# Synthesis of Direct and Indirect Interplant Water Network

**Irene Mei Leng Chew,[†] Raymond Tan,[‡] Denny Kok Sum Ng,[†] Dominic Chwan Yee Foo,*[,†] Thokozani Majozi,[§] and Jacques Gouws[§]**

*Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia, Center for Engineering and Sustainable Development Research, De La Salle University-Manila, 2401 Taft Avenue, 1004 Manila, Philippines, and Department of Chemical Engineering, University of Pretoria, Lynnwood Road, Pretoria 0002, South Africa*

To date, most work on water network synthesis has been focusing on a single water network. The increase of public awareness toward industrial ecology has inspired new research into interplant water integration (IPWI). In this context, each water network may be grouped according to the geographical location of the water-using processes or as different plants operated by different business entities. Water source(s) from one network may be reused/recycled to sink(s) in another network. In this work, two different IPWI schemes, that is, “direct” and “indirect” integration are analyzed using mathematical optimization techniques. In the former, water from different networks is integrated directly via cross-plant pipeline(s). A mixed integer linear program (MILP) model is formulated and solved to achieve a globally optimal solution. In the latter, water from different networks is integrated indirectly via a centralized utility hub. The centralized utility hub serves to collect and redistribute water to the individual plants, and may even function as a shared water regeneration unit. For the indirect integration scheme, a mixed integer nonlinear program (MINLP) is formulated and solved using a relaxation linearization technique to obtain an optimal solution.

## 1. Introduction

Resource conservation has gained more attention in the process industry in recent years. An efficient resource conservation strategy is beneficial since it enhances competitiveness through reduced operational costs and promotes sustainable development. Process integration has been proven as a promising approach in maximizing potential resource conservation. Apart from the earliest developments in energy conservation,[1−3] much recent process integration work on water network synthesis has been reported in the literature, ranging from insight-based pinch analysis to mathematical optimization approaches. Research in water network synthesis through pinch analysis has evolved from the targeting of minimum fresh water and wastewater flowrates[4−13] to the targeting of minimum regeneration[14−18] and wastewater treatment flowrates.[19−21] Apart from the insight-based approach, various mathematical optimization approaches have been developed to complement the insight-based approach in dealing with more complex problems, for example, multicontaminant systems[22−24] and complex operational constraints which include limiting the number of pipeline connections,[25] forbidden/compulsory matches between water-using processes,[26,27] and process uncertainty,[28,29] etc. As proven in previous works, one of the advantages of mathematical optimization approach is its capability in simulating the desired network structure and the operational condition for a water network.

It is worthy of note, that all the above-mentioned work was developed for a single water network, where water recovery is achieved by integrating water-using processes within the same network. A further means to enhance water recovery is via interplant water integration (IPWI), that is, water integration between different water networks. In this case, water-using processes may be grouped according to their geographical location or as different plants that are operated by different business entities. Hence, a water source in one network may be fed to another network as a new source.

Olesen and Polley[30] first addressed the IPWI problem using the pinch-based load table technique that was developed for fixed load problems. Spriggs et al.[31] later proposed to use the material recovery pinch diagram[6] for minimum flowrate targeting for the IPWI problem in the fixed flowrate problems. These authors also proposed the use of a centralized mixing and interception network (termed as “centralized utility hub” in this current work) for conducting byproduct or waste exchange among several process plants within an eco-industrial park. Recently, Foo[32] extended the use of water cascade analysis which was developed for flowrate targeting in a single water network,[7,12,13] to IPWI. However, the proposed work requires time-consuming steps as alternative integration schemes need to be considered to locate the true minimum water flowrates among all the schemes. Therefore, the proposed approach is cumbersome when the number of water networks involved in IPWI scheme is large.

On the other hand, mathematical optimization techniques have also been employed to handle more complicated cases of the IPWI problem. In a reported case in the integrated pulp and bleached paper production,[33] mass integration strategies were incorporated in the mathematical model to handle multiple contaminants present in the problem. More recently, work by Liao et al.[34] considered the multiperiod problem (unequal working hours in each period), where a mixed integer nonlinear programming (MINLP) model is solved to locate the minimum interplant water targets while a mixed integer linear program (MILP) is solved to obtain a water network that meets the water flowrate targets with simplest network configuration.

It is also worth noting that the IPWI problem is analogous to the interplant heat integration problem, where energy integration is conducted across different plants. The main benefit for carrying out interplant heat integration is that, it leads to a

* To whom correspondence should be addressed. E-mail: dominic.foo@nottingham.edu.my. Tel.: +60-3-8924-8130. Fax: +60-3-8924-8017.
[†] University of Nottingham.
[‡] De La Salle University-Manila.
[§] University of Pretoria.

10.1021/ie800072r CCC: $40.75 
Published on Web 11/08/2008

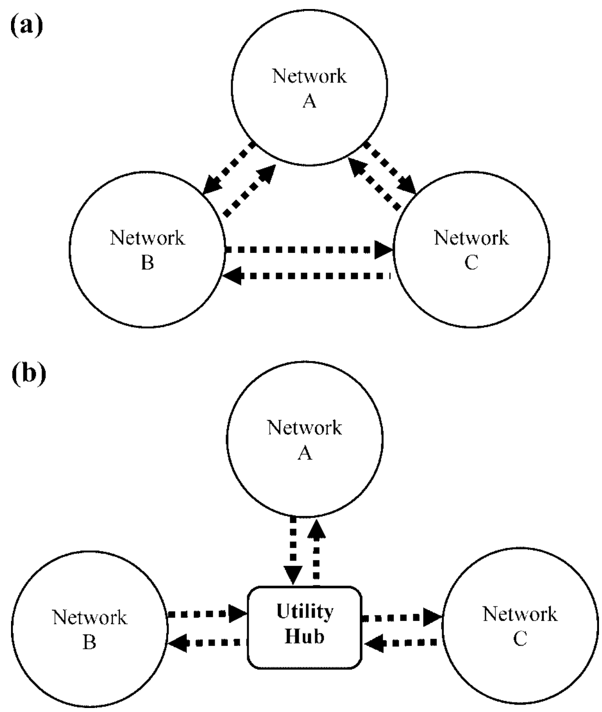


**Figure 1.** IPWI schemes: (a) direct integration and (b) indirect integration via utility hub.

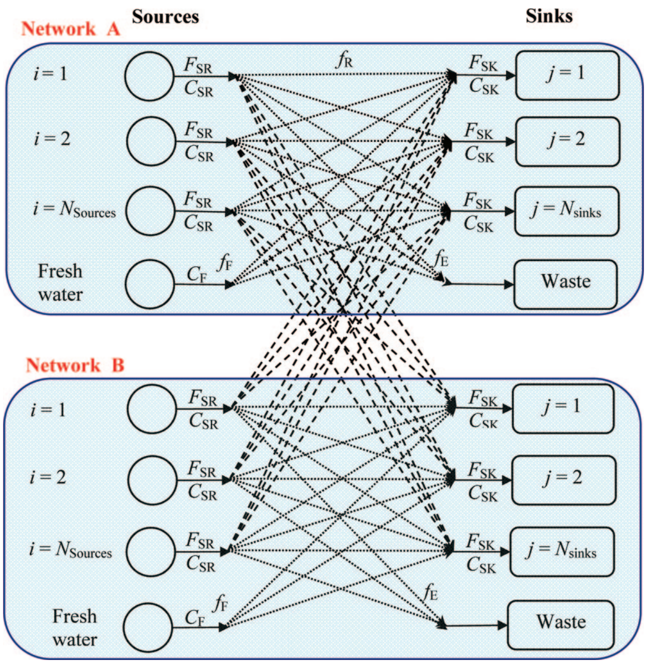


**Figure 2.** Superstructure for direct integration.

simpler network structure which is more favorable when dealing with operation flexibility, controllability, and hazard.[35−38] Ahmad and Hui[35] first addressed the interplant heat integration problem by dividing the process plants into different regions, with each region associated with its processing tasks. The scheme that offers the minimum energy consumption with the least interconnections between the regions is next identified. Amidpour and Polley[36] later utilized the problem decomposition method for interplant heat integration to avoid expensive piping cost and complex network. Rodera and Bagajewicz[37] introduced two alternative schemes for interplant heat integration, i.e. direct integration using process streams, and indirect integration using intermediate fluids (e.g., steams). A special case study that involves heat integration between two plants was illustrated. The work was later extended to heat integration for multiple plants.[38]

This paper focuses on IPWI that is useful in enhancing water recovery. In the first two parts of this paper, two different schemes of IPWI are discussed, that is, direct and indirect integration. In the former, integration between water sources and sinks of different networks is carried out directly via cross-plant pipelines (as shown in Figure 1a). In the indirect integration scheme, water networks are interconnected via a centralized utility hub that serves as a buffer (as shown in Figure 1b). The main advantage of using a centralized utility hub is that, it is more practical in handling a large number of water networks in the IPWI scheme. In particular, geographical distances between different water networks are much larger than typically encountered for within a single water network. Hence, an interplant network that includes a centralized utility hub will reduce the associated piping cost by pooling together water streams to be exported from each plant. At the same time, controllability problems are reduced by the attenuation of unavoidable fluctuations in stream flowrates and concentrations. Note that the centralized utility hub is commonly used in eco-industrial parks, wherein exchange of common utilities is often a precursor of more extensive exchange of different types of industrial wastes. A centralized utility hub is viable in the context of promoting sustainable development through industrial symbiosis between companies in close proximity. Conceptually, the utility hub can be seen as an internal water main in a single water network with the main objective to increase water network flexibility and controllability.[39−45] Venkatasubramanian et al.[46] did a theoretical analysis of the self-organization of different network schemes, which showed that hub-based systems have favorable properties for certain applications.

The third part of the paper presents a variant model that includes a regeneration unit in the utility hub. Hence, a water source that is sent to the hub is purified before it is redistributed to the water network. All the above scenarios are modeled and solved using mathematical optimization techniques to obtain an optimum interplant water network which is cost-effective.

## 2. Problem Statement

Given a set of water networks of the fixed flowrate type problem, with process sinks and sources that may be considered for water reuse/recycle, where each sink and source has a limiting water flowrate and concentration, it is required to synthesize an optimum interplant water network with direct and indirect water integration schemes. In the former, the water

**Table 1. Limiting Data for Integrated Pulp Mill and Bleached Paper Plant**

| | | | | mass load, $m_j$ (t/h) | | | | | | mass load, $m_j$ (t/h) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| plant | unit | sink $SK_j$ | flowrate $F_{SK}$ (t/h) | Cl | K | Na | unit | source $SR_i$ | flowrate $F_{SR}$ (t/h) | Cl | K | Na |
| pulp (A) | washer | 1 | 13995 | 0.4813 | 0.1775 | 1.2514 | stripper 1 | 1 | 8901 | 0 | 0 | 0 |
| | screening | 2 | 1450 | 0.3495 | 0.0035 | 0.3495 | screening | 2 | 1450 | 0.4475 | 0.1675 | 1.2185 |
| | washer /filter | 3 | 5762 | 0 | 0 | 0 | stripper 2 | 3 | 1024 | 0 | 0 | 0 |
| paper (B) | bleaching | 4 | 30990 | 0.1146 | 0.0341 | 0.1116 | bleaching | 4 | 30990 | 15.4950 | 0.1550 | 15.4950 |

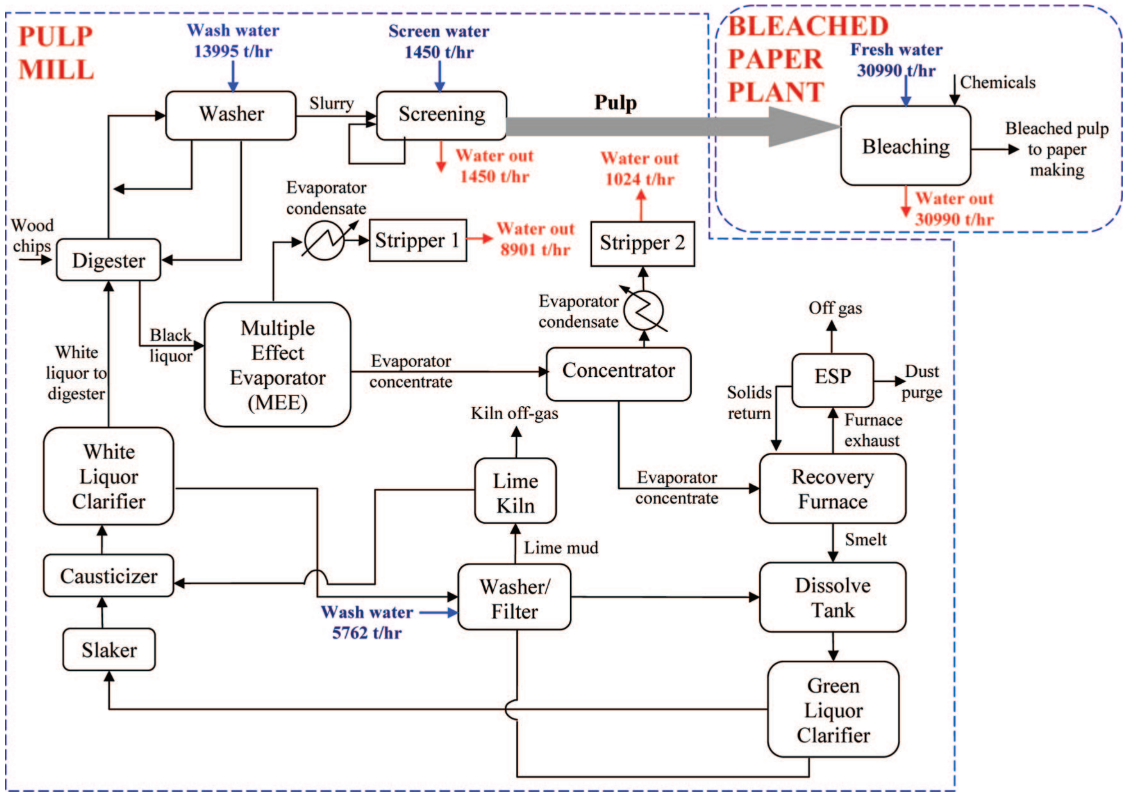


**Figure 3.** Process flow diagram for an integrated pulp mill and bleached paper plant.

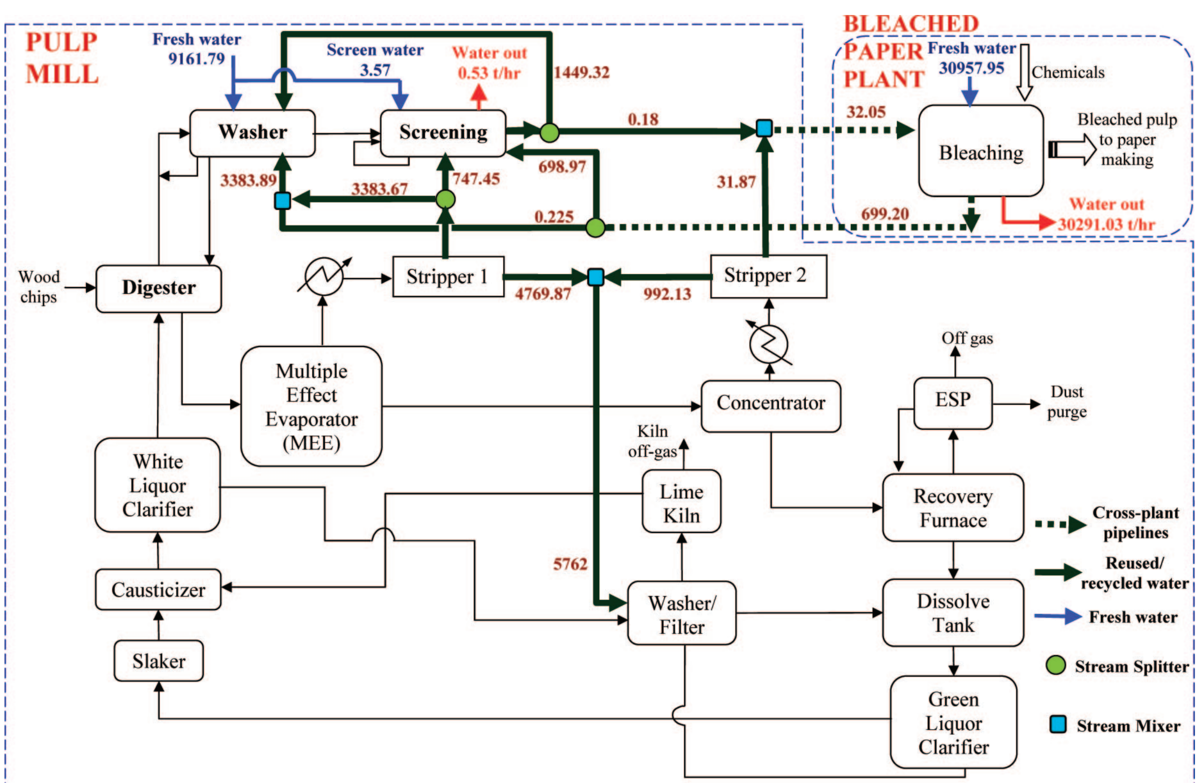


**Figure 4.** Integrated pulp mill and bleached paper plant with direct integration.

source(s) from one network is allowed to integrate directly with the water sink(s) located in another network via cross-plant pipelines (Figure 1a). For the latter, water networks are interconnected via a centralized utility hub. Hence, direct water integration between different networks is forbidden (Figure 1b).

This problem is categorized as a fixed flowrate problem in recent work in water network synthesis.[5−13,16,19−21] The assumption of a fixed water flowrate differs slightly from the conventional fixed load problem[4,15,17,18] in which processes are modeled as mass exchange units with a fixed contaminant load

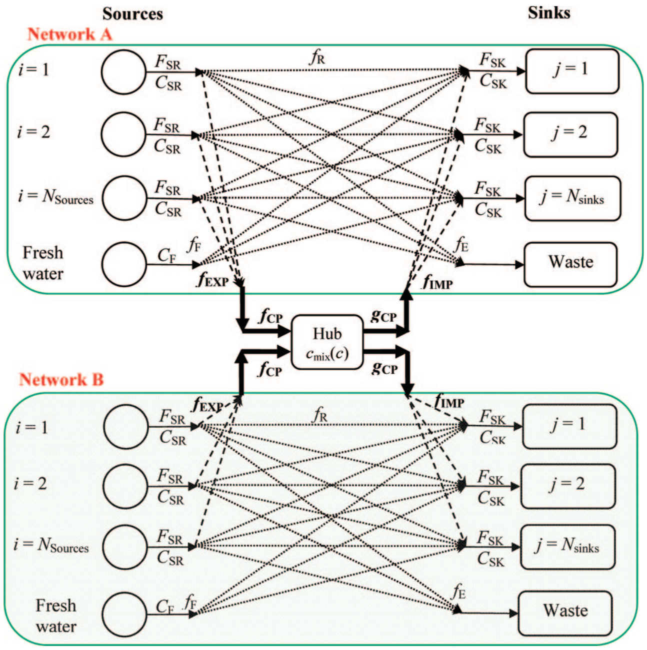


**Figure 5.** Superstructure for indirect integration via centralized utility hub.

**Table 2. Limiting Data for Example 2**

| water network | sink $SK_j$ | flowrate $F_{SK}$ (t/h) | concentration $C_{SK}$(ppm) | source $SR_i$ | flowrate $F_{SR}$(t/h) | concentration $C_{SR}$ (ppm) |
|---|---|---|---|---|---|---|
| | 1 | 20.00 | 0 | 1 | 20.00 | 100 |
| | 2 | 66.67 | 50 | 2 | 66.67 | 80 |
| A | 3 | 100.00 | 50 | 3 | 100.00 | 100 |
| | 4 | 41.67 | 80 | 4 | 41.67 | 800 |
| | 5 | 10.00 | 400 | 5 | 10.00 | 800 |
| | 6 | 20.00 | 0 | 6 | 20.00 | 100 |
| | 7 | 66.67 | 50 | 7 | 66.67 | 80 |
| B | 8 | 15.63 | 80 | 8 | 15.63 | 400 |
| | 9 | 42.86 | 100 | 9 | 42.86 | 800 |
| | 10 | 6.67 | 400 | 10 | 6.67 | 1000 |
| | 11 | 20.00 | 0 | 11 | 20.00 | 100 |
| | 12 | 80.00 | 25 | 12 | 80.00 | 50 |
| C | 13 | 50.00 | 25 | 13 | 50.00 | 125 |
| | 14 | 40.00 | 50 | 14 | 40.00 | 800 |
| | 15 | 300.00 | 100 | 15 | 300.00 | 150 |

which is transferred to a water stream. In the fixed flowrate case each process may function both as a sink and a source, in which case the properties of the inlet and outlet streams do not affect each other. It is useful as it allows for processes in which water only exists as an output (e.g., as a byproduct of a chemical reaction) or input (e.g., as a constituent of the product stream).[5,7]

## 3. Mathematical Model for Direct Integration

The superstructure for direct integration scheme of an IPWI is shown in Figure 2. As shown, apart from being reused/recycled to sinks in the local network (dotted line), process sources may also be integrated with sinks in other water networks (dashed line) for further water recovery. Fresh water is the external source to be considered after the available process sources are fully utilized. The unused water from the process source(s) is then sent for treatment, before it is discharged to the environment.

The mathematical model for direct integration scheme is formulated as follows.

$$\min \text{obj}_{\text{cost}} = \left(\sum_{j\in J} f_F(j)\, W_{\text{cost}} + \sum_{i\in I} f_E(i)\, E_{\text{cost}}\right)\text{AWH} + P_{\text{cost}} \tag{1}$$

$$\sum_{i\in I} f_R(i,j) + f_F(j) = F_{SK}(j) \qquad j\in J \tag{2}$$

$$\sum_{j\in J} f_R(i,j) + f_E(i) = F_{SR}(i) \qquad i\in I \tag{3}$$

$$\sum_{i\in I} f_R(i,j)\, C_{SR}(c,i) + f_F(j)\, C_F(c) \le F_{SK}(j)\, C_{SK}(c,j) \qquad j\in J,\ c\in C \tag{4}$$

Equation 1 is the objective function which minimizes the total annualized cost, $\text{obj}_{\text{cost}}$ for the water network system. This includes the total fresh water cost (first term), effluent treatment cost (second term), and also the annualized cross-plant piping cost, $P_{\text{cost}}$. Note that the presence of a wastewater treatment system is implied by the second term of the objective function, even if such a process is not explicitly included in the superstructure. Equations 2 and 3 are the flowrate balances for a sink, $F_{SK}(j)$ and source, $F_{SR}(i)$, respectively, with variable $f_R(i,j)$ denoted reuse/recycle flowrate from source $i$ to sink $j$. Equation 4 ensures the contaminant load for a sink does not exceed its maximum limit.

Equation 5 gives the upper and lower bounds of the cross-plant flowrates $f_R(i, j)$. Binary variable $x_{DIR}(i, j)$ in the equation indicates the existence of a cross-plant pipeline for direct integration, in which source $i$ is from network $k$ and sink $j$ is from another network $k'$. To limit the capital cost of the pipelines, eq 6 limits the total number of cross-plant pipelines to $N$. Note that the binary term $x_{DIR}(i, j)$ in eqs 5 and 6 makes the model an MILP.

$$\text{LB}_{CP}\, x_{DIR}(i,j) \le f_R(i,j) \le \text{UB}_{CP} x_{DIR}(i,j) \qquad \forall\, i\in I_k,\ \ \forall\, j\in J_{k'},\ k\ne k' \tag{5}$$

$$\sum_{i\in I_k}\sum_{j\in J_{k'}} x_{dir}(i,j) \le N \qquad k\ne k' \tag{6}$$

The capital cost for the cross-plant pipeline ($P_{\text{cost}}$) in eq 1 is adapted from Kim and Smith[47] and is given in eq 7. The piping cost considers the use of carbon steel pipes (USD), with the cost parameters of $p = 7200$ and $q = 250$ (CE plant index = 318.3). It is further assumed that the stream flowrate velocity is $v = 1$ m·s$^{-1}$ and water density is $\rho = 1000$ kg·m$^{-3}$ throughout this study. An equal Manhattan distance, $D$, is assumed for all cross-plant pipelines. Piping cost within the individual network is assumed negligible, as it is relatively much smaller as compared to the cross-plant pipeline.

$$P_{\text{cost}} = D\left(p\sum_{i\in I_k}\sum_{j\in J_{k'}} \frac{f_R(i,j)}{3600\rho v} + q x_{dir}(i,j)\right)\text{AF} \qquad \forall\, i\in I_k,\ \ \forall\, j\in J_{k'},\ k\ne k' \tag{7}$$

An annualized factor (AF) is used to annualize the piping capital cost, defined as[3]

$$\text{AF} = \frac{m(1+m)^n}{(1+m)^n - 1} \tag{8}$$

where $m$ = fractional interest rate per year, $n$ = number of years. Example 1 is used to demonstrate the proposed method. Constraints 1−6 constitute a mixed integer linear programming (MILP) model for which global optimality is readily attainable.

**3.1. Example 1−Integrated Pulp Mill and Bleached Paper Plant.**[31,33] Figure 3 shows the process flow diagram of an integrated pulp mill and a bleached paper plant, taken from Lovelady and co-workers.[31,33] As this example involves only

**Table 3. Optimal Solutions through Fresh Water Minimization for Different Integration Schemes−Example 2**

| | integration scheme | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | without water integration | direct integration | | | | indirect integration via centralized utility hub | | | |
| | | pinch[32] | MILP | | | MINLP | | | |
| minimum fresh water, $obj_{fresh}$ (t/h) | 339.64 | 316.26 (Figure 6) | 316.26 | 314.36 (Figure7) | 314.36 | 317.30 | 316.26 | 314.96 (Figure 9) | 314.96 |
| total cross-plant flowrate, (t/h) | | 61.19 | 61.19 | 78.45 | 96.99 | 50.95 | 180.16 | 187.87 | 187.87 |
| hub concentration, $c_{mix}(c)$ (ppm) | | | | | | 100.00 | 135.86 | 134.92 | 134.92 |
| cross-plant pipelines, $N$ | 0 | 2 | 2 | 3 | 4 | 3 | 4 | 5 | 6 |
| CPU time (s) | | | 0.187 | 0.203 | 0.156 | 0.795 | 0.936 | 0.827 | 0.685 |

two plants, a direct integration scheme is implemented. To be comparable with the original finding of Lovelady et al.,[33] the capital cost of the cross-plant pipelines as well as the freshwater and wastewater costs are not considered. Hence, the objective function in eq 1 is simplified to eq 1a, which then minimizes the total fresh water required. Objective function in eq 1a is solved subject to the constraints in eqs 2–6. The mathematical model was formulated in GAMS version 2.5 and solved using CPLEX. A 1.66 GHz Intel Core Duo Processor was used throughout the study.

$$\min obj_{fresh} = \sum_{j \in J} f_F(j) \tag{1a}$$

Table 1 summarizes the limiting data for both plants. As shown, it is a multicontaminant problem where recovery is dictated by the concentration of three ions: chlorine ($Cl^-$), potassium ($K^+$), and sodium ($Na^+$).[33] The concentrations of $Cl^-$, $K^+$, and $Na^+$ in fresh water are taken as 3.7 ppm, 1.1 ppm, and 3.6 ppm, respectively. Solving the MILP model yields an overall minimum fresh water flowrate of 40123 t/h (Figure 4), which is consistent with the result reported in previous work.[31,33] A maximum of two cross-plant pipelines is needed for this case. Note that the individual reuse/recycle flowrates between the process sinks and sources between the two works are slightly different. This is expected as most problems have more than a single solution corresponding to the same objective value. The MILP model in this work entails 57 continuous variables, 16 binary variables, and 56 constraints with a solution found in 0.015 CPU seconds.

## 4. Mathematical Model for Indirect Integration via Utility Hub

The second type of IPWI scheme addressed in this work is indirect integration where a centralized utility hub is included in the network. Figure 5 shows the superstructure for the indirect integration scheme, where the centralized utility hub acts as storage tank that stores cross-plant flowrate. The cross-plant flowrate that is sent from source $i$ to the utility hub is known as the export flowrate ($f_{exp}(i)$) while the cross-plant flowrate that is sent from utility hub to sink $j$ is known as the import flowrate ($f_{imp}(j)$). The resulting water mixture in the centralized utility hub has a contaminant concentration of $c_{mix}(c)$.

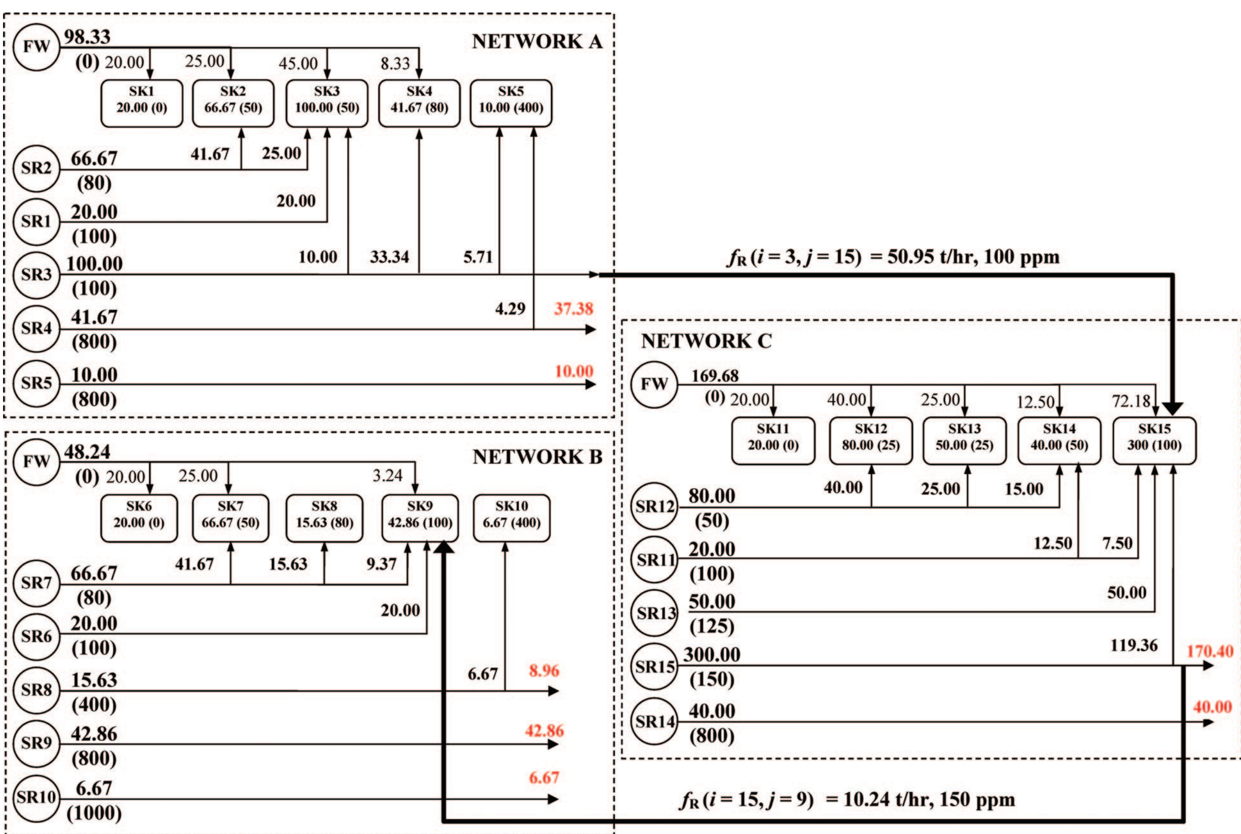


**Figure 6.** Direct integration through pinch approach.[32]

The mathematical model for the indirect integration scheme is developed based on the superstructure given in Figure 5. The objective function for the model remains the same as that given in eq 1, with the following additional constraints:

$$\sum_{i\in I} f_{\mathrm{R}}(i,j) + f_{\mathrm{imp}}(j) + f_{\mathrm{F}}(j) = F_{\mathrm{SK}}(j) \qquad j \in J \tag{9}$$

$$\sum_{j\in J} f_{\mathrm{R}}(i,j) + f_{\mathrm{exp}}(i) + f_{E}(i) = F_{\mathrm{SR}}(i) \qquad i \in I \tag{10}$$

$$\sum_{i\in I} f_{\mathrm{R}}(i,j)\, C_{\mathrm{SR}}(c,i) + f_{\mathrm{F}}(j)\, C_{\mathrm{F}}(c) + f_{\mathrm{imp}}(j)\, c_{\mathrm{mix}}(c) \le F_{\mathrm{SK}}(j)\, C_{\mathrm{SK}}(c,j) \qquad j \in J,\ c \in C \tag{11}$$

$$\sum_{i\in I} f_{\mathrm{exp}}(i) = \sum_{j\in J} f_{\mathrm{imp}}(j) \tag{12}$$

$$\sum_{i\in I} f_{\mathrm{exp}}(i)\, C_{\mathrm{SR}}(c,i) = \sum_{j\in J} f_{\mathrm{imp}}(j)\, c_{\mathrm{mix}}(c) \qquad c \in C \tag{13}$$

In eq 9, the water flowrate required for a process sink is fulfilled by fresh water $f_{\mathrm{F}}(j)$, the external water source from the centralized utility hub $f_{\mathrm{imp}}(j)$, and any reuse/recycle water from other process sources within single water network $f_{\mathrm{R}}(i,j)$. Equation 10 states that the total source flowrate comprises the reuse/recycle flowrate to sink $f_{\mathrm{R}}(i,j)$, water supply to the centralized utility hub $f_{\mathrm{exp}}(i)$, and discharged effluent $f_{\mathrm{E}}(i)$ from source $i$. Equation 11 sets the maximum allowable contaminant

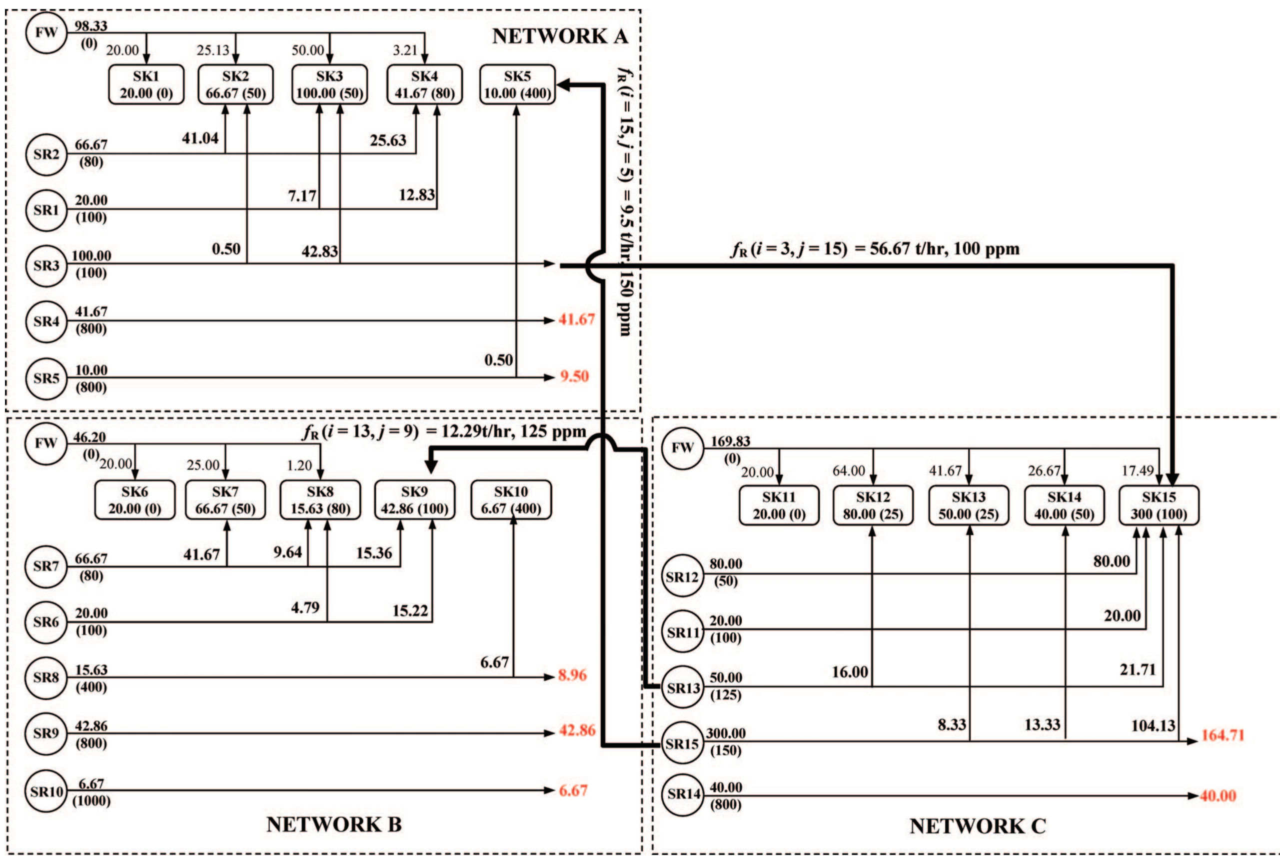


**Figure 7.** Direct integration using the proposed approach (optimized for minimum fresh water flowrate).

**Table 4. Optimal Solutions through Total Annualized Cost Minimization for Different Integration Schemes−Example 2**

| | integration scheme | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | direct integration (MILP) | indirect integration via centralized utility hub (MINLP) | | | | | | | | |
| Regeneration RR | (Figure 8) | (Figure 10) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 (Figure 11) | 0.6 | 0.7 | 0.8 |
| total annualized cost, $obj_{cost}$(million \$/year) | 0.89 | 0.90 | 0.87 | 0.81 | 0.78 | 0.76 | 0.72 | 0.76 | 0.82 | 0.87 |
| total fresh water cost (million \$/year) | 0.33 | 0.33 | 0.29 | 0.25 | 0.22 | 0.20 | 0.15 | 0.15 | 0.15 | 0.15 |
| total wastewater cost (million \$/year) | 0.55 | 0.55 | 0.49 | 0.43 | 0.38 | 0.33 | 0.25 | 0.25 | 0.25 | 0.25 |
| total regeneration cost (million \$/year) | - | - | 0.02 | 0.06 | 0.10 | 0.15 | 0.24 | 0.30 | 0.36 | 0.43 |
| total cross-plant pipeline capital cost (million \$/year) | 0.01 | 0.02 | 0.07 | 0.07 | 0.08 | 0.07 | 0.08 | 0.06 | 0.05 | 0.05 |
| minimum fresh water, $\sum_j f_{\mathrm{F}}(j)$ (t/h) | 316.26 | 317.30 | 283.28 | 244.90 | 218.40 | 191.21 | 145.69 | 144.44 | 144.44 | 144.44 |
| total cross-plant flowrate, (t/h) | 61.19 | 50.95 | 419.32 | 428.17 | 449.46 | 434.41 | 486.74 | 345.66 | 278.88 | 249.50 |
| hub concentration, $c_{\mathrm{mix}}(c)$ (ppm) | - | 100.00 | 107.28 | 100.00 | 78.31 | 67.23 | 53.30 | 50.40 | 40.16 | 26.18 |
| cross-plant pipelines, $N$ | 2 | 3 | 5 | 6 | 6 | 6 | 6 | 5 | 5 | 4 |
| CPU time (s) | 0.171 | 1.592 | 1.452 | 1.295 | 1.093 | 1.248 | 0.858 | 1.358 | 1.358 | 1.311 |

load entering sink $j$. Equation 12 is the overall utility hub inlet and outlet flowrate balance, which states that the sum of the exported water to the hub must equal the sum of the water imported from the hub. Equation 13 is the contaminant load balance for the centralized utility hub.

As shown by the superstructure in Figure 5, all export flowrates ($f_{\mathrm{exp}}$) are mixed in a single export cross-plant pipeline ($f_{\mathrm{CP}}$) (within the plant) before being sent to the hub. Meanwhile, the import flowrate from the centralized utility hub ($f_{\mathrm{imp}}$) will be distributed to the water network through a single import cross-plant pipeline ($g_{\mathrm{CP}}$). Both of these scenarios are represented by eqs 14 and 15. Equations 16 and 17 set the upper and lower bounds of the cross-plant flowrates to and from the centralized utility hub, respectively, with binary variables $x_{\mathrm{ind}}(k)$ and $y_{\mathrm{ind}}(k)$ indicating the existing of cross-plant pipelines. Equation 18 limits the total number of cross-plant pipelines to $N$.

$$\sum_{i\in I} f_{\mathrm{exp}}(i) = f_{\mathrm{CP}}(k) \qquad \forall k \in K \tag{14}$$

$$\sum_{j\in J} f_{\mathrm{imp}}(j) = g_{\mathrm{CP}}(k) \qquad \forall k \in K \tag{15}$$

$$\mathrm{LB_{CP}}\, x_{\mathrm{ind}}(k) \le f_{\mathrm{CP}}(k) \le \mathrm{UB_{CP}}\, x_{\mathrm{ind}}(k) \qquad \forall k \in K \tag{16}$$

$$\mathrm{LB_{CP}}\, y_{\mathrm{ind}}(k) \le g_{\mathrm{CP}}(k) \le \mathrm{UB_{CP}}\, y_{\mathrm{ind}}(k) \qquad \forall k \in K \tag{17}$$

$$\sum_{k\in K} x_{\mathrm{ind}}(k) + \sum_{k\in K} y_{\mathrm{ind}}(k) \le N \tag{18}$$

Since an indirect integration scheme is considered, no direct integration between water networks is allowed. Hence, the number of cross-plant pipelines for direct integration in eq 6 is set to zero, as given below.

$$\sum_{i\in I_k}\sum_{j\in J_{k'}} x_{\mathrm{dir}}(i,j) = 0 \qquad k \neq k' \tag{6a}$$

For indirect integration, the cross-plant piping cost in eq 7 is reformulated to eq 7a, assuming an equal Manhattan distance, $D$, for all cross-plant pipelines. A storage tank cost coefficient $H_{\mathrm{cost}}$ is also included proportional to the total hub flowrate.

$$P_{\mathrm{cost}} = D\left\{\left[p\sum_{k\in K}\frac{f_{\mathrm{CP}}(k)}{3600\rho\nu} + qx_{\mathrm{ind}}(k)\right] + \left[p\sum_{k\in K}\frac{g_{\mathrm{CP}}(k)}{3600\rho\nu} + qy_{\mathrm{ind}}(k)\right]\right\}\mathrm{AF} + \sum_{k\in K} f_{\mathrm{CP}}(k)\, H_{\mathrm{cost}} \qquad k \in K \tag{7a}$$

Equations 11 and 13 each contain a bilinear term, comprising two continuous variables, which renders the model an MINLP problem. On the basis of the linearization technique proposed by Quesada and Grossmann,[48] the bilinear term can be linearized through a reformulation−linearization technique. According to Quesada and Grossmann,[48] a tightened starting point is provided to solve for the exact MINLP model. Consequently, global optimal solution can be achieved provided that the solutions for both relaxed and exact model are equal.

## 5. Centralized Utility Hub with Wastewater Regeneration Unit

In this section, the centralized utility hub consists of regeneration unit(s) where the water source quality is improved before it is sent for further water recovery. The stored water in the

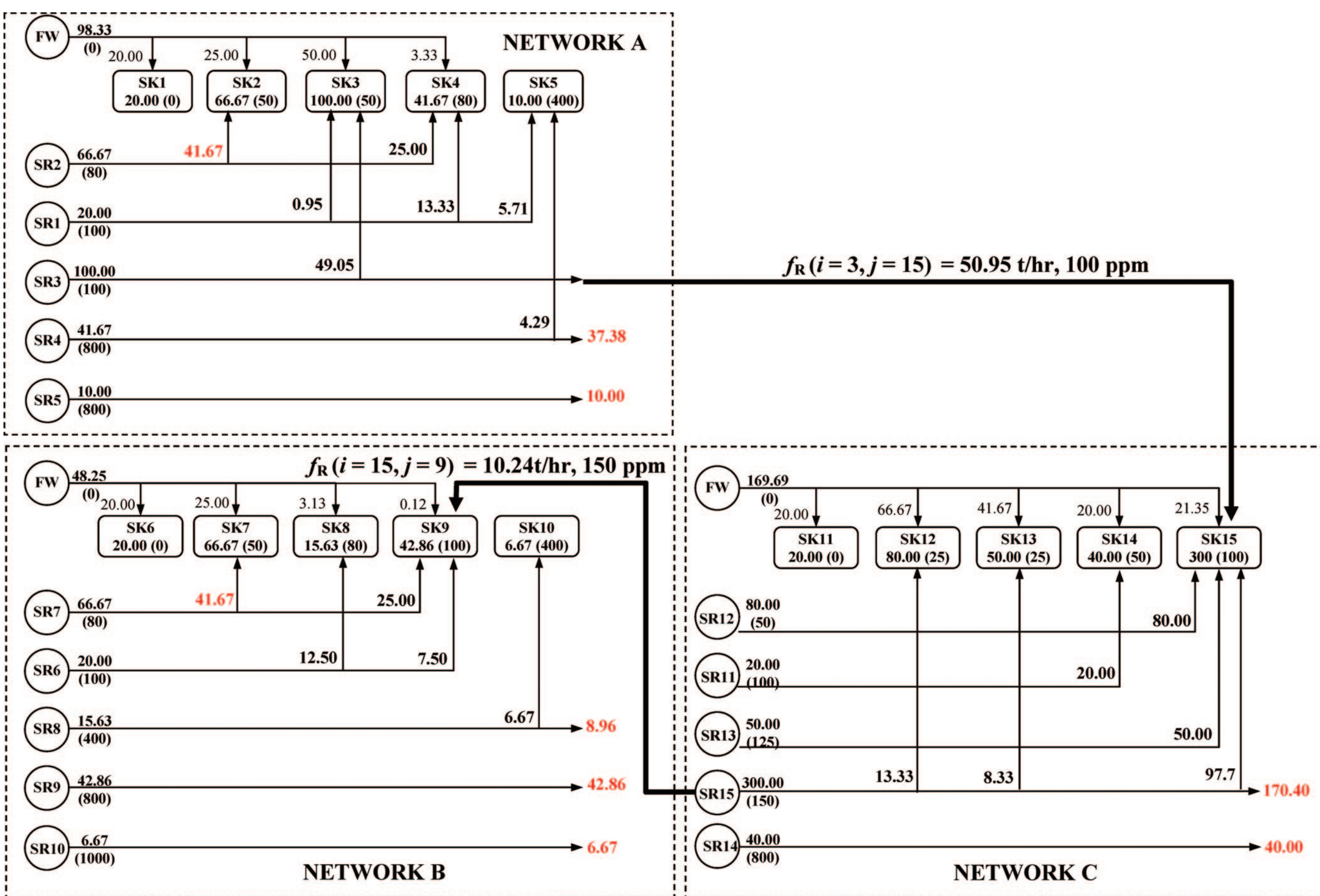


**Figure 8.** Direct integration using the proposed approach (optimized for minimum total annualized cost).

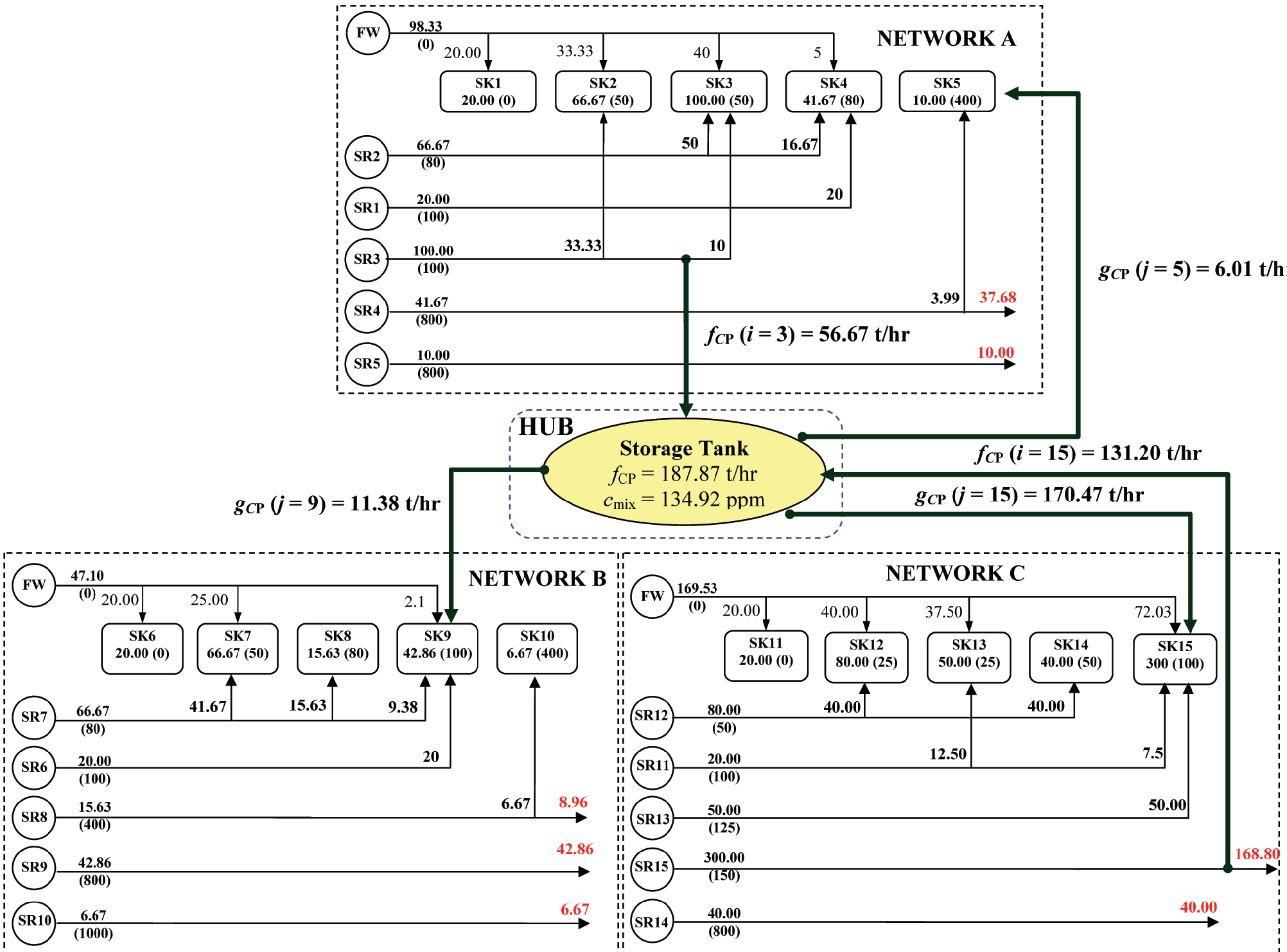


**Figure 9.** Indirect integration via utility hub (optimized for minimum fresh water flowrate).

centralized utility hub is treated to a certain concentration level before it is exported to a water network. In this work, a regeneration unit with a fixed removal ratio (RR) is used. The RR is defined as the ratio of the total contaminant mass removed, $m_{reg}$, to the total inlet contaminant load,[4] as shown at eqs 19 and 20.

$$\mathrm{RR} = \frac{\sum_{i \in I} f_{exp}(i)\, C_{SR}(c,i) - \sum_{j \in J} f_{imp}(j)\, c_{mix}(c)}{\sum_{i \in I} f_{exp}(i)\, C_{SR}(c,i)} \tag{19}$$

$$m_{reg} = \sum_{i \in I} f_{exp}(i)\, C_{SR}(c,i) - \sum_{j \in J} f_{imp}(j)\, c_{mix}(c) \tag{20}$$

When regeneration is considered, the contaminant load balance to and from the centralized utility hub in eq 13 is modified to become eq 13a:

$$\sum_{j \in J} f_{imp}(j)\, c_{mix}(c) = \sum_{i \in I} f_{exp}(i)\, C_{SR}(c,i)\,(1 - \mathrm{RR}) \qquad c \in C \tag{13a}$$

In this work, it is assumed that the cross-plant flowrates are not allowed to split before being sent to the regenerator for contaminant removal.

**5.1. Example 2.** The second example is a single contaminant problem taken from Olesen and Polley.[30] Table 2 shows the limiting data that consists of 15 process sinks and sources, respectively. The sinks and sources are segregated into three individual water networks (i.e., A, B, and C). This example is used to illustrate the aforementioned scenarios, that is, direct and indirect integration, as well as indirect integration with a water regeneration unit. The mathematical models are formulated in two mathematical optimization softwares: GAMS version 2.5 and also LINGO version 10. In GAMS, the nonlinear models are solved using DICOPT with CPLEX as the MIP solver and CONOPT as the NLP solver; while in the linear case the models were solved using CPLEX. On the other hand, LINGO with Dual Simplex solver is used to solve linear models, while mixed integer models are solved using an integer solver. In solving an MINLP model, LINGO using nonlinear and global solvers is used to obtain a global optimum solution. The model is solved using a PC with 1.66 GHz Intel Core Duo Processor.

In this example, the following assumptions are made: (1) A storage tank is readily available in the utility hub; hence, the storage tank cost coefficient $H_{cost}$ is set to zero. (2) The fresh water contains no contaminant. (3) Equal Manhattan distance of $D$ = 100 m between all water networks and the utility hub, and within different networks. (4) The capital cost for the cross-plant pipelines were annualized to a five year period, assuming a fixed interest rate of 5%. (5) Difference of piping capital cost for different reuse or recycle schemes within each plant is negligible. (6) The cross-plant flowrate lower and upper bounds are set to 5 and 300 t/h, respectively. (7) Unit cost for fresh water and effluent treatment are assumed at USD \$0.13/ton and \$0.22/ton, respectively.[49]

**5.1.1. Direct Integration.** To compare the minimum water targets obtained from the pinch approach,[32] the MILP model was first solved using the objective function in eq 1a to minimize

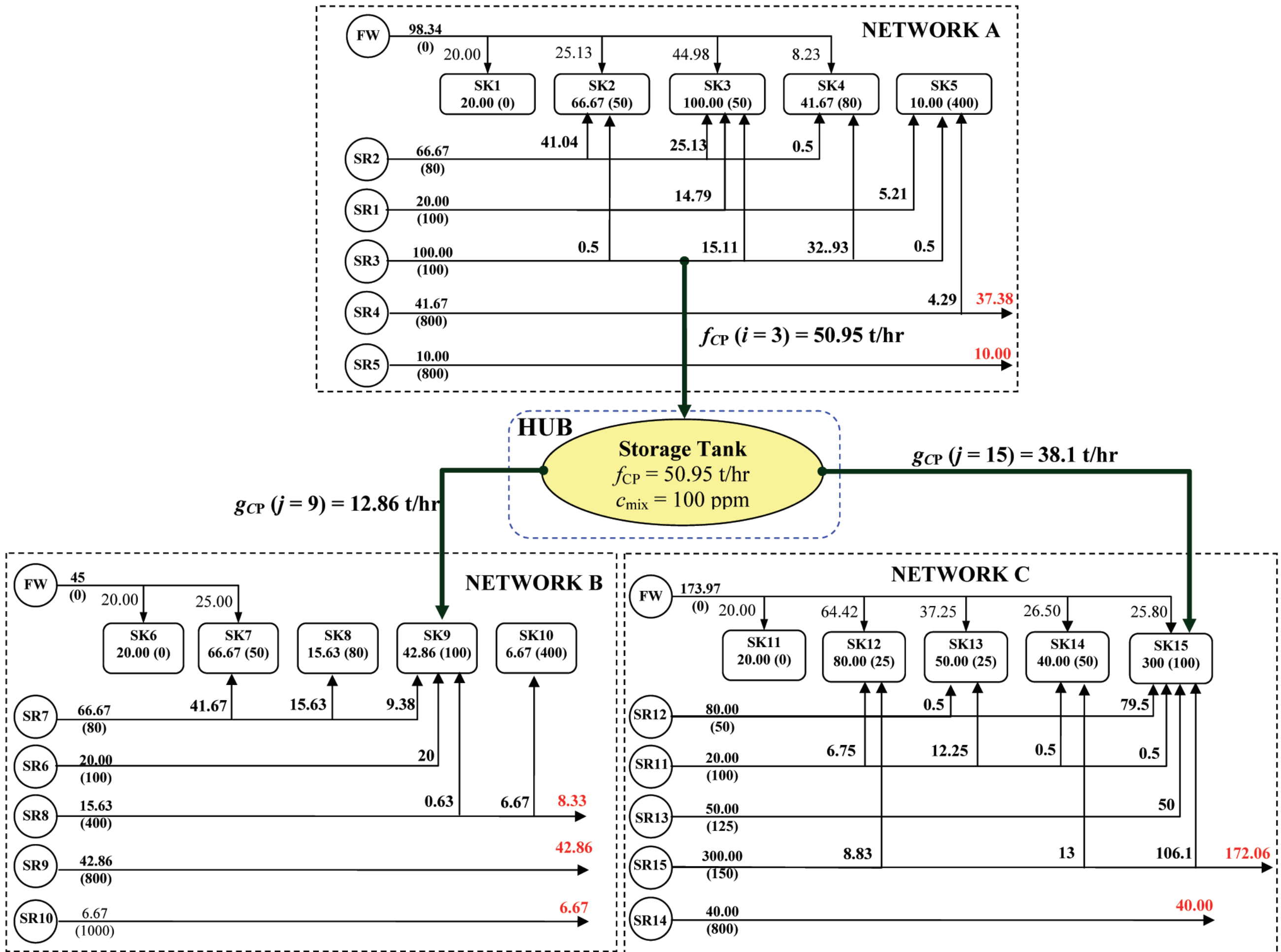


**Figure 10.** Indirect integration via utility hub (optimized for minimum total annualized cost).

**Table 5. Cost for Wastewater Stripping at Different RR**[49]

| RR | cost (\$/kg removed) |
|---|---|
| 0.1 | 0.540 |
| 0.2 | 0.695 |
| 0.3 | 0.850 |
| 0.4 | 1.005 |
| 0.5 | 1.160 |
| 0.6 | 1.460 |
| 0.7 | 1.760 |
| 0.8 | 2.060 |

the total fresh water flowrate, subject to the constraints in eqs 2−6. Equation 1a is the simplified objective function assuming cross-plant pipeline capital cost is negligible. Next, the MILP model was also solved using the objective function in eq 1 to minimize the total annualized cost, subject to the constraints in eqs 2−8.

A global optimum solution is achieved for both scenarios (i.e., fresh water and total annualized cost minimization), with the results summarized in Table 3. Results from the earlier work using the pinch targeting approach[32] are also included in the second column of Table 3. It is observed that same amount of fresh water is required (316.26 t/h) for both the pinch targeting and the mathematical optimization approaches, when the total number of cross-plant pipelines (for the latter case) is set to two ($N$ = 2). Besides, it is also observed that both the network designs possess the same cross-plant pipeline connections, as shown in Figure 6.

Analyzing the optimal solutions in Table 3, higher water savings are observed when the number of cross-plant pipelines is increased. As shown, the minimum fresh water flowrate solution is obtained when the number of cross-plant pipelines is set to three ($N$ = 3), that is, a fresh water flowrate of 314.36 t/h, with its network design shown in Figure 7. The main reason for having a lower flowrate in this approach when compared to the pinch approach[32] is that the superstructure in Figure 2 allows for all possible connections between the sinks and sources in separate networks, whereas in the pinch approach, only the net wastewater discharging from a local plant network may be integrated with sinks in another plant network.[32] Note also that adding an extra cross-plant pipeline ($N$ = 4) will not further reduce the fresh water requirement, as shown in Table 3.

Next, the MILP model is optimized by minimizing the total annualized cost using eq (1). Optimization results tabulated in Table 4 show that the minimum annualized cost for direct integration is approximated at \$0.89 million, with both minimum fresh water and wastewater flowrates at 316.26 t/h. The optimal network design obtained as shown in Figure 8.

GAMS and LINGO are used to solve the direct integration model and both generate identical solutions that ensure global optimality. The model is solved with a total of 264 continuous variables, 225 binary variables and 345 constraints.

**5.1.2. Indirect Integration.** On the other hand, the MINLP model for indirect integration scheme was first solved using objective function in eq 1a subject to constraints given in eqs 9−18 and 6a to minimize the total fresh water flowrate. As no direct integration between water networks A, B, and C is allowed in this indirect integration scheme, eq 6a is written as follows:

$$\sum_{i\in I_k}\sum_{j\in J_{k'}} x_{\text{dir}}(i,j)=0 \qquad \forall\, k\neq k',\; k\in K=\{A,B,C\} \tag{6a-i}$$

Various solutions were obtained for a given number of cross-plant pipelines, as shown in Table 3. As shown, the best network is achieved with a minimum fresh water flowrate of 314.96 t/h when the number of cross-plant pipelines is set to five (Figure 9). Notice that there is only 0.19% extra fresh water consumption that is incurred in indirect integration compared to direct integration.

Next, the MINLP model for indirect integration scheme was solved for minimum annualized cost using the objective function in eq 1 subject to constraints given in eqs 9−18, 6a, and 7a. The optimal solutions as shown in Table 4 show that the minimum annualized cost is approximated at USD \$0.90 million, with minimum fresh water consumption of 317.30 t/h. The optimal network design is shown in Figure 10 with a total of three cross-plant pipelines. An additional 1.12% total annualized cost is incurred in the indirect integration scheme when compare to the direct integration scheme. Detailed results for these models are summarized in Table 4.

GAMS/DICOPT with CPLEX as the MILP solver and CONOPT as the NLP solver is used in solving the indirect integration via the utility hub model, which entails 299 continuous variables, 231 binary variables, and 515 constraints. When the same mathematical formulation is solved using LINGO global optimization solver, global optimal solution is achieved and is identical to the solution obtained using GAMS.

Although the indirect integration scheme has the disadvantages of higher fresh water consumption (0.19%) and total annualized cost (1.12%), when compared to the direct integration scheme, the utility hub scheme will be more practical in serving larger industrial complexes, for reasons described previously. The penalty of additional water requirement and total annualized cost is easily negligible when other operational benefits, particularly with respect to ease of control and coordination resulting from network simplification, are important criteria for consideration during plant operation. Furthermore, simplified cross-plant pipelines allow better flexibility for each plant to make internal modifications (e.g., due to an increase in production capacity) as compared to direct integration schemes. This is similar to the earlier work on interplant heat integration.[35−38]

**5.1.3. Indirect Integration with Wastewater Regeneration Unit.** Using the same example as above, a more complicated scenario is considered by introducing a regeneration unit in the centralized utility hub. The regeneration cost is added to the objective function in eq 1, which then becomes eq 1b given below. The objective function in eq 1b is solved subject to the constraints given in eqs 9−20, 6a, 7a and 13a. Table 5 shows the regeneration cost at different RR of contaminant adapted from El-Halwagi.[49]

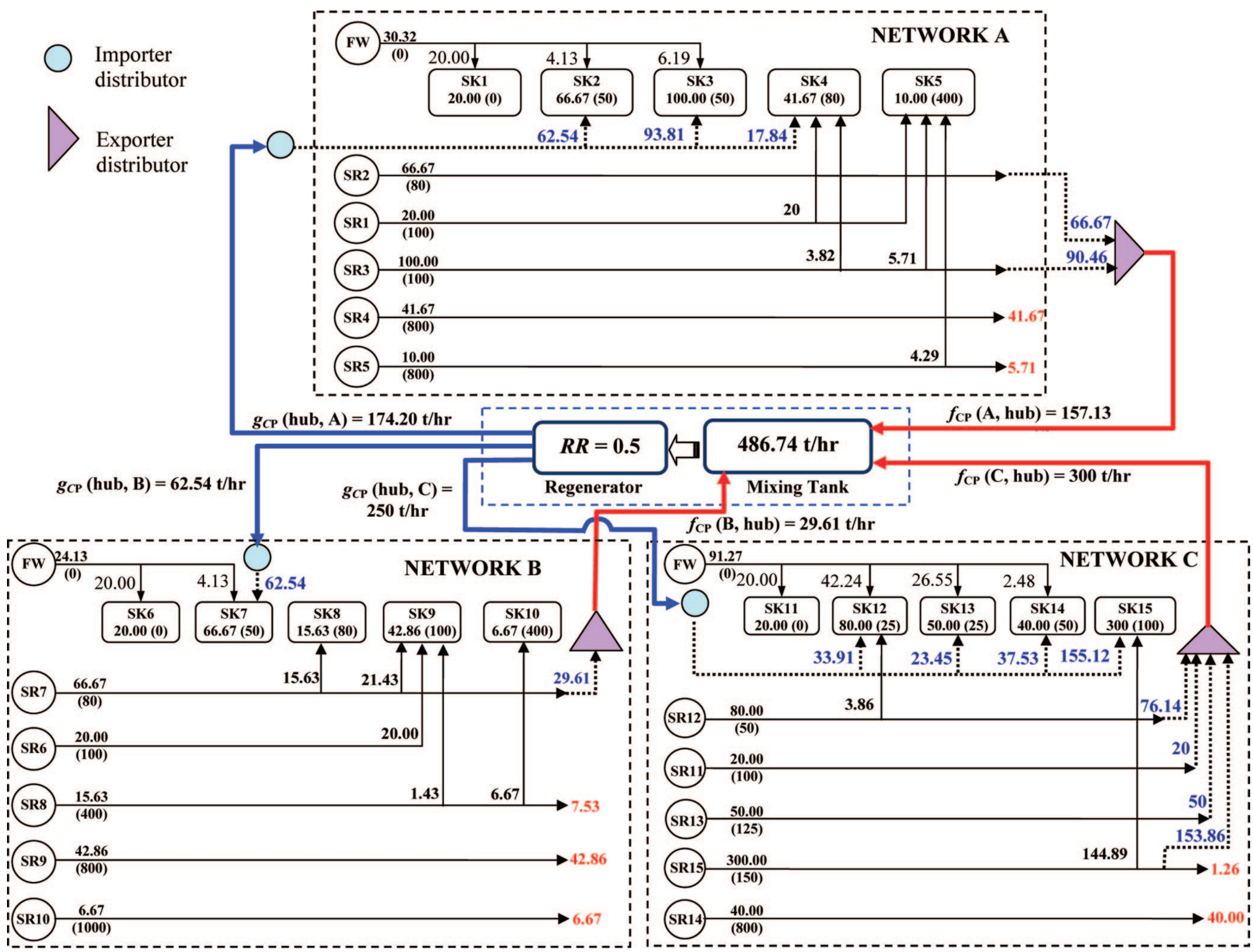


**Figure 11.** Indirect integration via utility hub with regeneration.

$$\min \text{obj}_{\text{cost}} = \left(\sum_{j\in J} f_{\text{F}}(j)\, W_{\text{cost}} + \sum_{i\in I} f_{\text{E}}(i)\, E_{\text{cost}} + m_{\text{reg}} R_{\text{cost}}\right)\text{AWH} + P_{\text{cost}} \quad (1b)$$

Table 4 summarizes the optimal solutions for various indirect integration scheme with wastewater regeneration at different RR. As the RR value is increased, both cross-plant and fresh water flowrates decrease. The former lead to reduced piping cost, while the latter reduce the operating cost. Note that the fresh water consumption remains constant for RR higher than 0.6. However, the increase of RR value also leads to higher regeneration cost. The minimum total annualized cost is achieved when the RR is set at 0.5, that is, USD \$0.72 million, with the network design given in Figure 11. In this case, the total fresh water consumption is significantly reduced to 145.69 t/h, with a total cross-plant flowrate of 486.74 t/h. GAMS/DICOPT with CPLEX as the MILP solver and CONOPT as the NLP solver was used to solve the model, which entails 299 continuous variables, 231 binary variables, and 515 constraints. Again, when the model is solved using LINGO, global optimal solution is achieved and is identical to solution obtained using GAMS.

## Conclusion

Two interplant water integration schemes are presented in this work. In the direct integration scheme, water sources may be integrated with sinks in different water networks directly. On the other hand, a new concept of indirect integration via the centralized utility hub scheme is also presented. The implementation of centralized utility hub improves the overall water network practicability and flexibility when serving a greater numbers of plants comprising the individual water network. To further improve the functionality of the centralized utility hub, a regeneration unit is introduced in the centralized utility hub with its objective to partially regenerate water for further water recovery. This leads to lower fresh water and wastewater flowrates in the overall water networks.

In future work, a dual functioning hub with a regeneration plant and raw wastewater storage tank (without wastewater regeneration) will be considered in indirect integration. Furthermore, multiple utility hubs, perhaps serving as water regeneration plants for different wastewater grades, can be included in such models. Subsequently, the optimum interplant water network with the corresponding utility hub scheme can be selected on the basis of the optimized total cost function combining both capital cost (regeneration, piping cost, etc.) and water saving (fresh water, wastewater treatment cost, etc.). Future modeling efforts can also delve into the design of networks for flexibility, to allow for seasonality of plant operations and to allow for future expansion of participating plants. In particular, uncertainties inherent in such scenarios can be incorporated into the model using fuzzy or stochastic parameters.

## Acknowledgment

The financial support from University of Nottingham through New Researcher Fund (NRF 3822/A2RBR9) and Research Studentship is gratefully acknowledged. Funding from the Ministry of Science, Technology and Innovation (MOSTI) Malaysia through Science Fund (Grant 03-02-12-SF0018) is deeply appreciated.

## Nomenclature

*Sets*

$I = \{i = 1, 2,..., N_{\text{sources}} \mid i$ is a set of process sources$\}$
$J = \{j = 1, 2,..., N_{\text{Sinks}} \mid j$ is a set of process sinks$\}$
$C = \{c \mid c$ is a contaminant$\}$
$K = \{k \mid k$ is a network$\}$

*Variables*

$f_{\text{F}}(j)$ = fresh water flowrate required by sink $j$
$f_{\text{E}}(i)$ = effluent flowrate from source $i$
$f_{\text{R}}(i,j)$ = reuse/recycle flowrate from source $i$ to sink $j$
$f_{\text{exp}}(i)$ = export flowrate from source $i$ for indirect integration
$f_{\text{imp}}(j)$ = import flowrate to sink $j$ for indirect integration
$f_{\text{CP}}(k)$ = total export cross-plant flowrate from water network $k$ to hub for indirect integration
$g_{\text{CP}}(k)$ = total import cross-plant flowrate from hub to water network $k$ for indirect integration
$c_{\text{mix}}(c)$ = concentration of contaminant $c$ of the water mixture in utility hub
$m_{\text{reg}}$ = total contaminant mass load removed through wastewater regeneration
$x_{\text{dir}}(i,j)$ = binary variable for cross-plant pipelines for direct integration
$x_{\text{ind}}(k)$ = binary variable for export cross-plant pipelines for indirect integration
$y_{\text{ind}}(k)$ = binary variable for import cross-plant pipelines for indirect integration

*Parameters*

$F_{\text{SR}}(i)$ = limiting flowrate of source $i$
$F_{\text{SK}}(j)$ = limiting flowrate of sink $j$
$C_{\text{SR}}(c,i)$ = maximum concentration of contaminant $c$ in source $i$
$C_{\text{SK}}(c,j)$ = maximum concentration of contaminant $c$ in sink $j$
$C_{\text{F}}(c)$ = concentration of contaminant $c$ in fresh water
$N$ = total number of cross-plant pipelines
$\text{LB}_{\text{CP}}$ = lower bound of cross-plant flowrate for both direct and indirect integration schemes
$\text{UB}_{\text{CP}}$ = upper bound of cross-plant flowrate for both direct and indirect integration schemes
$W_{\text{cost}}$ = fresh water unit cost
$E_{\text{cost}}$ = effluent treatment unit cost
$P_{\text{cost}}$ = total annualized capital cost for cross-plant piping
$R_{\text{cost}}$ = regeneration unit cost
$D$ = cross-plant pipelines distance
AF = annualized factor
AWH = annual working hours

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*Received for review* January 16, 2008
*Revised manuscript received* August 19, 2008
*Accepted* September 5, 2008

IE800072R