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Total Site Centralised Water Integration for Efficient Industrial Site Water Minimisation

Ahmad Fikri Ahmad Fadzil[a,b], Sharifah Rafidah Wan Alwi[a,b*], Zainuddin Abd Manan[a,b], Jiří Jaromír Klemeš[c]

[a]Process Systems Engineering Centre (PROSPECT), Research Institute of Sustainable Environment, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[b]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia
[c]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT BRNO, Technická 2896/2, 616 69 Brno, Czech Republic
syarifah@utm.my

Water is used in process industry for a wide range of applications. Water minimisation has received growing attention due to stricter environmental regulations and scarcity of quality water. Rising price of fresh water and cost of wastewater treatment, as well as the relation with the energy (generating emissions) needed for preparing and supplying water, have created an urgent need for efficient water utilisation, especially in the industrial sector. Demand for clean water has been rapidly growing also in the commercial and domestic sector, and very substantially in the agricultural sector. In some regions, water has become a strategic commodity that is even more important than energy. Numerous research works have been performed on Total Site Water Integration (also known as Interplant Water Integration in some papers). However, a superstructure that considers all possibilities of water exchange among sources and demands in industrial sites or a region, are practically challenging to implement since most plants prefer to keep their data and processes confidential. The cost of piping and pumping can be very high due to the need to transfer water across complex industrial water networks. In this study, the option of using centralised headers managed by a third party is explored for a simpler and easy to manage water reuse and recycling among plants. Two centralised water reuse headers with different wastewater quality range, located along a set of plants are proposed. A new Pinch Analysis methodology known as Total Site Centralised Water Integration (TS-CWI) to target the minimum freshwater requirement and wastewater generated resulted from the integration of plants with this centralised water reuse headers are presented. The methodology is illustrated with a case study with 55.1 % of reduction of freshwater requirement and 54.7 % of reduction of wastewater generated.

1. Introduction

Growing water scarcity, stricter environmental regulations and population growth have driven efforts towards water minimisation (Klemeš, 2012). Based on the assessment of water resources, it is estimated that by the year of 2025, water consumption will increase by 62 % (Rosegrant et al., 2002). The rising price of fresh water supply and wastewater treatment cost have created an urgent need for efficient water utilisation especially in the industrial sector (Rosegrant et al., 2002). This matter can be effectively addressed by Process Integration (PI) techniques. There are many systematic design methods developed for water minimisation such as Pinch Analysis (PA) based techniques or Mathematical Optimisation (MO) based techniques (Klemeš and Kravanja, 2013). In the context of Interplant Water Integration (IPWI), many of the works are MO-based compared to the numerical method of PA techniques. Some of the recent MO-based works of IPWI such as work on direct and indirect interplant water network by Chew et al. (2008), automated targeting for interplant water network by Chew and Foo (2009), interplant integration considering water supply constraint and water price by Jia et al. (2015), MO model for interplant water network considering treatment systems by Alnouri et al. (2015) and developed MO model for eco-industrial parks considering water quality by Tiu and Cruz (2016). There are only a few works on Total Site Water Integration (TSWI) using a numerical method such as the seminal work of flowrate targeting algorithm for unassisted integration scheme by Chew et al. (2010a) and assisted integration scheme by Chew et al. (2010b). However, both those works do not consider the proximity of the plant where it is assumed that all plants are located closely. It is also assumed that all streams of water sources and water demands can be integrated where this is not practical as there would be a lot of water interconnections (piping) and pumping which would make the water network very costly. The usage of centralised water reuse headers could minimise the number of water interconnections and pumping for TSWI and it could be managed by a third party. The idea of using header have been applied for Carbon Total Site Planning by Mohd Nawi et al. (2016). This concept can protect the confidentiality between plants. In presented paper, numerical PA-based technique methodology for Total Site Centralised Water Integration (TS-CWI) are presented to minimise the amount of freshwater required and wastewater generated.

2. Problem Statement

Total Site Centralised Water Integration (TS-CWI) involves the integration of water supply, demand and end-of-pipe treatment across the Total Site. To minimise the number of interconnections (piping) and pumping which would make a very costly water network, headers concept is introduced for TS-CWI. The TS-CWI planning problem can be stated as follows:

Given a set of plants with a set of water sources and water demands at different concentrations. The system is assumed to be a single contaminant. The plants are assumed not to have any existing water integration within its plant. All the plants are located along two centralised water reuse headers which can accept a certain range of water sources with contaminants from the plants. It is desired to determine the flowrate and contaminant concentration of the accumulated water sources in the headers which can be utilised by the plant water demands located downstream. Note that the accumulated water sources can only move in one direction along the header aided by the water pump (s). It is desired to develop a planning tool to minimise the amount of freshwater required by each of the plants after it reuses some of the water sources from either of the two headers. It is also desired to minimise the amount of wastewater sent to the centralised wastewater treatment facilities.

Figure 1 shows a case study to illustrate the methodology. The arrangement of the plant across the header is from Plant C, Plant A, Plant E, Plant B and at the end of the header is Plant D. Each plant is assumed to supply water sources into the header first before extracting water demands from the header.

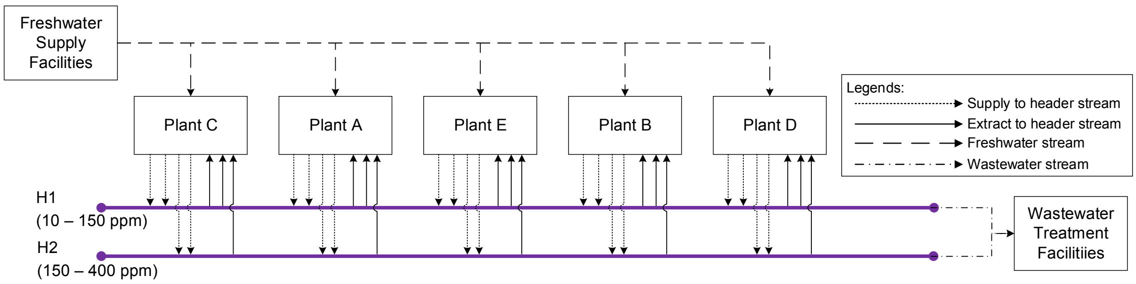

Figure 1: Illustration of TS-CWI network and arrangement of plants across the centralised water reuse header

Water reuse header refers to water pipeline system, which is heading to centralised wastewater treatment facilities as the end-of-pipe solution. Freshwater is available to be mixed with water source extracted from header to satisfy the minimum contaminant concentration required by demand operation.

3. Methodology

Methodology for targeting minimum freshwater required and wastewater generated for TS-CWI is developed using a numerical method. The detailed methodology is explained below.

3.1 Step 1: Data extraction

Data for water sources and demands are extracted from each plants located along the water header. Water source refers to wastewater generated by an operation. Water demand refers to feed water required by an operation. The limiting water data consisting of the stream flowrate and concentration of contaminant are extracted. The contaminant is a parameter for the quality of water that indicates concentration of impurities in water. It is usually measured in ppm of Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) or others.

3.2 Step 2: Water header allocation

The number of water reuse headers is based on the extracted data of water sources from each plants. For example, the first header is set for high purity water streams with a range of concentration. The second header is set for low purity water streams with a certain range of concentration. Water streams that are more than the upper limit concentration of the headers are sent directly to the centralised wastewater treatment facilities.

3.3 Step 3: Construction of Water Reuse Header (WRH) Table

The water sources from each plants are distributed according to the headers set earlier. WRH table is constructed for each header considering the amount of water source received, extracted and unutilised by each plant. The calculation is conducted based on the arrangement of plant along the headers.
The accumulated flowrate of water source received by each plant is calculated using Eq(1)

$$F_{H1,i,received} = \sum F_{i,individual\ sources} + F_{i-1,unutilised} \quad (1)$$

The accumulated mass load of water source received by each plant is calculated using Eq(2).

$$m_{H1,i,received} = \sum m_{i,sources} + m_{i-1,unutilised} \quad (2)$$

The accumulated concentration of water source received by each plant is calculated using Eq(3).

$$C_{H1,i,received} = (m_{H1,i,received})/(F_{H1,i,received}) \quad (3)$$

The amount of water source extracted by each plant is taken from individual TSC-WCT conducted in Step 4. The flowrate is taken from Column 3, concentration from Column 2 and mass load is calculated using Eq(4).

$$m_{H1,i,extracted} = (F_{H1,i,extracted})(C_{H1,i,extracted}) \quad (4)$$

The flowrate of unutilised water source is calculated using Eq(5).

$$F_{H1,i,unutilised} = F_{H1,i,received} - F_{H1,i,extracted} \quad (5)$$

The mass load of unutilised water source is calculated using Eq(6).

$$m_{H1,i,unutilised} = m_{H1,i,received} - m_{H1,i,extracted} \quad (6)$$

The concentration of unutilised water source is the same as concentration of water source extracted earlier.

3.4 Step 4: Construction of Total Site Centralised Water Cascade Table (TSC-WCT)

The TSC-WCT is constructed to determine the amount of water exchange along the headers at the Total Site, and to target, the minimum freshwater required and wastewater generated. The TSC-WCT is constructed according to the arrangement of plants across the header. The maximum water recovery targeting method by an individual plant is similar to the previous work by Foo (2007) where the lower quality sources are maximised first before the higher quality source is utilised. Freshwater is added in the next step to satisfy the remaining demand. The main difference is only the water sources limiting data are the flowrate and concentration of the headers that reached the plant based on Step 3, instead of the individual sources streams from the plant. The water demands data are based on the demand streams limiting data from the plant. To protect data confidentiality, the plant can opt to perform this step on their own and only inform the centralised system owner the final amount of water they would like to acquire from the headers.

4. Case Study

The limiting water data (a table has not been shown for brevity) is adapted from Example 2 and 4 from Chew et al. (2010a) to demonstrate the developed TS-CWI tool. From the five plants, 21 water sources and 20 water demands were identified for integration in TS-CWI. Without any integration, the initial freshwater required is 1,534.2 t/h and initial wastewater generated is 1,544.2 t/h. For this case study, two headers were set, which is Header 1 (H1) with a concentration in the range of 10 to 150 ppm and Header 2 (H2) with a concentration in the range of 150 to 400 ppm. Single contaminant system is considered. The arrangement of plants follows Figure 1.
The methodology is illustrated for Plant A. The initial freshwater required and initial wastewater generated for Plant A are 300.0 and 280.0 t/h. Based on the water header set earlier, water sources from Plant A is sent to the headers based on its concentration. For example, source S-A1 and S-A2 has a concentration lower than

150 ppm and sent to H1. After water sources are designated to its suitable header, H1 WRH table is constructed to determine the amount of H1 water source received, extracted and unutilised by Plant A as shown in Table 1 below.

Table 1: H1 WRH table of Plant A

1 Name of plant	2 Name of streams	3 Type of streams	4 Flowrate, F (t/h)	5 Concentration, C (ppm)	6 Mass load, m (t/h)
C	S-CH1	Received	564.15	52.33	29.52
	S-CH1	Extracted	-157.89	52.33	-8.26
	S-CH1	Unutilised	406.26	52.33	21.26
A	S-A1		50.0	50.0	2.5
	S-A2		100.0	100.0	10.0
	S-AH1	Received	**556.3**	**60.7**	33.8
	S-AH1	Extracted	-155.6	60.7	-9.4
	S-AH1	Unutilised	400.6	60.7	24.3

The flowrate of unutilised water source cumulated from Plant C is sent to Plant A with the flowrate of 406.3 t/h and a concentration of 52.3 ppm (see Table 1, Rows 4). The water sources from Plant A are also added to the header based on the concentration (see Table 1, Rows 5 and 6). The accumulated flowrate of H1 received by Plant A is now 556.3 t/h with a concentration of 60.7 ppm (see Table 1, Row 7). The amount of flowrate of water source extracted by Plant A from Header 1 is taken from Step 4, which is 155.6 t/h with a concentration of 60.7 ppm (see S-AH1 in Table 2). TSC-WCT is constructed to determine the amount of water exchange, and to target the minimum freshwater required and wastewater generated by Plant A. TSC-WCT for Plant A is shown in Table 2.

Table 2: TSC-WCT for Plant A

1 Name of streams	2 C (ppm)	3 F_{net} (t/h)	4 $F_{cmltv\ net}$ (t/h)	5 m_{net} (t/h)	6 $m_{cmltv\ net}$ (t/h)	7 F_{H2} (t/h)	8 F_{H1} (t/h)
			0.0				
FW-A	**0.0**	**51.1**			0.0		
			51.1	1.0			
D-A1	20.0	-50.0			1.0		
			1.1	0.0			
D-A2	50.0	-100.0			1.1		
			-98.9	-1.1			
S-AH1	**60.7**	**155.6**			0.0		
			56.8	2.2			
D-A3	100.0	-80.0			2.2		
			-23.2	-2.2			
S-AH2	**196.2**	**93.2**			0.0		0.0
			70.0	0.3			
D-A4	200.0	-70.0			0.3	70.0	1.9
			0.0	-0.3			
WW-A	1,000,000.0	0.0			0.0	0.0	0.0
			0.0	0.3			

From Table 2, minimum freshwater required is 51.1 t/h while utilising 155.6 t/h of H1 and 93.2 t/h of H2. The remaining water source of H1 and H2 that are not utilised by Plant A are sent to the next plant (see Table 1, Row 6). Plant A optimal water network is designed to achieve the minimum targeted freshwater required and wastewater generated as shown in Figure 2. Repeating the same calculation for all plants until the last plant, the minimum overall total site freshwater required is 689.2 t/h (55.1 % reduction) and the minimum wastewater generated is 699.2 t/h (54.7 % reduction). H1 generates 520.2 t/h of wastewater with a concentration of 57.5 ppm, while H2 generates 89.0 t/h of wastewater with a concentration of 282.4 ppm to be sent to the centralised wastewater treatment facilities. Source stream S-B7, S-B8 and S-E21 are sent directly to the centralised wastewater treatment facilities because the concentration exceeds the maximum limit of the headers set. The total wastewater sent to the centralised wastewater treatment facilities is 609.3 t/h with a concentration of 89.4 ppm. The optimal total site water network for the case study is shown in Figure 3.

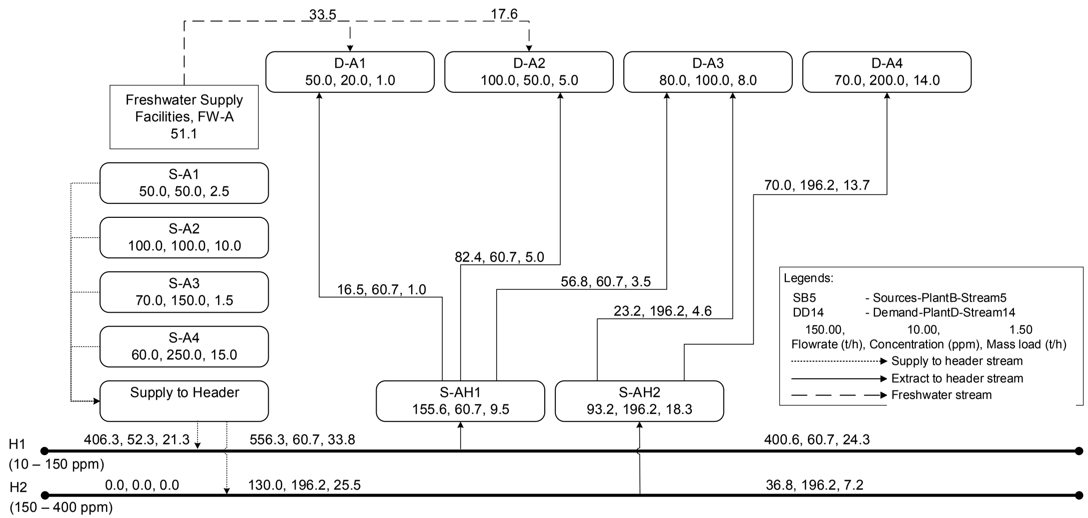

Figure 2: Plant A TS-CWI optimal water network

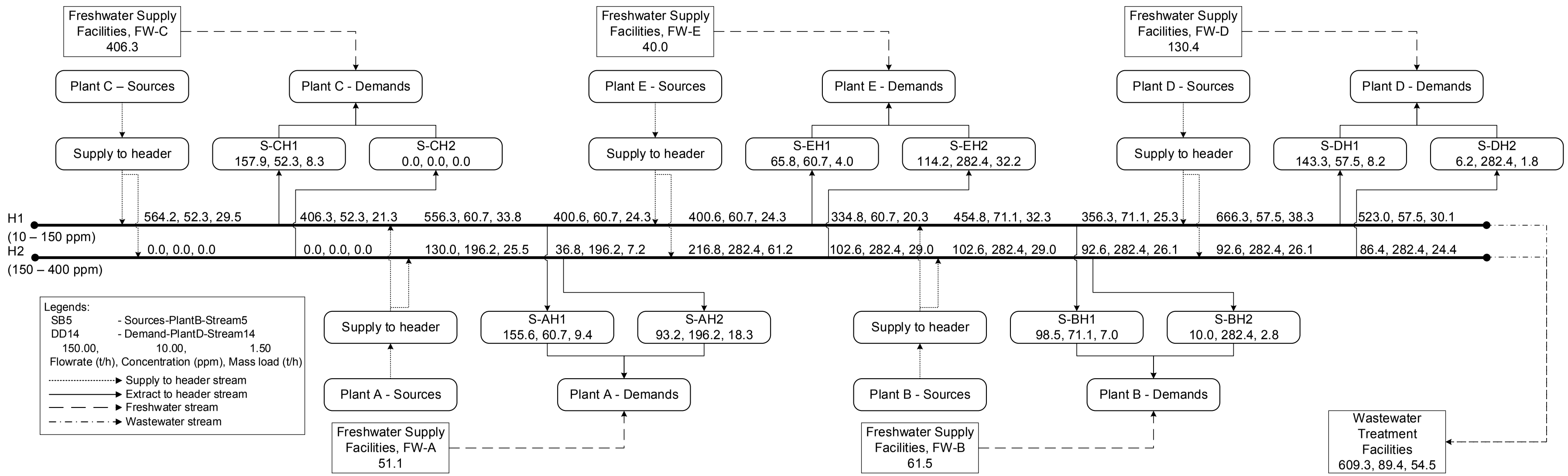

Figure 3: The case study TS-CWI optimal total site water network

5. Conclusion

The methodology for TS-CWI has been developed and utilised to address the issue of water minimisation to target the minimum freshwater required and minimum wastewater generated for a total site that is arranged across the water headers. This methodology has been applied to a case study with two centralised water reuse headers (high purity and low purity). The reduction of freshwater required and wastewater generated are 55.1 % and 54.7 %. The methodology is going to be extended for plants with existing water integration and will be presented in future work.

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