

## References


Bagajewicz M., 2000, A review of recent design procedures for water networks in refineries and process plants, Computers and Chemical Engineering 24, 2093-2113.

Chen C.-L., Hung S.-W. and Lee J.-Y., 2010, Design of inter-plant water network with central and decentralized water mains, Comp and Chem Engineering 34, 1522-1531.

Chew I.M.L., Tan R., Ng D.K.S., Foo D.C.Y., Majozi T. and Gouws J., 2008, Synthesis of direct and indirect interplant water network, Industrial and Engineering Chemical Research, 47, 9485-9496.

Foo D.C.Y., 2009, State-of-the-art review of pinch analysis techniques for water network synthesis, Industrial and Engineering Chemical Research, 48, 5125-5159.

Halim I. and Srinivasan R., 2010, Sequential methodology for simultaneous batch process scheduling and water reuse optimization, Chemical Engineering Transactions, 21, 727-732.

Jeżowski J., 2010, Review of water network design methods with literature annotations, Industrial and Engineering Chemistry Research, 49, 4475-4516.

Lovelady E.M., El-Halwagi M.M. and Krishnagopalan G.A., 2007, An integrated approach to the optimisation of water usage and discharge in pulp and paper plants, International Journal of Environment and Pollution, 29, 274-307.

Lovelady E.M. and El-Halwagi M.M., 2009, Design and integration of eco-industrial parks for managing water resources, Environmental Progress and Sustainable Energy, 28, 265-272.

Matijašević L., Spoja D. and Dejanović I., 2010, Water system integration by the process superstructure development, Chemical Engineering Transactions, 21, 373-378.

Olesen S.G. and Polley G.T., 1996, Dealing with plant geography and piping constraints in water network design, Process Safety and Environmental Protection, 74, 273-276.