OPTIMAL DESIGN OF INTER-PLANT WATER NETWORK WITH CENTRALIZED REGENERATION SYSTEM

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for the award of the degree of
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SUPERVISOR'S DECLARATION

I/We* hereby declare that I/We* have checked this thesis/project* and in my/our opinion, this thesis/project* is adequate in terms of scope and quality for the award of degree of Bachelor of Chemical Engineering in Chemical Engineering

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I hereby declare that the work in this thesis/project* is my own except for quotations and summaries which have been duly acknowledged. The thesis/project* has not been accepted for any degree and is not concurrently submitted for award of other degree.

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ABSTRACT

Water is a basic raw material in an industry. Without it, the production cannot run or will be hindered. But, nowadays we are lacking reliable sources of water. In the future, two thirds of the world population will face water crisis or stress by the year 2025. In 2025, industrial growth will rapidly speed up, hence the sources of water will be limited. The negative effect of lack of sources of water make the cost of the water will be increasing. Hence, a new model has been developing based on water network superstructure to simultaneously generate the maximum water recovery targets and design minimum water network. Nowadays, water system integration becomes the research focus, because the technology is effective for saving fresh water and reducing wastewater generation. The purpose of this study is to develop a systematic technique for designing the minimum water network for inter-plant with centralized regeneration system. This problem is formulated as mixed integer nonlinear programming (MINLP) based on water network superstructure and is implemented in Generalized Algebraic Modeling System (GAMS) in order to obtain simultaneous minimum water targets and design of water networks. The effectiveness of the proposed model is illustrated by using an industrial case study. A significant reduction of fresh water consumption and waste water generation has been achieved, illustrating the effectiveness of the proposed approach. The result show the potential maximum freshwater and wastewater reduction are 53.63% and 61.65% respectively.

ABSTRAK

Air merupakan bahan asas dalam industry. Tanpa air, pengeluaran tidak boleh beroperasi atau operasi akan terhalang. Tetapi, pada masa sekarang kita kekurangan sumber air. Pada masa akan datang, dua pertiga daripada penduduk dunia akan menghadapi krisis air atau tekanan menjelang 2025. Pada tahun 2025, pertumbuhan perindustrian yang amat pesat, maka sumber air akan menjadi semakin terhad. Kesan negative kerana sumber air yang terhad akan menjadikan kos air akan meningkat. Oleh itu, sebuah model telah dibangunkan berdasarkan superskruktur rangkaian air bagi menghasilkan sasaran pemulihan air yang maksimum serta mereka bentuk rangkaian air yang minimum. Pada hari ini, integrasi sistem air menjadi tumpuan penyelidikan kerana teknologi ini berkesan untuk menyimpan air bersih dan mengurangkan penghasilan air sisa buangan. Tujuan kajian ini adalah untuk membangunkan teknik sistematik untuk mereka bentuk rangkaian air minimum bagi antara loji-dengan sistem penjanaan semula berpusat. Masalah ini dirumuskan sebagai pengaturcaraan tidak linear (MINLP) berdasarkan superstruktur rangkaian air and dilaksanakan dalam Generalized Algebraic Modeling System (GAMS) bagi mendapatkan sasaran air yang minimum dan reka bentuk rangkaian air. Keberkesanan model yang dicadangkan adalah digambarkan dengan menggunakan kajian kes industri. Pengurangan yang ketara penggunaan air bersih dan penghasilan air sisa buangan dapat dicapai, yang menggambarkan keberkesanan pendekatan yang dicadangkan. Keputusan ini menunjukkan potensi maksimum pengurangan air bersih dan air sisa buangan adalah sebanyak 53.63% dan 61.54%.

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LIST OF SYMBOLS

i	Set of process sources
j	Set of process demand
k	Set of network
c_{mix}	Concentration of contaminant of the water mixture in utility hub
C_D	Maximum concentration of contaminant in demand j
C_S	Maximum concentration of contaminant in source i
C_W	Concentration of contaminant in freshwater
F	Reuse/recycle flow rate from source i to demand j
F_{exp}	Export flow rate from source i to demand j
F_{imp}	Import flow rate to demand j for indirect integration
F_W	Fresh water flow rate required by demand j
W	Unused portion of water source i
f_{cp}	Total export cross-plant flow rate from water network k to utility hub for indirect integration
g_{cp}	Total import cross-plant flow rate from utility hub to water network k for indirect integration
m_{reg}	Total contaminant mass load removed through wastewater regeneration
x_{ind}	Binary variable for export cross-plant pipelines for indirect integration
y_{ind}	Binary variable for import cross-plant pipelines for indirect integration
LB_{cp}	Lower bound of cross-plant flow rate for both direct and indirect integration
UB_{cp}	Upper bound of cross-plant flow rate for both direct and indirect integration

RR	Fixed removal ratio
D	Flow rate of water source *i*
S	Flow rate of water demand *j*
N	Total number of cross pipelines
F	Water flow rate entering and leaving
m	Mass load of the contaminant
Cin	Inlet concentrations of contaminant the water stream
Cout	Outlet concentrations of contaminant the water stream

LIST OF ABBREVIATIONS

GAMS	General Algebraic Modelling System
LP	Linear Program
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MTB	Mass Transfer Based
NMTB	Non Mass Transfer Based
TDS	Total Dissolve Solid
WCA	Water Cascade Analysis

CHAPTER 1

INTRODUCTION

1.1 GLOBAL WATER OUTLOOK

Most of the Earth's surface is covered in water. It covers about two-thirds of the Earth's surface which is about 70.9% but only 2.5% are fresh water. Fresh water can be defined as water with less than 0.5 parts per thousand of dissolved salts. It comes from the rain and snow that falls into a river and lakes. It also can be found in the groundwater, cave water, springs, floodplains, and wetlands. For the seawater, it contains about more than 50 parts per thousand of dissolved water make it not suitable for the life (Water: our rivers, lakes & wetlands). Figure 1.1 depicts the percentages of the sources of fresh water. Figure 1.1 show that the main sources of the fresh water is ice and snow which is about 68.7%. The second source of water is fresh groundwater (30.1%) followed by permafrost (0.86%), lakes (0.26%), soil moisture (0.05%), wetlands (0.03%) and the last is rivers which is about (0.006%).

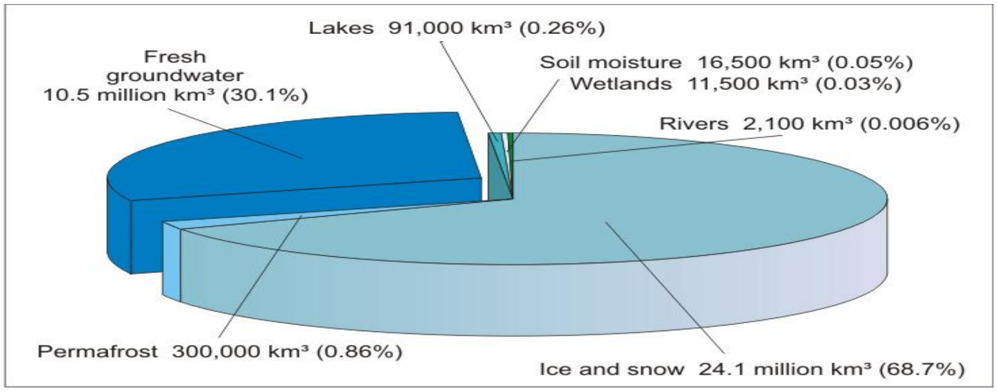

Figure 1.1: The world's fresh water resources

Water is the main part for the agriculture, industry and domestic use. Without it, for example, the plant cannot survive or will be hindered. For the industry, the operation of plant also cannot operate because majority of the plant use water. Water is mainly use in the agriculture follow by domestic, industrial and the last for reservoirs. The global water use is shown in Figure 1.2. From the figure, it is clearly shown that the highest water consumption is come from agriculture sector where the trend of water usage is increase from 1900 and it is predicted to be increased up to 3200 km2 in 2025. The second main usage of water is come from domestic sector, followed by industrial and reservoirs use.

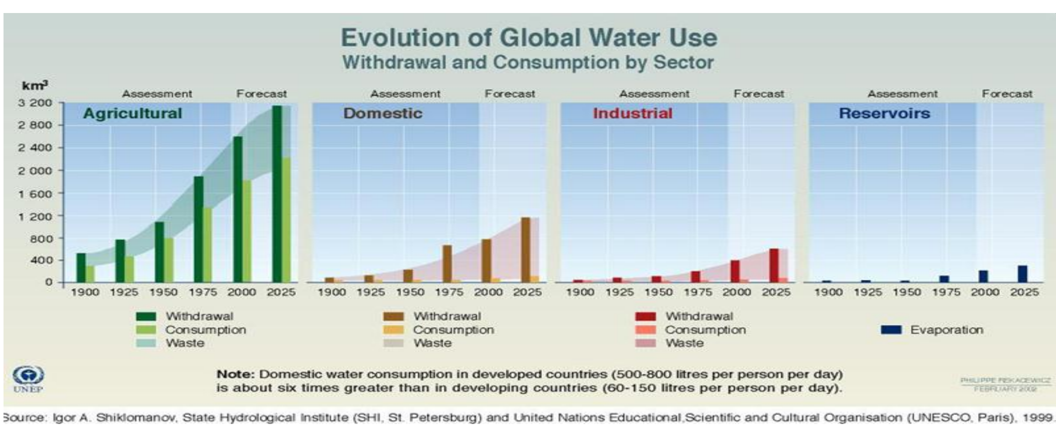

Figure 1.2: Global water uses

Figure 1.3 depicts the percentages of the water use in the world. It is clearly shows that agriculture is major sector that use water which is about 67%. The second sector of the water use is households (9%), followed by water supply (8%), electricity and gas (7%), manufacturing (2%), other (3%) and the last is mining which is about 2%.

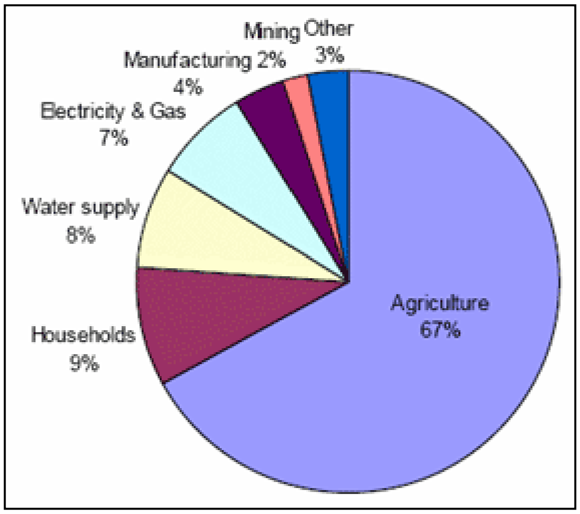

Figure 1.3: Water use in the world (2005)

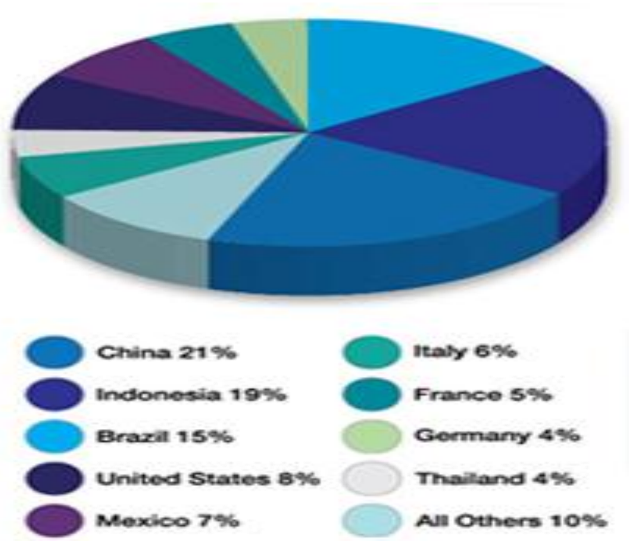

Figure 1.4: Global water uses (Pure water)

From the figure 1.4, water is mainly use in the China which is about 21% followed by Indonesia which is about 19 %. The main sector in the China is agriculture. That why this country uses a lot of fresh water in order to generate their agriculture sector.

1.2 PROBLEM STATEMENT

For the future, two third of the world population will face the water crisis or stress by year 2025. At this period, the sector of agriculture, industry and domestic will use more water. Besides that, the cost of freshwater also is increasing by year. In order to treatment the freshwater, more cost are needed because freshwater contain more contaminants. Hence, an effective measure is needed to reduce the usage of fresh water and wastewater in all sectors.

Over three decades, the main concern of wastewater is always focused on end-of-pipe treatment. Wastewater streams containing several contaminants (pH, total dissolve solid (TDS), hardness, heavy metal etc.) create an environmental pollution problem. It is important to note that end-of-pipe solutions have been employed as the only solution to meet the imposed discharge limits. However, due to water scarcity, fresh water minimization is being important agenda especially in industrial sector which also the minimization of water will also influence the wastewater minimization. Water system integration becomes the research focus, because this technology is effective for saving fresh water and reducing wastewater as it can assist organizations to maximize water saving. As a result, the current research on fresh water and wastewater minimization mainly focus on water integration.

1.3 RESEARCH OBJECTIVE

The main objective of this study is to develop the systematic technique for designing the minimum water network with centralized regeneration system.

1.4 SCOPE OF STUDY

The scope of study is focus on 3 topics. First, this study is to design an inter-plant water network. For the inter-plant, there are two types which is direct and indirect process. The centralized regeneration unit is added in indirect process. Second, this study is only focus on single contaminant which is heavy metal. Lastly, this study focuses on the method on how to solve the problem. Here, mathematical modeling method has been choosing to overcome this problem.

1.5 RATIONALE AND SIGNIFICANCE

After 2025, the industrial rapidly growth up, hence the source of water will be limited. The effect from this is cost of the freshwater also increases. Hence, to avoid this scenario happen, the wastewater from the plant can recycle and reuse in order minimize the usage of water. From water system integration technique, the cost of freshwater that needs to be paid by the plant or building owner and more money can be saved.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter recapitulates on the all article that have been read that relate to the research objectives. In here, there are three parts according to the objectives which contain mass transfer based (MTB) and non- mass transfer based (NMTB), inter plant water integration, and water system integration.

2.2 MASS TRANSFER BASED AND NONMASS TRANSFER BASED

Basically, there are two board categories which is mass transfer based (MTB) and non-mass transfer based (NMTB). For the MTB, it also knows as a fixed contaminant load problem (Handani et al., 2009). In this category, the operation is quality controlled (Polley and Polley, 2000) and water as the only mass separating agent. This principle assumes that the inlet and outlet flow rates are equal and is determined by

$$\Delta m = F\ (C_{out} - C_{in}) \qquad (2.1)$$

where m is the mass load of the contaminant, F is the water flow rate entering and leaving, and C_{in} and C_{out} are the inlet and outlet concentrations of contaminant the water stream (Yongjian et al., 2007). The examples of this operation are washing, scrubbing and extraction. For example, during cleaning, water is fed into the vessel which is as a demand while wastewater is generated will act as a source as shown in Figure 2.1.

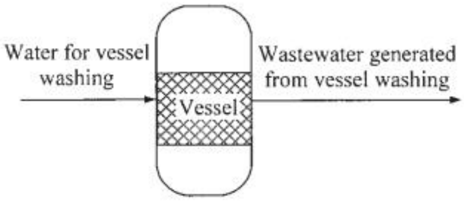

Figure 2.1: Mass transfer-based water-using operations in vessel washing

Other name of NMTB is the fixed flow rate operation which is quantity control (Polley and Polley, 2000) and it covers functions of water other than as a mass separating agent. In this category, the water flow rate is more important than the amount of contaminant accumulated. This unit has specified inlet and outlet flow rates, which may not necessarily be equal and therefore can account for water losses or generations. The outlet streams always leave at the maximum concentrations, while the inlet streams have maximum allowable concentrations (Prakash and Shenoy, 2005). The example of this operation is water is fed as a material or being withdrawn as a product or byproduct in chemical reaction as shown in Figure 2.2.

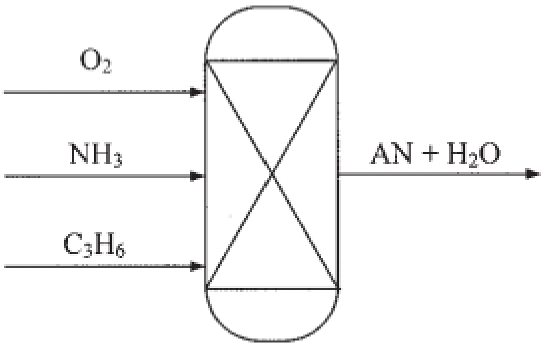

Figure 2.2: Non-mass transfer based water using operations in a reactor that produces water as a byproduct in acrylonitrile production

2.3 INTER – PLANT WATER INTEGRATION (IPWI)

The inter-plant water integration consist two or more intra-plant. Intra-plant is single water network, where water recovery is achieved by integrating water-using processes within the same network (Irene and Dominic, 2009). For inter- plant, it has two types which is direct and indirect integration. Rodera and Bagajewicz (1999) have introduced these two alternative schemes for interplant heat integration which is direct integration by using process streams and indirect integration using intermediate fluids.

2.3.1 Direct Integration

For the direct integration, water from different networks is integrated directly via cross-plant pipeline. Figure 2.3 describe the direct integration process. It shows that these schemes have 3 intra-plants at different location but connected directly using pipelines. Water from network A sent to network B and C or vise verse.

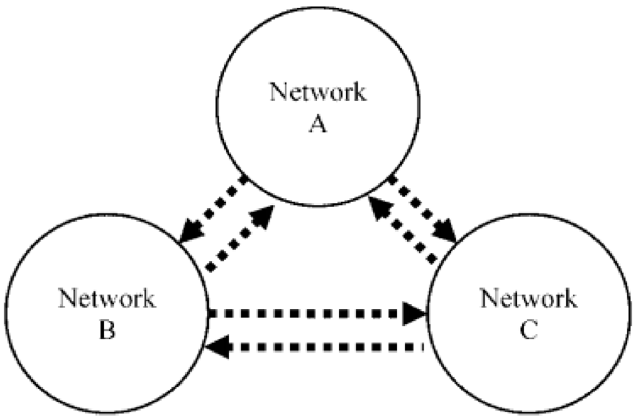

Figure 2.3: IPWI schemes (direct integration)

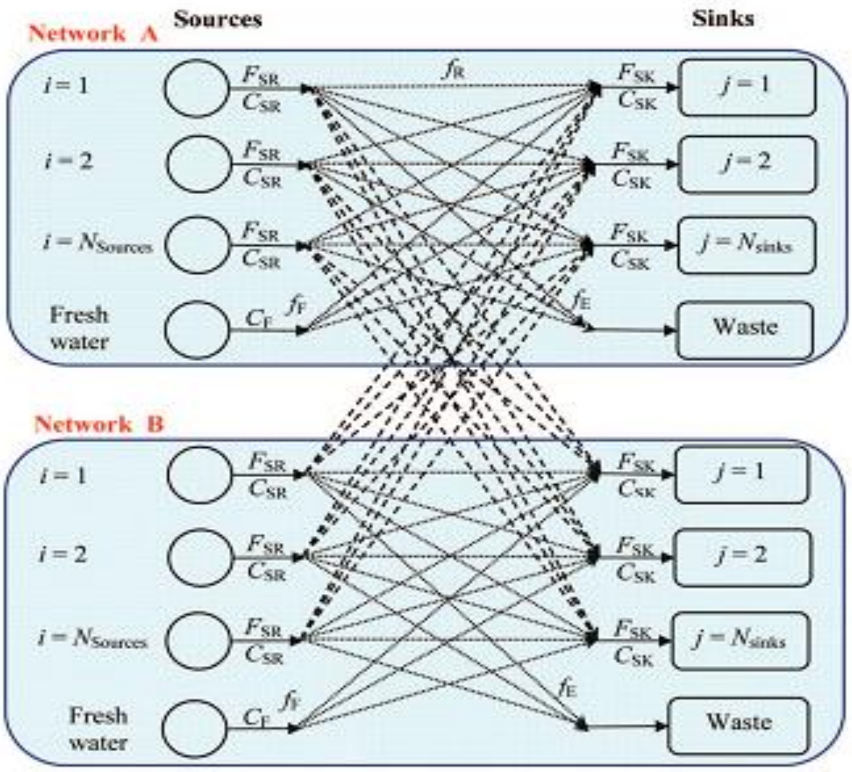

Figure 2.4: Superstructure for direct integration

Figure 2.4 depict the superstructure for direct integration. Apart from being reuse or recycle to demand, water source it can be integrated with other demand in other network. The unused water which is wastewater generation from sources will sent to the treatment before discharge to the environment.

2.3.2 Indirect Integration

In the indirect integration scheme, water networks are interconnected via a centralized utility hub that serves as a buffer as shown in Figure 2.5. 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. 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 (Irene et al., 2008).

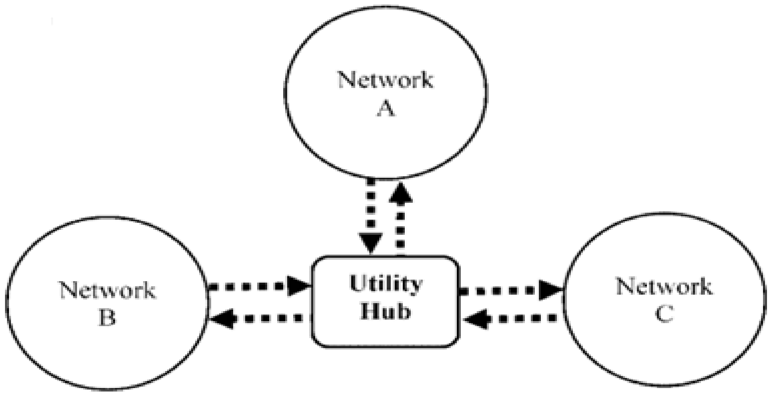

Figure 2.5: IPWI schemes (indirect integration)

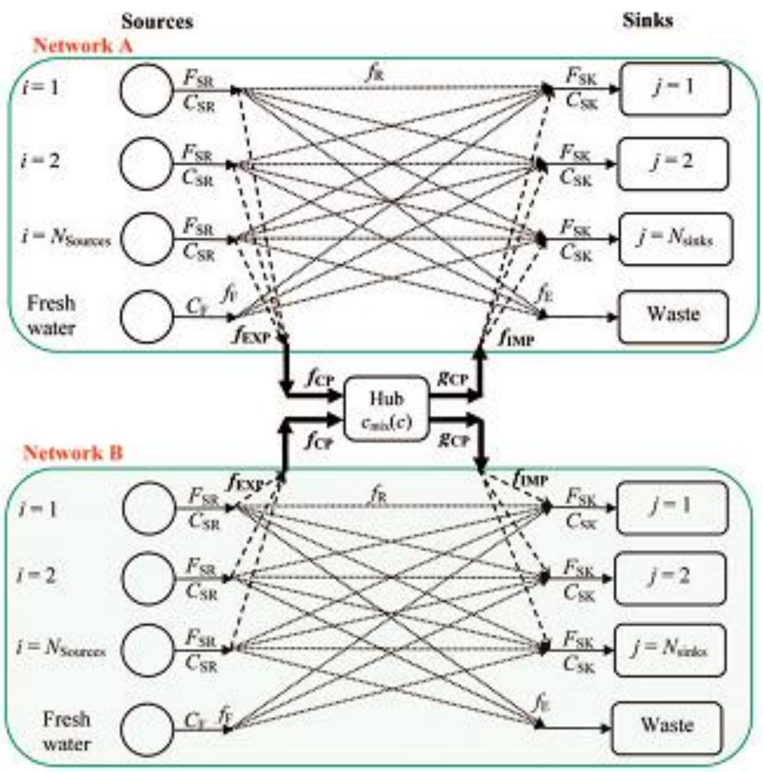

Figure 2.6: Superstructure for indirect integration

Figure 2.6 illustrate the superstructure for indirect integration process. The hub can acts as a storage tank that stores the water sources or demand for all network. Water that comes from source to hub is called as export water while water from hub to demand is called import water. The resulting of water mixture in the hub has a contaminant concentration.

2.3.2.1 Centralized Utility Hub with Wastewater Regeneration Unit

Recently, inter-plant is deal with the wastewater regeneration unit. In this scheme, the centralized utility hub consists a regeneration unit. The function of regeneration unit is to treat or improve water quality before use it again for further water recovery. The water in the centralized utility hub will be treated at a certain concentration level before export to the water network.

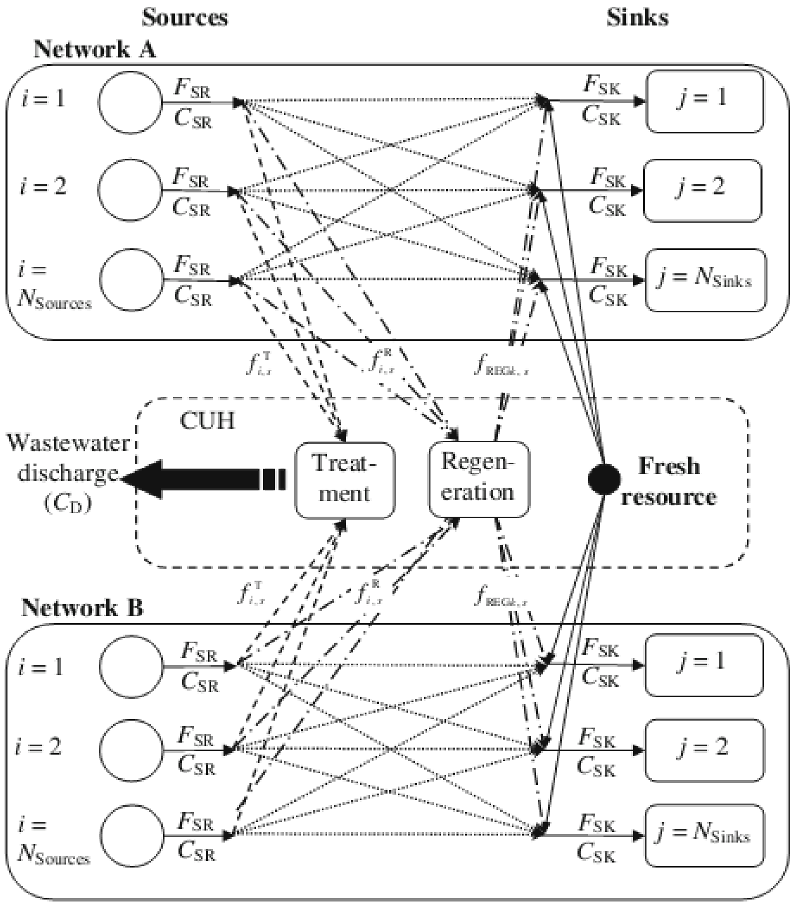

Figure 2.7: Superstructure for indirect integration via regeneration unit

2.4 WATER SYSTEM INTEGRATION

Typically, two approaches have been used to obtain good designs of these systems which are pinch analysis technology and mathematical programming.

2.4.1 Pinch Analysis Technology

In the past decades, research in water network synthesis based on insight-based pinch analysis techniques has evolved from the targeting of minimum fresh water and waste water to the targeting of minimum regeneration and wastewater treatment flow rates.

Wang and Smith (1994) proposed the first pinch-based method to maximize savings in a water network with reuse, recycling and regeneration strategies. The concept of limiting composite curves that was originally developed for utility targeting in water reuse/recycling network was extended to include targeting for network with regeneration–reuse and regeneration–recycling schemes. The minimum utility targets are located prior to detailed network design. This method is applicable for MTB water systems that involve single contaminant. The author extended their targeting and network design procedure for multiple contaminants but some of the graphical procedures for targeting and design are rather tedious since they require elaborate shifting of streams in the concentration versus mass load diagram.

Later on, Kuo and Smith (1998) pointed out that this approach may fail to obtain the true utility targets when the pinch points are relocated after regeneration. They proposed a new methodology where the minimum water targets are refined by migrating streams that have been classified into different water groups which include streams that are fed by freshwater and those that require regenerated water. The numbers of regeneration and effluent treatment units' targets were also included in their approach.

Hallale (2002) established an alternative graphical targeting method called the water surplus diagram that is applicable to NMTB. The authors located the minimum utility targets for a grassroots water network with reuse/recycle scheme and provide some guidelines for the placement of regenerations units to purify water sources and further reduce in utility consumption.

Manan et al., (2004) introduced a new method which is water cascade analysis (WCA). The WCA technique, which is based on the principles of water surplus diagram, allows quick and accurate determination of water targets as well as assessment of options for regeneration and process changes.

2.4.1.1 Advantages and Disadvantages of Pinch Analysis Technology

The main advantage of graphical pinch analysis technique is that, the various water network targets such as freshwater and wastewater flow rates and pinch location are identified ahead of detailed network design. However, this technique is often limited to single-component systems. It also becomes cumbersome as the number of streams and units increases. Additionally, the graphical technique suffers from scaling problems when the compositions or flows of the various units and streams are vastly different which can skew the representation (El-Halwagi et al., 2008).

2.4.2 Mathematical Programming

The first mathematical optimization-based approach for water regeneration was introduced by Takama et al., (1980). The authors addressed the problem of designing optimal water recovery network for a petroleum refinery by generating a superstructure of all possible re-use and regeneration opportunities. The mathematical programming technique has emerged primarily to overcome the limitations of the graphical approaches particularly for large-scale and complex problems involving multiple contaminants.

In the recent years, much research has been done to synthesize optimal water networks using the mathematical programming approach. Most of the mathematical programming approaches were based on nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP) involving multiple contaminants applicable for MTB and NMTB systems (Handani et al., 2010).

However, the non-convex NLP model is very difficult to initialize. Gunaratnam et al., (2005) proposed an automated design methodology based on the optimization of a superstructure that gives rise to a MINLP formulation. The binary variables are used to enforce certain network connections and/or to eliminate some substructures from consideration. In the first stage, a decomposition strategy divides the problem into MILP and LP problems. These are then solved in an iterative manner to provide an initial starting point that is then refined in the second stage through the solution of the general MINLP. Therefore, many authors use a solved the problem using a two stage optimization to approximate the optimal solution (Doyle et al., 1997; Teles et al., 2008; Gunaratnam et al., 2005; Putra, 2007).

Another technique to obtain a relaxed linear program (LP) formulation is reformulation linear technique by Sherali and Alameddine (1992). In this technique, the entire binary variables have to consider the bounds over the variables (Quesada and Grossman, 1995).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Based on previous study, most of multiple contaminants problems have been solved using mixed integer nonlinear programming (MINLP) in order to maximize water recovery through the centralized regeneration system. This method consists of five main steps as shown in Figure 3.1.

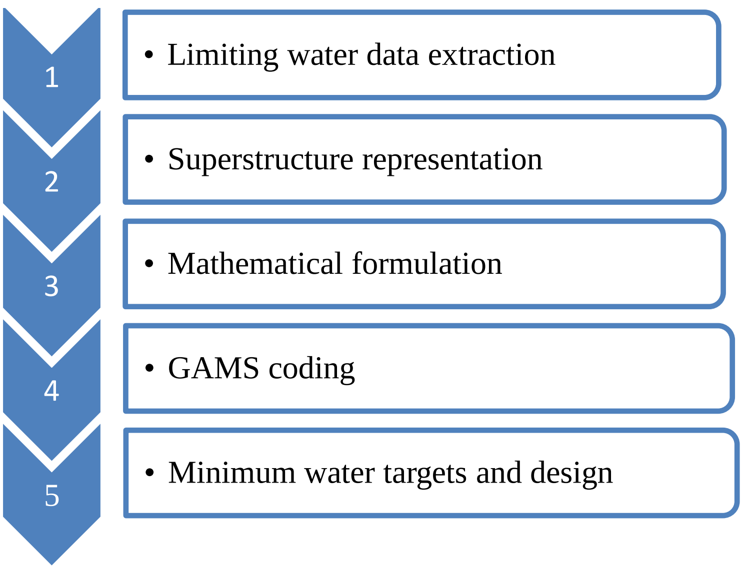

Figure 3.1: The steps of obtain minimum water targets through centralized regeneration system.

3.1.1 Step 1: Limiting Water Data Extraction

The first step is to extract and identify the limiting data from a given industrial complex. The limiting water data include limiting contaminant data and flow rate for all water sources and demands available in the system. Water that is available to recycle or reuse called it water source while water demand is the actual requirements for this operation or system. The water sources and demands were listed in terms of quantity (flow rate) and quality (contaminant concentration). For this system, the contaminant that will use is heavy metal. All contaminant concentrations of each demand and source are fixed at their maximum values.

3.1.2 Step 2: Superstructure Representation

The second step is to develop the superstructure for the water network in the plant. It is represent all the possible connection between water sources, demands and wastewater discharges from different plants. Figure 3.2 represent the superstructure for the direct process. As shown in the Figure 3.2, apart from being reuse/recycle to demand for in their network, process sources may also be integrated with demand in other networks.

Figure 3.3 represent a superstructure which is involving centralized regeneration hub options. Water demand can be obtained from the fresh water, reuse/recycle water from others operations/sources, and regenerated water from the centralized regeneration hub. The water outlets from sources can de discharge to the centralized regeneration hub before being reuse/recycle in other operations/demand. The centralized regeneration hub acts as a set of storage tank and regeneration unit that stored cross-plant wastewater flow rate before import to others operation/demand. A water sources with high concentration of contaminant need to be further treated through regeneration unit before distribute/import water to other operations/demand. Export wastewater is known when the cross-plant wastewater flow rate that is send from the sources to the centralized regeneration hub while the cross-plant regenerated water flow rate is sent from centralized regeneration hub to the demand called as an import flow rate. The resulting water mixture in the centralized regeneration hub has a contaminant concentration of $c_r(c)$.

The differences between direct and indirect integration are the cross-plant pipelines. For the direct integration, a water source from one network is integrated directly with water demands located in another network via cross-plant pipelines. However, for indirect integration, a water network is connected via centralized regeneration hub. Hence, direct water integration between different networks is forbidden.

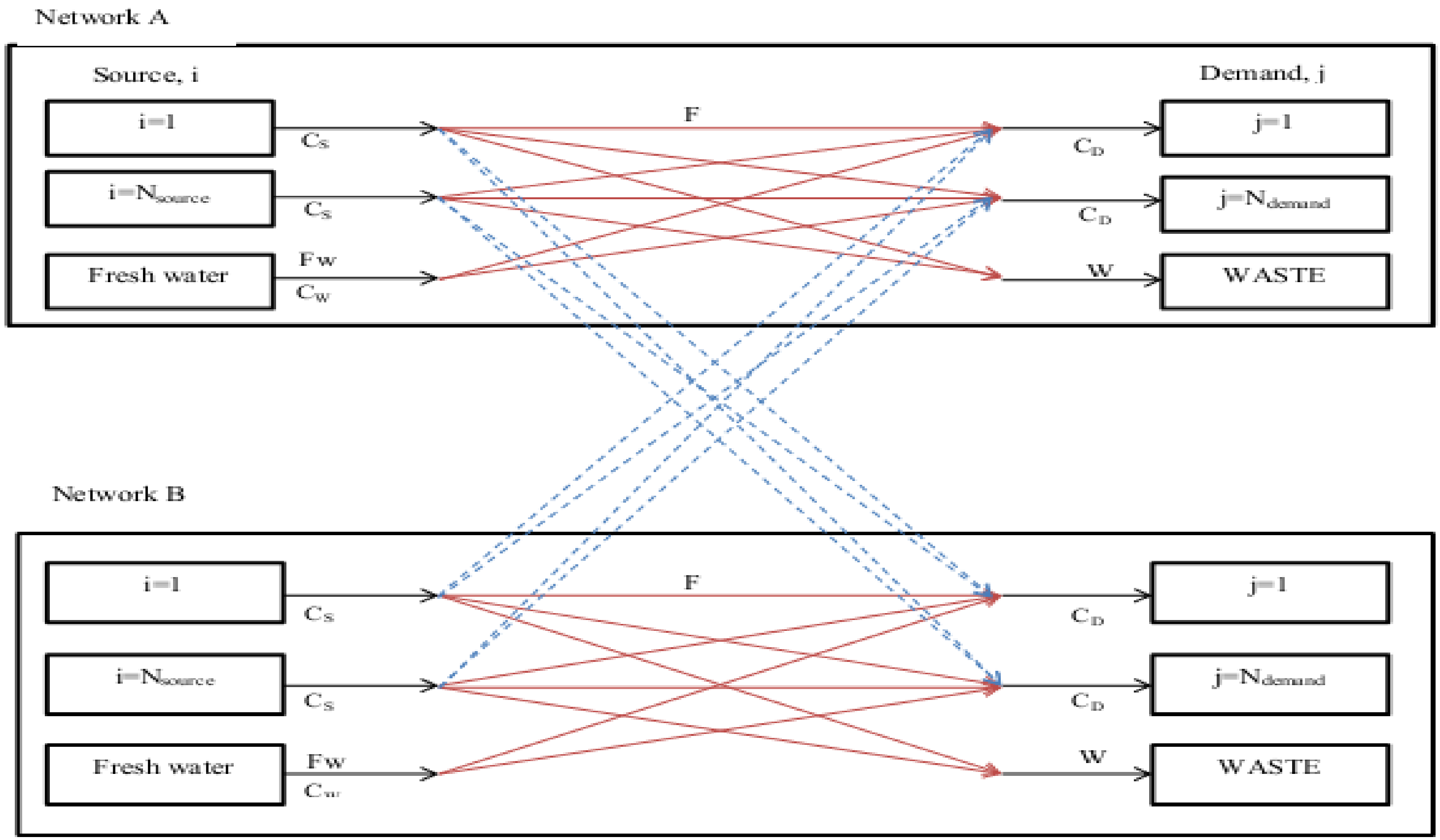

Figure 3.2: Superstructure for direct integration

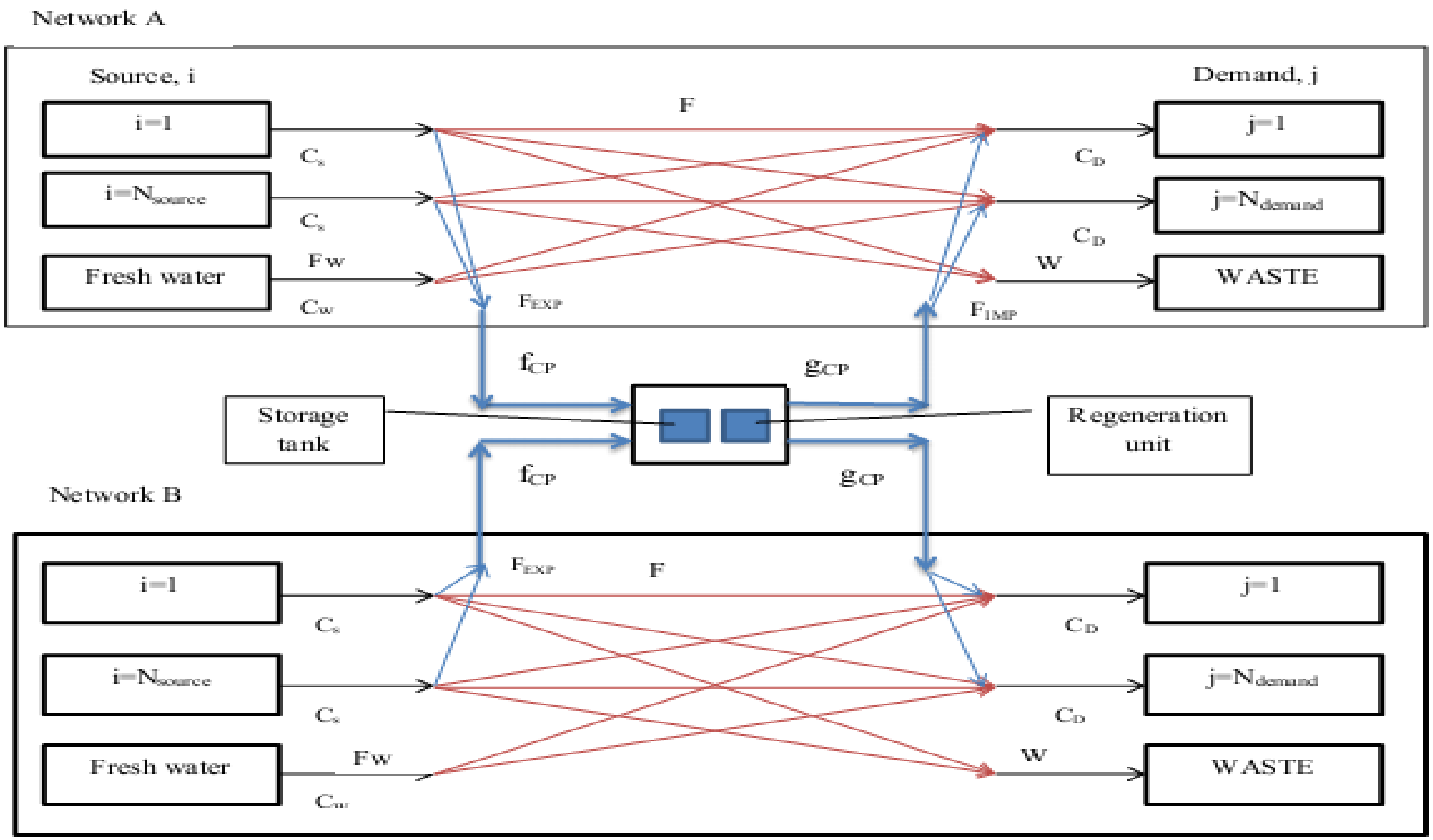

Figure 3.3: Superstructure for indirect integration via centralized regeneration hub

3.1.3 Step 3: Mathematical Formulation

3.1.3.1 Direct integration

The third step is to develop a mathematical model that corresponding the given superstructure. The objective function of the mathematical model is minimizing fresh water consumption as well as wastewater regeneration by considering all water minimization option intra-plant and inter-plant that lead the minimization of freshwater consumptions. *D (j)* and *S (i)* represent the water flow rate of a demand *j* and source *i* with a given maximum contaminant concentration, C_S *(j, c)* and C_D *(i, c)*. Let *F (i, j)* denotes potential reuse/recycle water from source *i* to demand *j*. Besides that, *W (i)* refer to wastewater flow rate from water source *i*. For a better understanding of a network superstructure, refer to Figure 3.2. The mathematical model for direct integration is formulated as follows:

a) Objective function:

The objective function is to minimize the total amount of freshwater demand, F_{wj} .

$$Min \sum_{j} Fw_j \tag{3.1}$$

b) Water balance for each demand:

For each demand *j*, the reuse/recycle water $F_{i,j}$, the water supply from freshwater F_{wj} must be equal to the desired water demand D_j.

$$\sum_{i} F(i,j) + F_W(j) = D(j) \tag{3.2}$$

c) Water balance for each source:

For each source i, the reuse/ recycle water Fi,j , and wastewater generation W_i must equal to the available water source S_i.

$$\sum_j F\,(i,j) + W(i) = S(i) \tag{3.3}$$

d) Maximum allowable contaminant load balance:

Contaminant load from demand j, is supplied from the contaminant at freshwater C_W and contaminant at reuse/recycle water C_S.

$$\sum_i F\,(i,j)C_S(i) + F_W(j)C_W \leq D(j)C_D(j) \tag{3.4}$$

3.1.3.2 Indirect Integration

The second type of IPWI is indirect integration where a centralized regeneration unit is included in the network. Export flow rate F_{exp} *(i)* is known as the cross-plant flow rate that is send the water sources i to the centralized regeneration unit. Import flow rate F_{imp} *(j)* denotes water generated at the centralized regeneration unit transfer to water demand j with quality c_r *(c)*. For a better understanding of the network superstructure, Figure 3.3 shows the details of the superstructure.

The mathematical modelling for indirect integration is developed based on the superstructure given in the Figure 3.3. The objective function for the model is same with direct integration as the given in Eq. (3.1), with the following additional constraints:

a) Water balance for each source:

For the total source flow rate *S (i)*, it must equal to the generated waste water, *W (i)* and reused/recycle water from source *i* to demand *j*, *F (i, j)* and water supply to the centralized hub F_{exp} *(i)*.

$$\sum_{j} F\,(i,j) + F_{exp}(i) + W(i) = S(i) \tag{3.5}$$

b) Water balance for each demand:

The water flow rate required for the demand, *D (j)* is fulfilled by the reused/recycle water from source i, fresh water F_w *(j)* and external water source from the centralized hub F_{exp} *(j)*.

$$\sum_{i} F(i,j) + F_{imp}(j) + F_W(j) = D(j) \tag{3.6}$$

c) Maximum allowable contaminant load balance:

Contaminant mass load for demand *j* is supplied from a different source. Hence, a mixed of contaminant mass load from different source enter the demand *j*. Thus, the contaminant for all sources must satisfy the contaminant load for demand *j*.

$$\sum_{i} F\,(i,j)C_S(i) + F_W(j)C_W + F_{imp}(j)c_r \leq D(j)C_D(j) \tag{3.7}$$

d) Overall centralized unit inlet and outlet flow rate balance:

The sum of exported water to the centralized regeneration hub must equal to the sum of imported water from centralized regeneration hub.

$$\sum_{i} F_{exp}\,(i) = \sum_{j} F_{imp}(j) \tag{3.8}$$

e) Contaminant load balance for the centralized unit:

At centralized hub, the contaminant load balance for export flow rate must equal to the contaminant load for import flow rate.

$$\sum_{i} F_{exp}(i)C_S\,(i) = \sum_{j} F_{imp}(j)c_r \tag{3.9}$$

f) Single export cross- plant pipelines balance:

All export flow rate F_{exp} are mixed in a single export cross– plant pipelines f_{CP} before sent to the centralized hub.

$$\sum_{i} F_{exp}\,(i) = f_{CP}(k) \tag{3.10}$$

g) Single import cross- plant pipelines balance:

All import flow rate F_{imp} from centralized hub will be sent to the water network k through a single import cross- plant pipelines g_{cp}.

$$\sum_{i} F_{imp}\,(j) = g_{CP}(k) \tag{3.11}$$

h) Overall centralized main inlet and outlet flow rate balance:

Single export cross- plant pipelines g_{CP} must be equal to the single import cross- plant pipelines f_{CP}.

$$f_{CP}(k) = g_{CP}(k) \tag{3.12}$$

i) Lower and upper boundary for cross- plant flow rates:

The lower and upper boundary of the cross- plant flow rates to and from flow rate the centralized hub, respectively, with binary variables x_{ind} *(k)* and y_{ind} *(k)* indicating the existing of cross- plant pipelines.

$$LB_{CP}x_{ind}(k) \leq f_{CP}(k) \leq UB_{CP}x_{ind}(k) \tag{3.13}$$

$$LB_{CP}y_{ind}(k) \leq g_{CP}(k) \leq UB_{CP}y_{ind}(k) \tag{3.14}$$

j) Limitation of total number of cross- plant pipelines:

The binary variable for import y_{ind} and export x_{ind} must be equal or less than the total of number of cross- plant pipelines *N*.

$$\sum_k x_{ind}(k) + \sum_k y_{ind}\,(k) \leq N \tag{3.15}$$

k) Fixed removal ratio:

The centralized hub is acts regeneration unit where the water source quality is improved before sent it back for further water recovery. The storage water in the centralized hub will be treated to a certain concentration level before export it to water network. Hence, the regeneration unit with fixed removal ratio (RR) is used. The *RR* is defined as the ratio of the total contaminant mass removed m_{reg} per total inlet contaminant load.

$$RR = \frac{\sum_i F_{exp}\,(i)C_S(i) - \sum_j F_{imp}(j)c_r}{\sum_i F_{exp}\,(i)C_s(i)} \tag{3.16}$$

$$m_{reg} = \sum_i F_{exp}\,(i)C_S(i) - \sum_j F_{exp}(j)c_r \tag{3.17}$$

Since regeneration is consider, the contaminant load balance to and from the centralized hub in Eq. (3.9) is modified to become Eq. (3.9a):

$$\sum_{j} F_{imp}(j) c_{mix} = \sum_{i} F_{exp}(i) C_S\,(i)(1 - RR) \tag{3.9a}$$

l) Non- negativity constraints:

The fresh water supply, waste water generation, reused/recycled water flow, and import and export water flow rate must be greater than zero. Hence, the fresh water supply, waste water generation, reused/recycled water flow, and import and export water flow rate is defined as positive value/ non- negativity variables.

$$F_W(j), W(i), F(i,j), F_{imp}(j), F_{exp}(i) \geq 0 \tag{3.18}$$

3.1.4 Step 4: GAMS Coding

The fourth step is coding the information and equation from mathematical model into General Algebraic Modeling System (GAMS) software. The problem is formulated as MILP for direct integration while MINLP for indirect integration. Through the commercial mathematical optimisation software package (GAMS), the minimum freshwater and wastewater target can be identified and the optimum water network can be found.

3.1.5 Step 5: Minimum water targets and design

Once the freshwater targets have been established, the next step is to design a minimum water network. Example of design water network is depicts on Figure 3.4. (Irene et al., 2008)

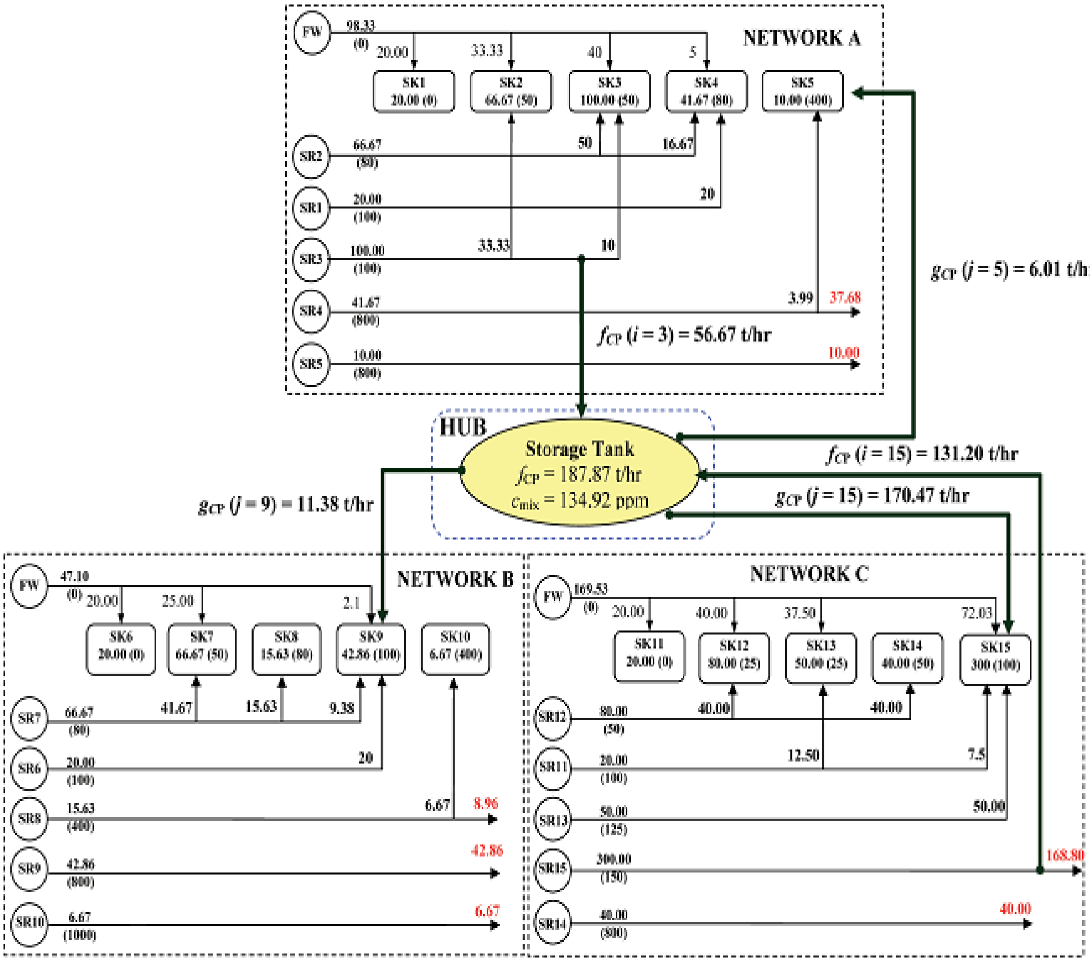

Figure 3.4: Designing of minimum water target

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter will explain the result based on the given case study. Case study for this research is wafer fabrication plant (Chew and Foo, 2009). From the result also the design of minimum water targets will also presented.

4.2 WAFER FABRICATION PLANT CASE STUDY

4.2.1 Process Description

An industrial wafer fabrication process is used to illustrate the application of the centralized regeneration unit. In this plant, they are using a pre- treatment system in order to generate ultra-pure water (UPW). 70% of the inlet flow rate of ultra-filtration to pass through the membrane as permeates, while about 30% of the flow rate is rejected as wastewater with constant water quality. Hence, to reduce the freshwater consumption, the recovery of reject stream from pre-treatment system should be considered.

Figure 4.1 depicts a schematic diagram for a wafer fabrication process with a water pre- treatment system. Here, there are four sections in the wafer fabrication plant that require UPW supply which are called “Wet”, “Lithography”, “CMP” (combined chemical and mechanical processing) and “etc.” (miscellaneous processes).

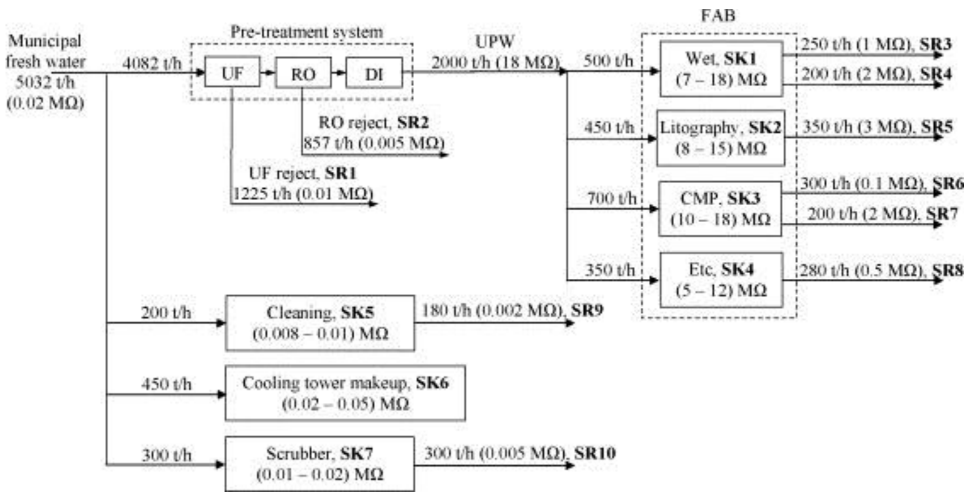

Figure 4.1: Schematic diagram for wafer fabrication plant

In this study, the pre-treatment is replaced by the centralized regeneration unit. Same function with pre-treatment which is to improve water source quality. Besides that, it involves two wafer fabrication plants. Figure 4.2 shows the inter-plant network for wafer fabrication plants.

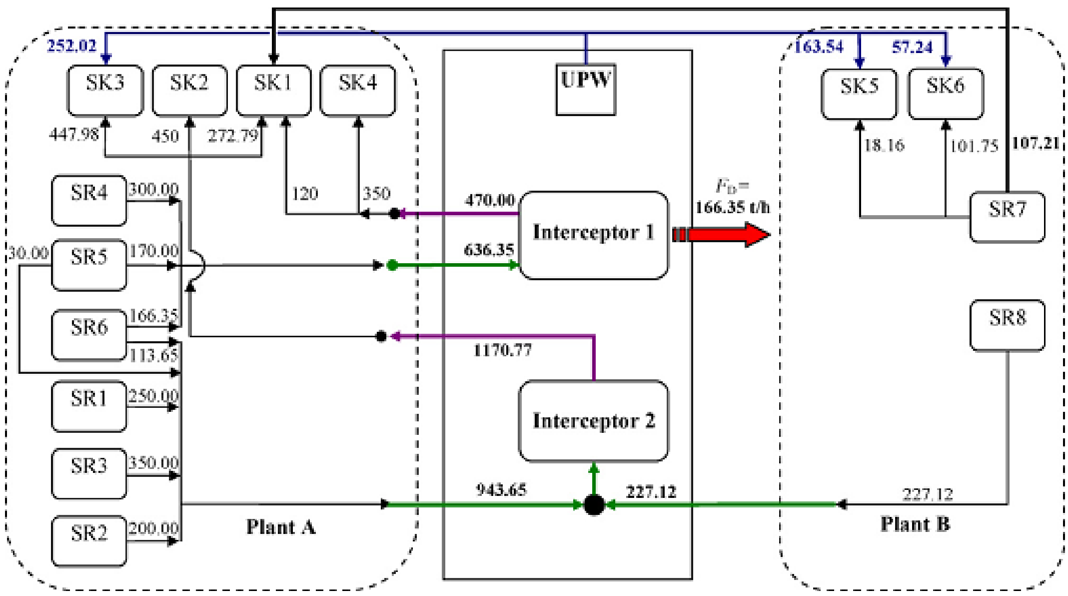

Figure 4.2: Inter-plant water network design for wafer fabrication plants

Before implemented IPWI, the total minimum of freshwater and wastewater flow rates for both network in reuse/recycle case are 1736.85 and 1430.41 ton per hour respectively. The objective function of the IPWI problem is to minimize the total amount of fresh water for demand F_{wj}. Limiting data for water sources and demand are taken from the (Irene and Dominic, 2009) and given in Table 4.1. Table 4.1 show the water sources and demand extracted for wafer fabrication plants listed in terms of flow rate and contaminant concentration. The contaminant (in ppm) represents the heavy metal.

Table 4.1: Limiting water data for wafer fabrication plants

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

For this plant, the “Wet” (I and II) , “Lithography” , “CMP”(I and II) are declare as a water source while “Water Fab”, “Wet” and CMP is called water demand. Total sources and demand for both networks are eight and six respectively. There are two network available in these plant which called A and B. For this case it only involves single contaminant which is heavy metal.

4.2.2 Direct Integration

Table 4.1 shows the limiting data for two water networks in wafer fabrication plant. In this case, it involve two plants, hence direct integration schemes are implemented. The objective function in Eq. (3.1) is solved subject to the constraints in Eq. (3.2) until Eq. (3.4). Note that from equation for direct integration; render the model of LP problem. The mathematical model was formulated in GAMS version 8 and solved using CPLEX. A 1.86 GHz Intel Pentium Dual Core Processor was used for this study.

Note that, the concentration of freshwater is assumed as free contaminant, C_W = 0 ppm. Solving the LP model yield an overall minimum freshwater flow rate of 1021.90 t/h. Wastewater generate for both networks is 765.14 t/h.

As shown in Figure 4.3, it is explain the distribution of water. Fresh water will enter the demand D1, D2, D, D5 and D6 respectively. Wastewater generation occur at source S1, S4, S7 and S8 respectively. From the Figure 4.3, it is clearly show the cross-plant from network A to network B allocated at source S1. Wastewater generate from source S1 will enter the demand D5 and D6.

4.2.3 Indirect Integration

The superstructure of indirect integration is shown in Figure 3.3. In this section, centralized regeneration unit is added in water network. Apart from being reused/recycle to demand in the local network, water source can be recycling at the regeneration unit. Then, water from regeneration unit will redistribute to other demand for both networks.

For indirect integration, there are some limitation and assumption that have been made up. Firstly, all contaminant concentration for each demand and source are fixed to their maximum values. Meaning that, the value of contaminant does not change at all. Next, there are no flow rate losses or gains, hence no changes in water flow rates. Another that, the system is operating isothermally. The assumption that have been made is the freshwater is free of contaminant (C_W= 0 ppm). Next, the cross plant flow rate for lower and upper boundary (LB_{cp} and UB_{cp}) are set to 0 and 350 t/h respectively. Besides that, the percent removal of contaminant in regeneration unit is assumed 50 % removal. Lastly, the concentration in the regeneration (c_r) unit is assumed about 3 ppm.

Based on the indirect integration model, it is render the MINLP problem. The mathematical model was formulated in GAMS version 8 and solved using DICOPT. A 1.86 GHz Intel Pentium Dual Core Processor was used for this study. Solving the objective function in Eq. (3.1) subjects to the constrains in Eq. (3.5) until Eq. (3.17), the total amount of freshwater to demand *j* is about 805.33 t/h while wastewater generated is about 548.59 t/h.

Figure 4.4 depicts the water distribution for both networks. Freshwater will distribute to demand D1, D2, D3 and D5 respectively. Source S4, S6, S7, and S8 will generate the wastewater. The water sources that will export water to the centralized regeneration unit are coming from source S1 and S6 for network A, while for network B, it come from source S7 and S8. After a few time, water from centralized regeneration unit will distribute to demand D1, D5, and D6 respectively. The total amount of water at storage tank is about 630.85 t/h. From the Figure 4.4 it is clearly show the total number of cross-plant is equal to 4.

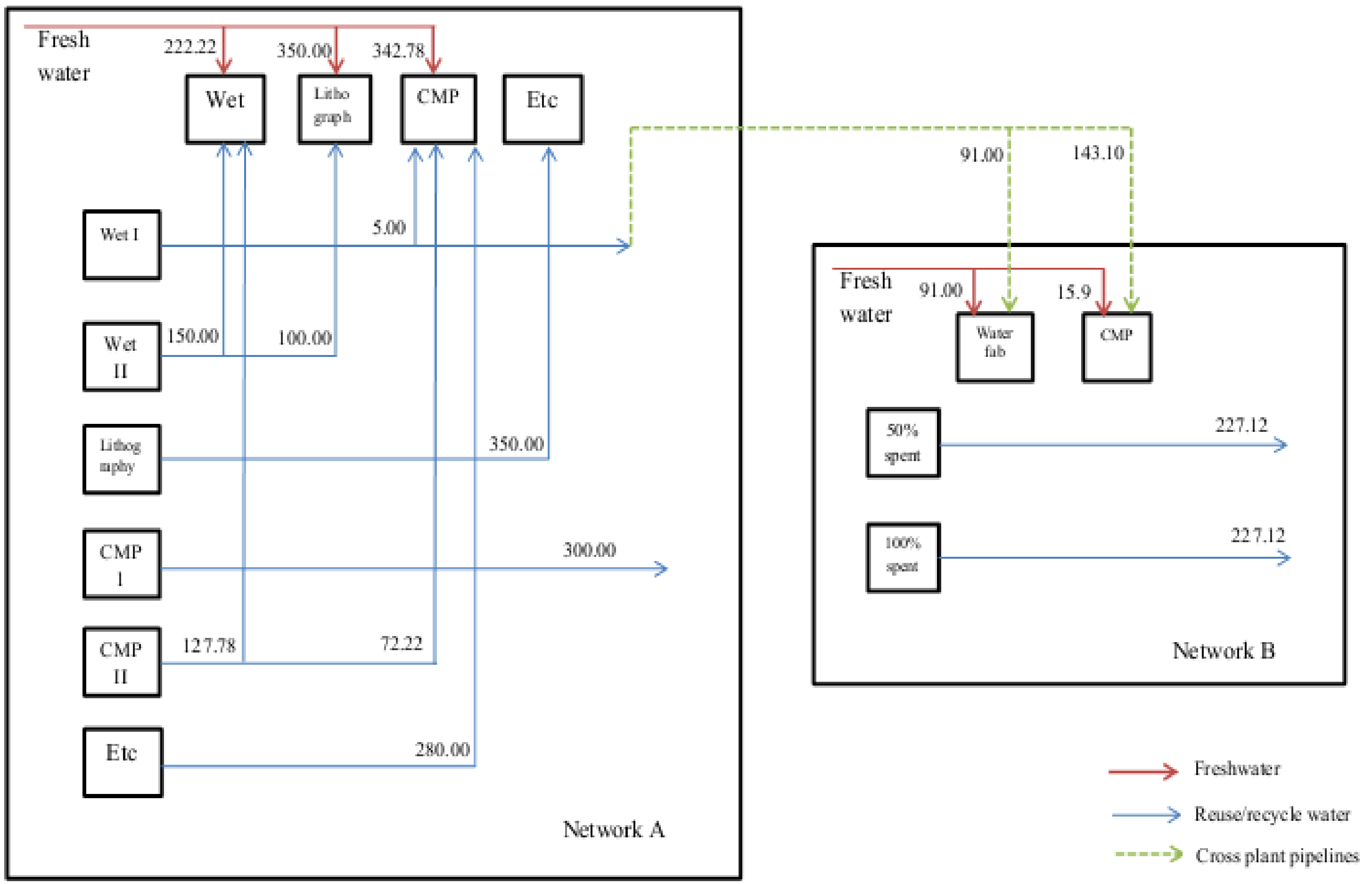

Figure 4.3: Direct integration water network design

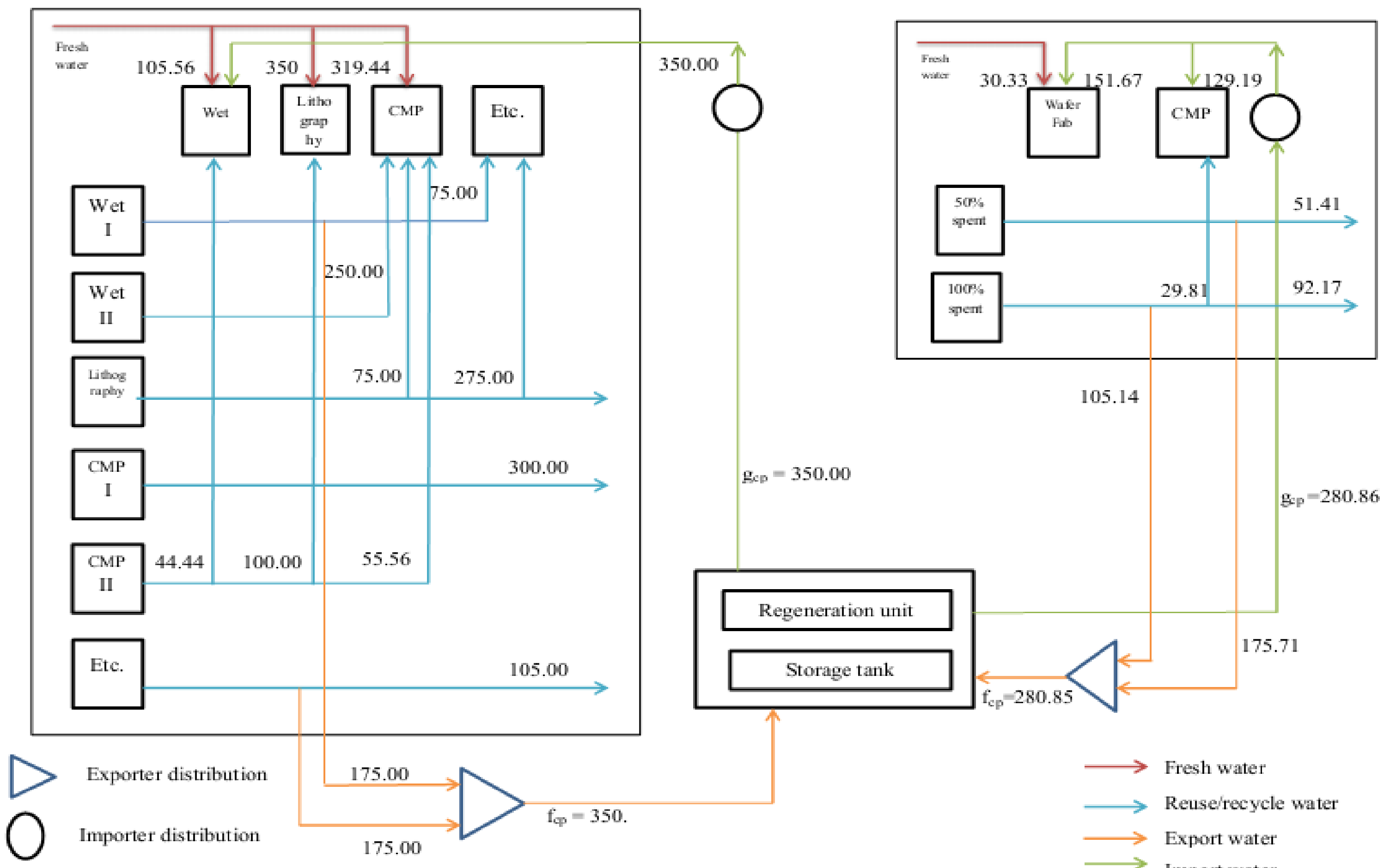

Figure 4.4: Indirect integration via centralized regeneration unit

4.2.4 Comparison between two schemes

After the direct and indirect integration have been implemented, it shows that the differences of freshwater consumption and wastewater generation. For the direct integration, freshwater consumption and wastewater generation are 1021.90 t/h and 765.14 t/h respectively. On the other hand, freshwater consumption and wastewater generation are about 805.33 t/h and 548.59 t/h. Table 2 shows the differences total amount of freshwater consumption and wastewater generation.

Table 2: Amount of freshwater and wastewater before and after IPWI

Utility	**Before IPWI (t/h)**	**After IPWI (t/h) Direct**	**After IPWI(t/h) Indirect**
Total freshwater	1736.85	1021.90	805.33
Total wastewater	1430.41	765.14	548.59

From the Table 4.2, the percentage reduction for both networks can be obtained. Percentage reduction for direct integration:

For freshwater:

$$percentage\ reduction = \frac{1736.85 - 1021.90}{1736.85} \times 100\%$$
$$= 41.16\ \%$$

For wastewater:

$$percentage\ reduction = \frac{1430.41 - 765.14}{1430.41} \times 100\%$$
$$= 46.50\ \%$$

Percentage reduction for indirect integration:

For freshwater:

$$percentage\ reduction = \frac{1736.85 - 805.33}{1736.85} \times 100\%$$
$$= 53.63\ \%$$

For wastewater:

$$percentage\ reduction = \frac{1430.41 - 548.59}{1430.41} \times 100\%$$
$$= 61.65\ \%$$

After compare the percent reduction between two schemes, it is clearly show that adding the regeneration unit for the network is a good choice. It can reduce the consumption the freshwater as well as reduce the wastewater generation.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

This section consists of two main sections. The first section is the conclusion for the research study. Here, all the result will be conclude based on the objective of study. The second section is for recommendations for the future study.

5.2 CONCLUSION

Two inter-plant water integrations have been successfully developed. For the direct integration, water sources may be integrated with sources at different network location. However, in indirect integration, water sources cannot be directly integrated. Water sources must passing through the centralized utility hub. In this research, the centralized utility hub consists of regeneration unit which is to treat the contaminant at certain level before redistribute in other demand. Based on the results that obtain from the GAMS, it can conclude based on the research objectives. A mathematical modelling approach to reduce freshwater consumption and waste water generation to achieve the maximum water recovery for systems involving single contaminant has been presented. A generic LP and MINLP model has been develop in order to solve the problem of water network based on the superstructure. The results show the maximum freshwater and wastewater reductions are 41.16% and 46.50% respectively for the direct integration. On the other hand, the percent reduction for indirect integration scheme is 53.63% for freshwater, while wastewater reduce up until 61.65%. It is show that adding a regeneration unit is a good option for the reducing the consumption of freshwater and generation of wastewater.

5.3 RECOMMENDATIOS

For sure, this research contain a certain infirmity and weaknesses while conduct this research. Therefore, the recommendation is provided in order to improve the quality of result and their effectiveness.

First, consider all the option on water management hierarchy (WMH). In this research, it only focuses on the regeneration option. Water management hierarchy consists of five levels, which are (1) source elimination, (2) source reduction, (3) direct reuse/ outsourcing of external water, (4) regeneration, and (5) use of freshwater. Figure 5.1 depicts the water management hierarchy. Each level represents various water management options where is the level are arranged in the order of priority. The most preferred option are the level 1 which is source elimination, while the least preferred are the level 5 which is use of freshwater.

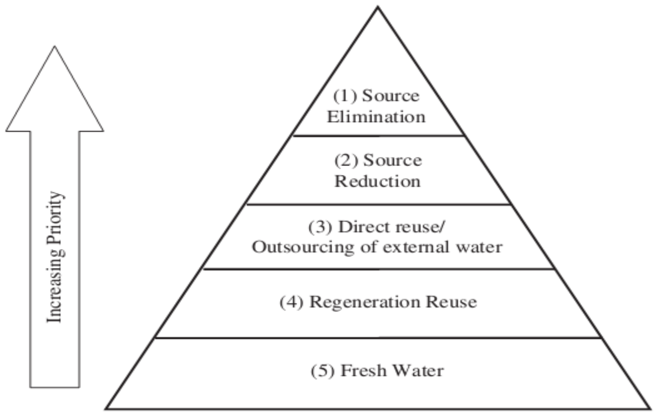

Figure 5.1: The water management hierarchy

Other improvement is adding outsources water. Example of outsources water is rainwater. It has the same function like freshwater. By adding an outsources water, the consumption of freshwater can be reduce. Hence, lead the reducing the cost of freshwater.

Another improvement can be done in this research is extend the research for the multiple contaminant. For example, consider the pH, total dissolve solid (TDS) or hardness. Besides that, adding the series of regeneration system for intra-plant and inter-plant. May be from this method, more freshwater can be save.

Lastly, extend this research by adding the costing for operation. Consider all the costing of pipelines, the cost of wastewater and so on. From here, either this model is feasible to build or not.

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The world's fresh water resources, *groundwater* (image) Retrieve January 3, 2011 from http://www.bgr.bund.de/nn_335088/EN/Themen/Wasser/Bilder/Was__wasser__startseite__abb2__g__en.html

APPENDIX A1

GAMS CODING FOR DIRECT INTEGRATION

```
SETS

  i     index for water source /1, 2, 3, 4, 5, 6, 7, 8/
  j     index for water demand /1, 2, 3, 4, 5, 6/

PARAMETERS

   S(i)   flowrate of water source in ton per hour for network A
   /1 250, 2 250, 3 350, 4 300, 5 200, 6 280, 7 227.12, 8 227.12/

   D(j)   flowrate of water demand in ton per hour for network A
   /1 500, 2 450, 3 700, 4 350, 5 182, 6 159 /

   CS(i)  source concentration in ppm for network A
   /1 5.0, 2 4.5, 3 5.0, 4 10.0, 5 4.5, 6 5.0, 7 5.0, 8 11.0/

   CD(j)  demand concentration in ppm for network A
   /1 2.5, 2 1, 3 2.5, 4 5.0, 5 2.5, 6 4.5/;

SCALAR Cw freshwater concentration /0/;
FREE VARIABLES Ftot total freshwater flowrate;
VARIABLES
  Fw(j)          flowrate of freshwater supply to demand j
  W(i)           unused portion of water source i (waste)
  F(i,j)         flowrate from source i to demand j ;

POSITIVE VARIABLES Fw(j), W(i), F(i,j) ;
EQUATIONS
  SUPPLY                    define objective function
  MASSSOURCE(i)             mass balance for each source
```

```
  MASSDEMAND(j)          mass balance for each demand
  MASSLOAD(j)            massload every internal demand
  TOTALBALANCE1          total balance for source
  TOTALBALANCE2          total balance for demand
  TOTALBALANCE3          total balance for demand mass load ;

  SUPPLY..
  Ftot =E= sum (j,Fw(j));

  MASSSOURCE(i)..
  W(i)+ sum (j,F(i,j)) =e= S(i);

  MASSDEMAND(j)..
  Fw(j)+ sum (i,F(i,j)) =e= D(j);

  MASSLOAD(j)..
  sum (i,CS(i)*F(i,j))+ Fw(j)*Cw =l= D(j)*CD(j);

  TOTALBALANCE1..
  sum (i,W(i))+ sum ((i,j),F(i,j)) =e= sum (i,S(i));

  TOTALBALANCE2..
  sum (j,Fw(j))+sum ((i,j),F(i,j)) =e= sum (j,D(j)) ;

  TOTALBALANCE3..
  sum ((i,j),CS(i)*F(i,j))+ sum (j,(Fw(j)*Cw)) =l= sum (j,D(j)*CD(j));

MODEL MWR /ALL/;
SOLVE MWR USING LP MINIMIZING Ftot  ;
DISPLAY Ftot.L, W.L, Fw.L, F.L;
```

APPENDIX A2

GAMS CODING FOR INDIRECT INTEGRATION

SETS

```
i     index for water source /1, 2, 3, 4, 5, 6, 7, 8/
j     index for water demand /1, 2, 3, 4, 5, 6/
k      index for network k /A, B/ ;
```

PARAMETERS

```
S(i)   flowrate of water source in ton per hour for network A
/1 250, 2 250, 3 350, 4 300, 5 200, 6 280/

T(i)   flowrate of water source in ton per hour for network B
/7 227.12, 8 227.12/

D(j)   flowrate of water demand in ton per hour for network A
/1 500, 2 450, 3 700, 4 350/

E(j)   flowrate of water demand in ton per hour for network B
/5 182, 6 159/

CS(i)  source concentration in ppm for network A
/1 5.0, 2 4.5, 3 5.0, 4 10.0, 5 4.5, 6 5.0/

CT(i)  source concentration in ppm for network B
/7 5.0, 8 11.0/

CD(j)  demand concentration in ppm for network A
/1 2.5, 2 1, 3 2.5, 4 5/
```

```
   CE(j)  demand concentration in ppm for network B
   /5 2.5, 6 4.5/;

SCALAR Cw freshwater concentration /0/;
*SCALAR N total number of cross plant pipeline /4/;
SCALAR LBcp lower bound of cross plant /0/;
SCALAR UBcp upper bound of cross plant /350/;
SCALAR RR fixed removal ratio /0.5/;
SCALAR Cmix concentration regen /3/;
FREE VARIABLE    Ftot    total freshwater flowrate
                 mreg
                 N       total pipelines;

VARIABLES
   FwA(j)       flowrate of freshwater supply to demand j for network A
   FwB(j)       flowrate of freshwater supply to demand j for network B
   WA(i)        unused portion of water source i for network A
   WB(i)        unused portion of water source i for network B
   FA(i,j)      flowrate from source i to demand j for network A
   FB(i,j)      flowratw from source i to demand j dor network B
   FimpA(j)     import flowrate to demand j for network A
   FimpB(j)     import flowrate to demand j for network B
   FexpA(i)     export flowrate from source i for network A
   FexpB(i)     export flowrate from source i for network B
   fcpA(k)      total export for network A
   fcpB(k)      total export for network B
   gcpA(k)      total import for network A
   gcpB(k)      total import for network B
*   Cmix        concentration of contaminant c of the water mixture in regen centralized
*  RR           fixed removal ratio for network A
*  RRB          fixed removal ratio for network B;
```

POSITIVE VARIABLES FwA(j), FwB(j), WA(i), WB(i), FA(i,j), FB(i,j), FimpA(j), FimpB(j),FexpB(i), FexpA(i), fcpA(k), fcpB(k), gcpA(k), gcpB(k);

BINARY VARIABLES xind(k) binary variable for export cross plant
yind(k) binary variable for import cross plant ;

EQUATIONS
SUPPLY define objective function
MASSSOURCEA(i) mass balance for each source for network A
MASSSOURCEB(i) mass balance for each source for network B
MASSDEMANDA(j) mass balance for each demand for network A
MASSDEMANDB(j) mass balance for each demand for network B
MASSLOADA(j) massload every internal demand for network A
MASSLOADB(j) massload every internal demand for network B
REGEN regeneration centralized balance
* RLOAD contaminant load for regeneration centralized
EXPORTA(k) export balance for A
EXPORTB(k) export balance for B
IMPORTA(k) import balance for A
IMPORTB(k) import balance for B
RBALANCE(k) overall centralized main inlet and outlet flowrate balance
LBOUNDEXPORTA(k) lower boundry for export cross plant pipelines for network A
UBOUNDEXPORTA(k) upper boundary for export cross plant pipelines for network A
LBOUNDEXPORTB(k) lower boundry for export cross plant pipelines for network B
UBOUNDEXPORTB(k) upper boundary for export cross plant pipelines for network B
LBOUNDIMPORTA(k) lower boundry for import cross plant pipelines for network A
UBOUNDIMPORTA(k) upper boundary for import cross plant pipelines for network A

```
  LBOUNDIMPORTB(k)     lower boundry for import cross plant pipelines for network
B
  UBOUNDIMPORTB(k)     upper boundary for import cross plant pipelines for
network B
  LIMITNUM             limitation of total number cross plant
  FIXEDRRA             fixed removal ratio for network A
*  FIXEDRRB            fixed removal ratio for network B
*  MREGA               total contaminant load removed through regen for network
A
*  MREGB               total contaminant load removed through regen for network
B
  MASSLOADA1           modified massload every internal demand for network A  ;
*  MASSLOADB1          modified masslad every internal demand for network B;

  SUPPLY..
  Ftot =E= sum (j,FwA(j))+ sum (j,FwB(j));

  MASSSOURCEA(i)..
  sum (j,FA(i,j))+ FexpA(i)+ WA(i) =e= S(i);

  MASSSOURCEB(i)..
  sum (j,FB(i,j))+ FexpB(i)+ WB(i) =e= T(i);

  MASSDEMANDA(j)..
  sum (i,FA(i,j))+ FimpA(j)+ FwA(j) =e= D(j);

  MASSDEMANDB(j)..
  sum (i,FB(i,j)) +FimpB(j)+ FwB(j) =e= E(j);

  MASSLOADA(j)..
  sum (i,FA(i,j)*CS(i))+ FwA(j)*Cw+ FimpA(j)*Cmix =l= D(j)*CD(j);

  MASSLOADB(j)..
```

```
  sum (i,FB(i,j)*CT(i))+ FwB(j)*Cw+ FimpB(j)*Cmix =l= E(j)*CE(j);

  REGEN..
  sum (i,FexpA(i))+ sum (i,FexpB(i)) =e= sum (j,FimpA(j))+ sum (j,FimpB(j));

* RLOAD..
* sum (i,FexpA(i)*CS(i))+ sum (i,FexpB(i)*CT(i)) =e= sum (j,FimpA(j))*Cmix+ sum
(j,FimpB(j))*Cmix;

  EXPORTA(k)..
  sum (i,FexpA(i)) =e= fcpA('A');

  EXPORTB(k)..
  sum (i,FexpB(i)) =e= fcpB('B');

  IMPORTA(k)..
  sum (j,FimpA(j)) =e= gcpA('A');

  IMPORTB(k)..
  sum (j,FimpB(j)) =e= gcpB('B');

  RBALANCE(k)..
  fcpA('A')+ fcpB('B') =e= gcpA('A')+ gcpB('B');

  LBOUNDEXPORTA(k)..
  LBcp*xind('A') =l= fcpA('A');

  UBOUNDEXPORTA(k)..
  UBcp*xind('A') =g= fcpA('A');
  LBOUNDEXPORTB(k)..
  LBcp*xind('B') =l= fcpB('B');

  UBOUNDEXPORTB(k)..
```

```
  UBcp*xind('B') =g= fcpB('B');

  LBOUNDIMPORTA(k)..
  LBcp*yind('A') =l= gcpA('A');

  UBOUNDIMPORTA(k)..
  UBcp*yind('A') =g= gcpA('A');

  LBOUNDIMPORTB(k)..
  LBcp*yind('B') =l= gcpB('B');

  UBOUNDIMPORTB(k)..
  UBcp*yind('B') =g= gcpB('B');

  LIMITNUM..
  sum (k,xind('A'))+ sum (k,yind('A'))+ sum (k,xind('B'))+ sum (k,yind('B')) =l= N;

  FIXEDRRA..
  RR*(sum (i,FexpA(i)*CS(i))+sum (i,FexpB(i)*CT(i))) =e=  (sum (i,FexpA(i)*CS(i)) +
sum (i,FexpB(i)*CT(i)))- (sum (j,FimpA(j))+sum (j,FimpB(j)))*Cmix;

*  FIXEDRRB..
*  RR*=e=  sum (i,FexpB(i)*CT(i))- sum (j,FimpB(j))*Cmix ;

*  MREGA..
*  mreg =e= (sum (i,FexpA(i)*CS(i))+sum (i,FexpB(i)*CT(i)))- (sum (j,FimpA(j))+sum
(j,FimpB(j)))*Cmix;

*  MREGB..
*  mreg =e= sum (i,FexpB(i)*CT(i))- sum (j,FimpB(j))*Cmix;

  MASSLOADA1..
```

```
sum (j,FimpA(j))*Cmix + sum (j,FimpB(j))*Cmix =e= sum (i,FexpA(i)*CS(i))*(1-RR)
+ sum (i,FexpB(i)*CT(i))*(1-RR);

MODEL MWR /ALL/;
SOLVE MWR USING MINLP MINIMIZING Ftot ;
DISPLAY Ftot.L, FwA.L, FwB.L, WA.L, WB.L, FA.L, FB.L, FimpA.L, FimpB.L,
FexpA.L, FexpB.L, fcpA.L, gcpA.L, fcpB.L, gcpB.L ;
```

APPENDIX B1

RESULT OBTAIN FROM GAMS (DIRECT INTEGRATION)

---- SUPPLY =E= define objective function

SUPPLY.. Ftot - Fw(1) - Fw(2) - Fw(3) - Fw(4) - Fw(5) - Fw(6) =E= 0 ; (LHS = 0)

---- MASSSOURCE =E= mass balance for each source

MASSSOURCE(1).. W(1) + F(1,1) + F(1,2) + F(1,3) + F(1,4) + F(1,5) + F(1,6) =E= 250 ; (LHS = 0, INFES = 250 ****)

MASSSOURCE(2).. W(2) + F(2,1) + F(2,2) + F(2,3) + F(2,4) + F(2,5) + F(2,6) =E= 250 ; (LHS = 0, INFES = 250 ****)

MASSSOURCE(3).. W(3) + F(3,1) + F(3,2) + F(3,3) + F(3,4) + F(3,5) + F(3,6) =E= 350 ; (LHS = 0, INFES = 350 ****)

REMAINING 5 ENTRIES SKIPPED

---- MASSDEMAND =E= mass balance for each demand

MASSDEMAND(1).. Fw(1) + F(1,1) + F(2,1) + F(3,1) + F(4,1) + F(5,1) + F(6,1)

+ F(7,1) + F(8,1) =E= 500 ; (LHS = 0, INFES = 500 ****)

MASSDEMAND(2).. Fw(2) + F(1,2) + F(2,2) + F(3,2) + F(4,2) + F(5,2) + F(6,2)

+ F(7,2) + F(8,2) =E= 450 ; (LHS = 0, INFES = 450 ****)

MASSDEMAND(3).. Fw(3) + F(1,3) + F(2,3) + F(3,3) + F(4,3) + F(5,3) + F(6,3)

+ F(7,3) + F(8,3) =E= 700 ; (LHS = 0, INFES = 700 ****)

REMAINING 3 ENTRIES SKIPPED

---- MASSLOAD =L= massload every internal demand

MASSLOAD(1).. 5*F(1,1) + 4.5*F(2,1) + 5*F(3,1) + 10*F(4,1) + 4.5*F(5,1)

+ 5*F(6,1) + 5*F(7,1) + 11*F(8,1) =L= 1250 ; (LHS = 0)

MASSLOAD(2).. 5*F(1,2) + 4.5*F(2,2) + 5*F(3,2) + 10*F(4,2) + 4.5*F(5,2)

+ 5*F(6,2) + 5*F(7,2) + 11*F(8,2) =L= 450 ; (LHS = 0)

MASSLOAD(3).. 5*F(1,3) + 4.5*F(2,3) + 5*F(3,3) + 10*F(4,3) + 4.5*F(5,3)

+ 5*F(6,3) + 5*F(7,3) + 11*F(8,3) =L= 1750 ; (LHS = 0)

REMAINING 3 ENTRIES SKIPPED

---- TOTALBALANCE1 =E= total balance for source

TOTALBALANCE1.. W(1) + W(2) + W(3) + W(4) + W(5) + W(6) + W(7) + W(8) + F(1,1)

+ F(1,2) + F(1,3) + F(1,4) + F(1,5) + F(1,6) + F(2,1) + F(2,2) + F(2,3)

+ F(2,4) + F(2,5) + F(2,6) + F(3,1) + F(3,2) + F(3,3) + F(3,4) + F(3,5)

+ F(3,6) + F(4,1) + F(4,2) + F(4,3) + F(4,4) + F(4,5) + F(4,6) + F(5,1)

+ F(5,2) + F(5,3) + F(5,4) + F(5,5) + F(5,6) + F(6,1) + F(6,2) + F(6,3)

+ F(6,4) + F(6,5) + F(6,6) + F(7,1) + F(7,2) + F(7,3) + F(7,4) + F(7,5)

+ F(7,6) + F(8,1) + F(8,2) + F(8,3) + F(8,4) + F(8,5) + F(8,6) =E= 2084.24

; (LHS = 0, INFES = 2084.24 ****)

---- TOTALBALANCE2 =E= total balance for demand

TOTALBALANCE2.. Fw(1) + Fw(2) + Fw(3) + Fw(4) + Fw(5) + Fw(6) + F(1,1) + F(1,2)

+ F(1,3) + F(1,4) + F(1,5) + F(1,6) + F(2,1) + F(2,2) + F(2,3) + F(2,4)

+ F(2,5) + F(2,6) + F(3,1) + F(3,2) + F(3,3) + F(3,4) + F(3,5) + F(3,6)

+ F(4,1) + F(4,2) + F(4,3) + F(4,4) + F(4,5) + F(4,6) + F(5,1) + F(5,2)

+ F(5,3) + F(5,4) + F(5,5) + F(5,6) + F(6,1) + F(6,2) + F(6,3) + F(6,4)

+ F(6,5) + F(6,6) + F(7,1) + F(7,2) + F(7,3) + F(7,4) + F(7,5) + F(7,6)

+ F(8,1) + F(8,2) + F(8,3) + F(8,4) + F(8,5) + F(8,6) =E= 2341 ;

(LHS = 0, INFES = 2341 ****)

---- TOTALBALANCE3 =L= total balance for demand mass load

TOTALBALANCE3.. 5*F(1,1) + 5*F(1,2) + 5*F(1,3) + 5*F(1,4) + 5*F(1,5) + 5*F(1,6)

+ 4.5*F(2,1) + 4.5*F(2,2) + 4.5*F(2,3) + 4.5*F(2,4) + 4.5*F(2,5)

+ 4.5*F(2,6) + 5*F(3,1) + 5*F(3,2) + 5*F(3,3) + 5*F(3,4) + 5*F(3,5)

+ 5*F(3,6) + 10*F(4,1) + 10*F(4,2) + 10*F(4,3) + 10*F(4,4) + 10*F(4,5)

+ 10*F(4,6) + 4.5*F(5,1) + 4.5*F(5,2) + 4.5*F(5,3) + 4.5*F(5,4)

+ 4.5*F(5,5) + 4.5*F(5,6) + 5*F(6,1) + 5*F(6,2) + 5*F(6,3) + 5*F(6,4)

+ 5*F(6,5) + 5*F(6,6) + 5*F(7,1) + 5*F(7,2) + 5*F(7,3) + 5*F(7,4)

+ 5*F(7,5) + 5*F(7,6) + 11*F(8,1) + 11*F(8,2) + 11*F(8,3) + 11*F(8,4)

+ 11*F(8,5) + 11*F(8,6) =L= 6370.5 ; (LHS = 0)

MODEL STATISTICS

BLOCKS OF EQUATIONS 7 SINGLE EQUATIONS 24
BLOCKS OF VARIABLES 4 SINGLE VARIABLES 63
NON ZERO ELEMENTS 323

GENERATION TIME = 0.016 SECONDS 4 Mb WIN237-237 Aug 23, 2011

EXECUTION TIME = 0.016 SECONDS 4 Mb WIN237-237 Aug 23, 2011
GAMS Rev 237 WIN-VS8 23.7.3 x86/MS Windows 01/19/12 02:40:21 Page 5
G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m
Solution Report SOLVE MWR Using LP From line 66

S O L V E S U M M A R Y

MODEL MWR OBJECTIVE Ftot
TYPE LP DIRECTION MINIMIZE
SOLVER CPLEX FROM LINE 66

**** SOLVER STATUS 1 Normal Completion
**** MODEL STATUS 1 Optimal
**** OBJECTIVE VALUE 1021.9000

RESOURCE USAGE, LIMIT 0.016 1000.000
ITERATION COUNT, LIMIT 22 2000000000

IBM ILOG CPLEX Jul 14, 2011 23.7.3 WIN 27723.27726 VS8 x86/MS Windows
Cplex 12.3.0.0

LP status(1): optimal
Optimal solution found.
Objective : 1021.900000

---- 67 VARIABLE Ftot.L = 1021.900 total freshwater flow rate

---- 67 VARIABLE W.L unused portion of water source i (waste)

1 10.900, 4 300.000, 7 227.120, 8 227.120

---- 67 VARIABLE Fw.L flowrate of freshwater supply to demand j

1 222.222, 2 350.000, 3 342.778, 5 91.000, 6 15.90

---- 67 VARIABLE F.L flowrate from source i to demand j

	1	2	3	4	5	6
1			5.000		91.000	143.100
2	150.000	100.000				
3				350.000		
5	127.778		72.222			
6			280.000			

APPENDIX B2

RESULT OBTAIN FROM GAMS (INDIRECT INTEGRATION)

---- SUPPLY =E= define objective function

SUPPLY.. Ftot - FwA(1) - FwA(2) - FwA(3) - FwA(4) - FwA(5) - FwA(6) - FwB(1)

- FwB(2) - FwB(3) - FwB(4) - FwB(5) - FwB(6) =E= 0 ; (LHS = 0)

---- MASSSOURCEA =E= mass balance for each source for network A

MASSSOURCEA(1).. WA(1) + FA(1,1) + FA(1,2) + FA(1,3) + FA(1,4) + FA(1,5)

+ FA(1,6) + FexpA(1) =E= 250 ; (LHS = 0, INFES = 250 ****)

MASSSOURCEA(2).. WA(2) + FA(2,1) + FA(2,2) + FA(2,3) + FA(2,4) + FA(2,5)

+ FA(2,6) + FexpA(2) =E= 250 ; (LHS = 0, INFES = 250 ****)

MASSSOURCEA(3).. WA(3) + FA(3,1) + FA(3,2) + FA(3,3) + FA(3,4) + FA(3,5)

+ FA(3,6) + FexpA(3) =E= 350 ; (LHS = 0, INFES = 350 ****)

REMAINING 5 ENTRIES SKIPPED

---- MASSSOURCEB =E= mass balance for each source for network B

MASSSOURCEB(1).. WB(1) + FB(1,1) + FB(1,2) + FB(1,3) + FB(1,4) + FB(1,5)

+ FB(1,6) + FexpB(1) =E= 0 ; (LHS = 0)

MASSSOURCEB(2).. WB(2) + FB(2,1) + FB(2,2) + FB(2,3) + FB(2,4) + FB(2,5)

+ FB(2,6) + FexpB(2) =E= 0 ; (LHS = 0)

MASSSOURCEB(3).. WB(3) + FB(3,1) + FB(3,2) + FB(3,3) + FB(3,4) + FB(3,5)

+ FB(3,6) + FexpB(3) =E= 0 ; (LHS = 0)

REMAINING 5 ENTRIES SKIPPED

---- MASSDEMANDA =E= mass balance for each demand for network A

MASSDEMANDA(1).. FwA(1) + FA(1,1) + FA(2,1) + FA(3,1) + FA(4,1) + FA(5,1)

+ FA(6,1) + FA(7,1) + FA(8,1) + FimpA(1) =E= 500 ;

(LHS = 0, INFES = 500 ****)

MASSDEMANDA(2).. FwA(2) + FA(1,2) + FA(2,2) + FA(3,2) + FA(4,2) + FA(5,2)

+ FA(6,2) + FA(7,2) + FA(8,2) + FimpA(2) =E= 450 ;
(LHS = 0, INFES = 450 ****)

MASSDEMANDA(3).. FwA(3) + FA(1,3) + FA(2,3) + FA(3,3) + FA(4,3) + FA(5,3)

+ FA(6,3) + FA(7,3) + FA(8,3) + FimpA(3) =E= 700 ;

(LHS = 0, INFES = 700 ****)

REMAINING 3 ENTRIES SKIPPED

---- MASSDEMANDB =E= mass balance for each demand for network B

MASSDEMANDB(1).. FwB(1) + FB(1,1) + FB(2,1) + FB(3,1) + FB(4,1) + FB(5,1)

+ FB(6,1) + FB(7,1) + FB(8,1) + FimpB(1) =E= 0 ; (LHS = 0)

MASSDEMANDB(2).. FwB(2) + FB(1,2) + FB(2,2) + FB(3,2) + FB(4,2) + FB(5,2)

+ FB(6,2) + FB(7,2) + FB(8,2) + FimpB(2) =E= 0 ; (LHS = 0)

MASSDEMANDB(3).. FwB(3) + FB(1,3) + FB(2,3) + FB(3,3) + FB(4,3) + FB(5,3)

+ FB(6,3) + FB(7,3) + FB(8,3) + FimpB(3) =E= 0 ; (LHS = 0)

REMAINING 3 ENTRIES SKIPPED

---- MASSLOADA =L= massload every internal demand for network A

MASSLOADA(1).. 5*FA(1,1) + 4.5*FA(2,1) + 5*FA(3,1) + 10*FA(4,1) + 4.5*FA(5,1)

+ 5*FA(6,1) + 3*FimpA(1) =L= 1250 ; (LHS = 0)

MASSLOADA(2).. 5*FA(1,2) + 4.5*FA(2,2) + 5*FA(3,2) + 10*FA(4,2) + 4.5*FA(5,2)

+ 5*FA(6,2) + 3*FimpA(2) =L= 450 ; (LHS = 0)

MASSLOADA(3).. 5*FA(1,3) + 4.5*FA(2,3) + 5*FA(3,3) + 10*FA(4,3) + 4.5*FA(5,3)

+ 5*FA(6,3) + 3*FimpA(3) =L= 1750 ; (LHS = 0)

REMAINING 3 ENTRIES SKIPPED

---- MASSLOADB =L= massload every internal demand for network B

MASSLOADB(1).. 5*FB(7,1) + 11*FB(8,1) + 3*FimpB(1) =L= 0 ; (LHS = 0)

MASSLOADB(2).. 5*FB(7,2) + 11*FB(8,2) + 3*FimpB(2) =L= 0 ; (LHS = 0)

MASSLOADB(3).. 5*FB(7,3) + 11*FB(8,3) + 3*FimpB(3) =L= 0 ; (LHS = 0)

REMAINING 3 ENTRIES SKIPPED

---- REGEN =E= regeneration centralized balance

REGEN.. - FimpA(1) - FimpA(2) - FimpA(3) - FimpA(4) - FimpA(5) - FimpA(6)

- FimpB(1) - FimpB(2) - FimpB(3) - FimpB(4) - FimpB(5) - FimpB(6)

+ FexpA(1) + FexpA(2) + FexpA(3) + FexpA(4) + FexpA(5) + FexpA(6)

+ FexpA(7) + FexpA(8) + FexpB(1) + FexpB(2) + FexpB(3) + FexpB(4)

+ FexpB(5) + FexpB(6) + FexpB(7) + FexpB(8) =E= 0 ; (LHS = 0)

---- EXPORTA =E= export balance for A

EXPORTA(A).. FexpA(1) + FexpA(2) + FexpA(3) + FexpA(4) + FexpA(5) + FexpA(6)

+ FexpA(7) + FexpA(8) - fcpA(A) =E= 0 ; (LHS = 0)

EXPORTA(B).. FexpA(1) + FexpA(2) + FexpA(3) + FexpA(4) + FexpA(5) + FexpA(6)

+ FexpA(7) + FexpA(8) - fcpA(A) =E= 0 ; (LHS = 0)

---- EXPORTB =E= export balance for B

EXPORTB(A).. FexpB(1) + FexpB(2) + FexpB(3) + FexpB(4) + FexpB(5) + FexpB(6)

+ FexpB(7) + FexpB(8) - fcpB(B) =E= 0 ; (LHS = 0)

EXPORTB(B).. FexpB(1) + FexpB(2) + FexpB(3) + FexpB(4) + FexpB(5) + FexpB(6)

+ FexpB(7) + FexpB(8) - fcpB(B) =E= 0 ; (LHS = 0)

---- IMPORTA =E= import balance for A

IMPORTA(A).. FimpA(1) + FimpA(2) + FimpA(3) + FimpA(4) + FimpA(5) + FimpA(6)

- gcpA(A) =E= 0 ; (LHS = 0)

IMPORTA(B).. FimpA(1) + FimpA(2) + FimpA(3) + FimpA(4) + FimpA(5) + FimpA(6)
- gcpA(A) =E= 0 ; (LHS = 0)

---- IMPORTB =E= import balance for B

IMPORTB(A).. FimpB(1) + FimpB(2) + FimpB(3) + FimpB(4) + FimpB(5) + FimpB(6)

- gcpB(B) =E= 0 ; (LHS = 0)

IMPORTB(B).. FimpB(1) + FimpB(2) + FimpB(3) + FimpB(4) + FimpB(5) + FimpB(6)

- gcpB(B) =E= 0 ; (LHS = 0)

---- RBALANCE =E= overall centralized main inlet and outlet flowrate balance

RBALANCE(A).. fcpA(A) + fcpB(B) - gcpA(A) - gcpB(B) =E= 0 ; (LHS = 0)

RBALANCE(B).. fcpA(A) + fcpB(B) - gcpA(A) - gcpB(B) =E= 0 ; (LHS = 0)

---- LBOUNDEXPORTA =L= lower boundry for export cross plant pipelines for netw
ork A

LBOUNDEXPORTA(A).. - fcpA(A) =L= 0 ; (LHS = 0)

LBOUNDEXPORTA(B).. - fcpA(A) =L= 0 ; (LHS = 0)

---- UBOUNDEXPORTA =G= upper boundary for export cross plant pipelines for net
work A

UBOUNDEXPORTA(A).. - fcpA(A) + 350*xind(A) =G= 0 ; (LHS = 0)

UBOUNDEXPORTA(B).. - fcpA(A) + 350*xind(A) =G= 0 ; (LHS = 0)

---- LBOUNDEXPORTB =L= lower boundry for export cross plant pipelines for netw
ork B

LBOUNDEXPORTB(A).. - fcpB(B) =L= 0 ; (LHS = 0)

LBOUNDEXPORTB(B).. - fcpB(B) =L= 0 ; (LHS = 0)

---- UBOUNDEXPORTB =G= upper boundary for export cross plant pipelines for net
work B

UBOUNDEXPORTB(A).. - fcpB(B) + 350*xind(B) =G= 0 ; (LHS = 0)

UBOUNDEXPORTB(B).. - fcpB(B) + 350*xind(B) =G= 0 ; (LHS = 0)

---- LBOUNDIMPORTA =L= lower boundry for import cross plant pipelines for neto
rk A

LBOUNDIMPORTA(A).. - gcpA(A) =L= 0 ; (LHS = 0)

LBOUNDIMPORTA(B).. - gcpA(A) =L= 0 ; (LHS = 0)

---- UBOUNDIMPORTA =G= upper boundary for import cross plant pipelines for net
work A

UBOUNDIMPORTA(A).. - gcpA(A) + 350*yind(A) =G= 0 ; (LHS = 0)

UBOUNDIMPORTA(B).. - gcpA(A) + 350*yind(A) =G= 0 ; (LHS = 0)

---- LBOUNDIMPORTB =L= lower boundry for import cross plant pipelines for neto
rk B

LBOUNDIMPORTB(A).. - gcpB(B) =L= 0 ; (LHS = 0)

LBOUNDIMPORTB(B).. - gcpB(B) =L= 0 ; (LHS = 0)

---- UBOUNDIMPORTB =G= upper boundary for import cross plant pipelines for net
work B

UBOUNDIMPORTB(A).. - gcpB(B) + 350*yind(B) =G= 0 ; (LHS = 0)

UBOUNDIMPORTB(B).. - gcpB(B) + 350*yind(B) =G= 0 ; (LHS = 0)

---- LIMITNUM =L= limitation of total number cross plant

LIMITNUM.. - N + 2*xind(A) + 2*xind(B) + 2*yind(A) + 2*yind(B) =L= 0 ;

(LHS = 0)

---- FIXEDRRA =E= fixed removal ratio for network A

FIXEDRRA.. 3*FimpA(1) + 3*FimpA(2) + 3*FimpA(3) + 3*FimpA(4) + 3*FimpA(5)

+ 3*FimpA(6) + 3*FimpB(1) + 3*FimpB(2) + 3*FimpB(3) + 3*FimpB(4)

+ 3*FimpB(5) + 3*FimpB(6) - 2.5*FexpA(1) - 2.25*FexpA(2) - 2.5*FexpA(3)

- 5*FexpA(4) - 2.25*FexpA(5) - 2.5*FexpA(6) - 2.5*FexpB(7) - 5.5*FexpB(8)
=E= 0 ; (LHS = 0)

---- MASSLOADA1 =E= modified massload every internal demand for network A

MASSLOADA1.. 3*FimpA(1) + 3*FimpA(2) + 3*FimpA(3) + 3*FimpA(4) +
3*FimpA(5)

+ 3*FimpA(6) + 3*FimpB(1) + 3*FimpB(2) + 3*FimpB(3) + 3*FimpB(4)

+ 3*FimpB(5) + 3*FimpB(6) - 2.5*FexpA(1) - 2.25*FexpA(2) - 2.5*FexpA(3)

- 5*FexpA(4) - 2.25*FexpA(5) - 2.5*FexpA(6) - 2.5*FexpB(7) - 5.5*FexpB(8)
=E= 0 ; (LHS = 0)

MODEL STATISTICS

BLOCKS OF EQUATIONS	24	SINGLE EQUATIONS	71
BLOCKS OF VARIABLES	18	SINGLE VARIABLES	162
NON ZERO ELEMENTS	490	NON LINEAR N-Z	0
DERIVATIVE POOL	6	CONSTANT POOL	16

CODE LENGTH 0 DISCRETE VARIABLES 4

196 VARIABLE Ftot.L = 805.333 total freshwater flowrate

196 VARIABLE FwA.L flowrate of freshwater supply to demand j for network A

1 105.556, 2 350.000, 3 319.444

196 VARIABLE FwB.L flowrate of freshwater supply to demand j for network B

5 30.333

196 VARIABLE WA.L unused portion of water source i for network A

4 300.000, 6 105.000

196 VARIABLE WB.L unused portion of water source i for network B

7 51.408, 8 92.165

196 VARIABLE FA.L flowrate from source i to demand j for network A

	1	2	3	4
1				75.000
2			250.000	
3			75.000	275.000
5	44.444	100.000	55.556	

196 VARIABLE FB.L flowratw from source i to demand j dor network B

6

8   29.813

196 VARIABLE FimpA.L import flowrate to demand j for network A

1 350.000

196 VARIABLE FimpB.L import flowrate to demand j for network B

5 151.667,   6 129.187

196 VARIABLE FexpA.L export flowrate from source i for network A

1 175.000,   6 175.000

196 VARIABLE FexpB.L export flowrate from source i for network B

7 175.712,   8 105.142

196 VARIABLE fcpA.L total export for network A

A 350.000

196 VARIABLE gcpA.L total import for network A

A 350.000

196 VARIABLE fcpB.L total export for network B

B 280.854

196 VARIABLE gcpB.L total import for network B

B 280.854