Optimization of Inter-Plant Water Network Design Involving Multiple Contaminants

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Abstract. Minimization of freshwater consumption and wastewater generation are being critical concerns in the process industry due to the scarcity in freshwater supply, the increase of freshwater and effluent treatment costs and stricter regulations. One of the efficient ways to reduce freshwater consumption in the process is by recycling and/or reusing wastewater that is generated by the process or utility after being treated to acceptable limits. This work presents the development of a systematic approach for synthesizing indirect inter-plant water network integration with centralized regeneration system involving multiple contaminants. In this approach, water reuse prospects were analysed within individual plants and between different plants via inter-plant water integration possibilities. The water network problem is formulated as a mixed integer nonlinear programming (MINLP) based on the water network superstructure and is solved using GAMS optimization software. The applicability of the proposed approach is illustrated using a wafer manufacturing process plants case study. At the end of this study, significant reductions of freshwater consumption and wastewater generation have been achieved, showing the effectiveness of the proposed approach. The results show that the freshwater consumption and wastewater generation reduced about 47.61% and 53.48% respectively.

1. Introduction
Nowadays, industrial water management is becoming a critical issue in the process industries when considering the overall management of the resources availability in the process plant. The rising cost associated to water use and wastewater treatment also push the industries to consider the all related water costs in the overall plant economics. Mathematical programming has become the method of choice for designing an optimal water network since the conceptual-based approach using water pinch analysis shows some limitations when it involves a complex system with multiple contaminants [1]. Savelski and Bagajewicz [2] suggested that at least one contaminant should meet the optimality condition for multi contaminants water network. Two initialization procedures are proposed by Teles et al., [3] that giving multiple starting points to linearize the nonlinear problem using global optimization methods for global water networks. However, the proposed approach needs highly computational efforts due to the large number of operations involved that would take an unreasonable amount of computation time.

Traditional industrial water conservation practices mainly focused on the 3R strategy (reduce, reuse and recycle) within an individual plant and this strategy can be implemented by using water system integration technique. In order to improve the water recovery, Chew et al. [4] extends the single plant water network into integration of inter-plant water network via cross-plant pipelines or centralized utility hub. Basically, the utility hub can be used as an internal water main as it is more useful in managing a
great number of water networks in the inter-plant water integration (IPWI) scheme. The IPWI consists of two or more intra-plants. Intra-plant is single water network, where water recovery is achieved by integrating water-using processes within the same network [5]. More recently, Alnouri et al. [6] proposed two different treatment options; on-site (distributed) treatment and shared (centralized) treatment to reduce the cost of inter-plant water network design. On the other hand, some works have also been reported on the implementation of IPWI in the Eco Industrial Park (EIP) context involving large industrial problems with multi objectives optimization [7] and in different scales of water network [8].

In this work, the optimization problem is formulated as mixed-integer nonlinear programming (MINLP) and solved using GAMS optimization software for indirect integration of IPWI. It involved multiple contaminants, which should optimally determine: (a) the amount of freshwater supplied to each plant; (b) the amount of water received and distributed between the plants; (c) the amount of wastewater generated from each plant; (d) the total number of cross-plant pipelines.

2. Methods

For the multiple contaminants problem, MINLP is always being used in order to maximizing recovery of wastewater and at the same time to minimizing freshwater consumption in a plant through a process known as indirect integration process. In this process, there are five main steps involved to achieve the objective of this study; the steps are summarized in Figure 1.

![Figure 1: Steps for minimum water target through indirect water integration process.](image-url)

**Legend**
- Software tool
- Workflow
2.1. Step 1: Problem Definition
The objective function of the optimization problem is selected based on the main goal of the optimization problem. In this step, the boundaries of the design problem are defined such as the wastewater characterization and the water quality requirement in each plant and centralized regeneration hub.

2.2. Step 2: Limiting Water Data Extraction
The limiting water data consists of sources and demands of the water in a network and were listed in terms of flow rate and contaminant concentration.

2.3. Step 3: Superstructure Definition and Generation
The superstructure in Figure 2 shows all the possible connections that can exist between water demands, water sources, centralized regeneration hub and waste water discharge in the IPWI. The following notations were adopted throughout the paper: $S_i$ and $D_j$ are the water flow rate of source $i$ and water demand $j$ with a concentration of contaminant $C_{i,C}$ and $C_{j,C}$ respectively. $F_{i,W}$ represents freshwater supply with a concentration, $C_w$. The reused/recycle water in an individual plant denotes as $F_{i,j}$. The water flow rate that is sent from source $i$ in each plant to the centralized regeneration hub is identified as the export flow rate, $F_{exp}^{i,j}$ while the regenerated water flow rate that is sent from regeneration hub to demand $j$ in each plant is known as the import flow rate $F_{imp}^{j}$. Meanwhile, $C_{mix}^{e}$ is a result of water mixture in the centralized regeneration hub.

![Figure 2: Superstructure of indirect integration with centralized regeneration hub.](image)

2.4. Step 4: Model Development
In this step, mathematical models were developed based on the superstructure representation as depicted in Figure 2. Equation 1 represents the objective function of this study is to minimize freshwater consumption and subjects to the constraints as shown in equation (2) - (13).
Objective function:

\[ \text{Min } \sum_{j} F_{j}^{\text{exp}} \]  

(1)

Constraints:

Water balance for each source:
The amount of generated waste water, \( F_{i}^{\text{w}} \), reused/recycle water \( F_{i,j}^{\text{exp}} \) and water supply to the centralized hub \( F_{i}^{\text{exp}} \) must be equal to the total source flow rate \( S_{i} \).

\[ \sum_{j} F_{i,j} + F_{i}^{\text{exp}} + F_{i}^{\text{w}} = S_{i} \]  

(2)

Water balance for each demand:
Water flow rate required by the demand, \( D_{j} \) is supplied by the reused/recycled water, freshwater \( F_{j}^{\text{w}} \), and regenerated water from centralized hub \( F_{j}^{\text{imp}} \).

\[ \sum_{i} F_{i,j} + F_{j}^{\text{imp}} + F_{j}^{\text{w}} = D_{j} \]  

(3)

Maximum allowable contaminant load balance:
Demand \( j \) received a mixed of contaminant mass load from different source. Hence, the contaminant for all sources must satisfy the contaminant load for demand \( j \).

\[ \sum_{i} F_{i,j} C_{i,c}^{s} + F_{j}^{\text{w}} C_{w} + F_{j}^{\text{imp}} C_{c}^{\text{mix}} \leq D_{j} C_{j,c}^{d} \]  

(4)

Overall centralized unit inlet and outlet flow rate balance:
The total exported water flow rate to the centralized regeneration hub, \( F_{i}^{\text{exp}} \) must be equal to the total imported water flow rate from centralized regeneration hub, \( F_{j}^{\text{imp}} \).

\[ \sum_{i} F_{i}^{\text{exp}} = \sum_{j} F_{j}^{\text{imp}} \]  

(5)

Contaminant load balance for the centralized unit:
The contaminant load balance at the centralized regeneration hub for the exported water flow rate, \( F_{i}^{\text{exp}} C_{i,c}^{s} \) must be equal to the contaminant load for the imported water flow rate.

\[ \sum_{i} F_{i}^{\text{exp}} C_{i,c}^{s} = \sum_{j} F_{j}^{\text{imp}} C_{c}^{\text{reg}} \]  

(6)

Single export cross-plant pipelines balance:
All exported water flow rates \( F_{i}^{\text{exp}} \) from plant \( k \) are combined in a single export cross-plant pipeline \( F_{k}^{\text{exp}} \) before sent to the centralized hub.
\[ \sum_i F_i^{\text{exp}} = f_k^{\text{cp}} \]  \tag{7}

Single import cross-plant pipelines balance:
All imported water flow rates \(F_j^{\text{imp}}\) from centralized hub are sent to plant \(k\) through a single import cross-plant pipelines \(g_{CP}^{\text{cp}}\).
\[ \sum_j F_j^{\text{imp}} = g_k^{\text{cp}} \]  \tag{8}

Overall centralized main inlet and outlet flow rate balance:
At the centralized regeneration hub, the single export cross-plant pipeline \(f_k^{\text{cp}}\) is equal to the single import cross-plant pipelines \(g_{CP}^{\text{cp}}\).
\[ f_k^{\text{cp}} = g_k^{\text{cp}} \]  \tag{9}

Lower and upper boundary for cross-plant flow rates:
The cross-plant flow rates to and from the centralized regeneration hub are defined by their lower and upper bounds, \(LB_\text{cp}^{\text{cp}}\) and \(UB_\text{cp}^{\text{cp}}\). Binary variables \(x_k^{\text{ind}}\) and \(y_k^{\text{ind}}\) showing the existing of cross-plant pipelines.
\[ LB_\text{cp}^{\text{cp}} x_k^{\text{ind}} \leq f_k^{\text{cp}} \leq UB_\text{cp}^{\text{cp}} x_k^{\text{ind}} \]  \tag{10}
\[ LB_\text{cp}^{\text{cp}} y_k^{\text{ind}} \leq g_k^{\text{cp}} \leq UB_\text{cp}^{\text{cp}} y_k^{\text{ind}} \]  \tag{11}

Limitation of total number of cross-plant pipelines:
Binary variable for import \(y_k^{\text{ind}}\) and export \(x_k^{\text{ind}}\) must be equal or less than the total of number of cross-plant pipelines, \(N\).
\[ \sum_k x_k^{\text{ind}} + \sum_k y_k^{\text{ind}} \leq N \]  \tag{12}

Fixed removal ratio:
Centralized regeneration hub is function as regeneration unit, the water source quality is improved before sent it back for water recovery. The storage water in the centralized hub are being treated first to a desired concentration level before export it to the plant water network. Hence, the regeneration unit with fixed removal ratio, \(RR\) is used.
\[ RR = \frac{\sum_i F_i^{\text{exp}} c_{i,C}^{\text{mix}} - \sum_j F_j^{\text{imp}} c_{j,C}^{\text{mix}}}{\sum_i F_i^{\text{exp}} c_{i,C}^{\text{mix}}} \]  \tag{13}

Since the fixed removal ratio is considered in the regeneration unit, the contaminant load balance for the centralized regeneration hub in Eq (6) is revised and can be written as in Eq (6a).
\[ \sum_j F_j^{\text{imp}} c_{e,C}^{\text{mix}} = \sum_i F_i^{\text{exp}} c_{i,C}^{\text{mix}} (1 - RR) \]  \tag{6a}
2.5. Step 5: Optimization problem formulation and solution
Optimization formulation contains of non linearity of continuous variables problem. The mathematical model was formulated as MINLP and solved using GAMS, version 8. In order to achieve an optimal IPWI network, GAMS/DICOPT solver was employed for solving MINLP problem. In this study, a personal computer with a 3.86 GHz Intel Core Two Duo Processor was used to run the GAMS software. All the equations were solved based on the objective function in equation (1) subjects to the constraints in equation (2) - (13).

3. Results and Discussion
The case study involves wafer manufacturing process plants [5] and it is used to highlight the features of the proposed approach. The data for water sources and demands extracted for wafer manufacturing process plants were tabulated in Table 1 and were listed in terms of flow rate and contaminant concentrations. The heavy metals concentration data were slightly modified from the original source and additional data of contaminant were added to suit with the case study and the proposed method. A hypothetical data (concentrations of contaminant A) were added to represent as another contaminant.

Table 1: Limiting water data for wafer fabrication plants.

| Plant | Process   | Flow rate (t/h) | Contaminants (ppm) |
|-------|-----------|-----------------|--------------------|
|       |           |                 | Heavy metals*      | Contaminant A |
|       | Demand    |                 |                    |               |
| A     | Wet (D1)  | 500.00          | 2.5                | 10.0          |
|       | Lithography (D2) | 450.00 | 1.0 | 5.0 |
|       | CMP (D3)  | 700.00          | 2.5                | 5.0           |
|       | Etc. (D4) | 350.00          | 5.0                | 10.0          |
|       | Source    |                 |                    |               |
|       | Wet I (S1) | 250.00 | 5.0 | 25.0 |
|       | Wet II (S2) | 250.00 | 4.5 | 15.0 |
|       | Lithography (S3) | 350.00 | 5.0 | 15.0 |
|       | CMP I (S4) | 300.00 | 10.0 | 30.0 |
|       | CMP II (S5) | 200.00 | 4.5 | 20.0 |
|       | Etc. (S6) | 280.00          | 5.0                | 35.0          |
| B     | Demand    |                 |                    |               |
|       | Water Fab(D5) | 182.00 | 2.5 | 5.0 |
|       | CMP (D6)  | 159.00          | 4.5                | 10.0          |
|       | Source    |                 |                    |               |
|       | 50% spent (S7) | 227.12 | 5.0 | 30.0 |
|       | 100% spent (S8) | 227.12 | 11.0 | 15.0 |

* The data was slightly modified from the original source [5].

The total amount of freshwater and wastewater for both plants without considering any water minimization strategy were 2341 t/hr and 2084.24 t/hr respectively. The freshwater consumption and wastewater generation can be further reduced after implementing indirect IPWI. In this strategy, there must be a centralized unit known as centralized regeneration hub. The centralized regeneration hub consists of storage tank and regeneration unit which the main functions are to receive and distribute the
regenerated water from both Plant A and B respectively. Beside that, water sources are partially being treated at the regeneration unit and reused in the processes for both networks.

Based on the result generated from GAMS, the water network for both plant is designed as shown in Figure 3. The freshwater is supplied to demand D1, D2, D3, D4 for network A and D5, D6 for network B respectively. For wastewater discharge, it merged from the source S1, S4, S6 for plant A and S7, S8 for plant B. The centralized regeneration unit received the wastewater that coming from source S1 and S6 for plant A and for plant B it comes from source S7 and S8. Water from centralized regeneration unit will take some time before it distributed to demand D1, D5, and D6 respectively. The total amount of water at storage tank is about 350 t/h and the total number of cross-plant pipelines is equal to 3. The results for the total amount of freshwater and wastewater generated after implementing the systematic approach is about 1226.45 t/h and 969.69 t/h respectively which corresponds with reduction of 47.61% freshwater consumption and 53.48% wastewater generation.

![Figure 3: Optimal inter-plant water network design.](image-url)
4. Conclusions
The results obtained from the GAMS are concluding based on the research objective. The indirect IPWI involving multiple contaminants are proven to be applicable to minimize the amount of freshwater and wastewater generation by maximizing water recovery in the process plants. In this work, the problems of water network based on the superstructure have been successfully developed by using generic MINLP models. Based on the results, the percentage reduction of freshwater is 47.61%, while the wastewater can be reduced up to 53.48%. This shows that the indirect inter-plant water networks with a centralized regeneration hub can help to reduce utility consumption for different plants located in close proximity to each other.

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