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A Model for the Design of Optimal Total Water Network (OTWN)

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Water reuse network can reduce tremendously the freshwater consumption and wastewater generation. However, it requires major investment in the piping and pumping as well as reuse tank. Many industries still prefer to buy freshwater and treating all their wastewater as it is typically cheaper. However, this scenario is changing as the freshwater price, wastewater penalty to achieve the discharge standard, wastewater treatment cost and land price are increasing. There are many works in minimising water and wastewater cost in the industries. However, most of the work simplifies the wastewater treatment cost into simple equations that favours water reuse. The benchmarking methodologies focusing on measurements of wastewater treatment plant to achieve an establish output (contaminants removed) using the minimum of inputs (cost of energy, labour, maintenance, etc.). The wastewater treatment model is actually more complex as biological effects, detention time and many other factors should also be considered. The detention time and wastewater treatment plant volume will also affect the land price. This work presents a mixed-integer non-linear programming (MINLP) model for the synthesis of optimal total water network (OTWN). The aim is to find the minimum cost that considers all the trade-offs and considering a more detail calculations of the wastewater treatment plant and land area needed. The wastewater treatment is assumed to consist of primary and secondary treatment units. The model is applied to a synthetic fabric production in a textile plant and the result has shown that the OTWN model is able to determine the total cost of water and wastewater treatment network while accounting for the land cost when a water reuse has been included in the model.

1. Introduction

Industrial process plants such as petroleum refinery, bio-refinery, pulp and paper, food manufacturing and electroplating consume massive amount of freshwater as raw materials, mass separating agents, energy carriers or washing mediums during operations. The wastewater which contain various contaminants are then generated by the processes. Rising price of freshwater and wastewater treatment costs has encouraged many industries to reduce the consumption of freshwater and to control effluent generation. In recent years, there have been many researches done on the synthesis water networks using mathematical programming approaches which have been useful for handling complex processes with multiple contaminants. The review on these developments can be referred to Klemeš (2012). Handani et al. (2010) presented a new generic MILP model that holistically considered process changes via all water management hierarchy in order to select the best water minimisation schemes. Realising the limitations in Handani's research, Lee et al. (2014) developed four stage mathematical model based on MILP and MINLP to minimise the freshwater and wastewater consumptions, the number of storage tanks as well as the number of inter-connections for a fixed scheduled batch process that includes the MTB and NMTB operations with multiple contaminants. Deng et al. (2012) used mathematical modelling to identify an optimal water conservation network incorporated with process model to minimise freshwater consumption, intercepted flowrate and mass load. In another work by Grzegorz (2014), a flexible water network (FWN)

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containing the sources and sinks of process water has been solved via optimal design of regeneration processes. The author also considered both the variation of the concentration of pollution in the regenerated water and periodic downtimes of selected sources and sinks. Some researchers have also considered the economic factor in water network synthesis such as the minimum freshwater cost, the total annual cost, the maximum profit and the internal rate of return (Pintarič et al., 2014). Nápoles-Rivera et al. (2014) maximised the total revenue by the sales income after the cost of water treatment, storage and distribution were deducted in a macroscopic water distribution system. Other than that, mathematical programming has also been used for the optimal design of distributed wastewater treatment networks with multiple contaminants (Castro et al., 2009) and the synthesis of heat-integrated water and wastewater treatment networks developed by Ahmetovic et al. (2014).

In all the referenced literature sources, most of the available design methods and approaches have focused on minimising water consumption and its operating cost. Typically, the authors perform water minimisation network synthesis and wastewater treatment plant network synthesis in separation. Very few have presented an integrated water and wastewater treatment plant synthesis simultaneously. For example, the works on the integrated water and wastewater treatment network design has been address by Huang et al.(1999). The authors used the mathematical modelling to determine the optimal water usage and treatment unit (WUTN), which features the least amount of freshwater and/or minimum wastewater treatment capacity. Neither any economic factor nor other parameters such as piping network, treatment unit detention time, volume and land area were taken into account to the earlier research. To address the gap, this paper presents a mixed-integer non-linear programming (MINLP) model for design of optimal total water network (OTWN) by taking into account the cost of freshwater, piping, wastewater treatment unit involving primary and secondary treatment unit and the land area required for the treatment plant.

2. Overview of OTWN Design Method

The first part of this model extends the works of Handani et al. (2011) for targeting the OTWN. The original work by Handani et al. (2011) is a holistic approach for the design of minimum water network. The model in this paper is focuses only on the maximum water recovery (MWR) part follows by the wastewater treatment network which is a new feature to the study.

The OTWN general superstructure is shown in Figure 1. The following notation is adopted throughout the paper. S_i, D_j, FW, WW, P and S represent water flowrate from source *i*, demand *j*, freshwater, wastewater, primary and secondary treatment unit.

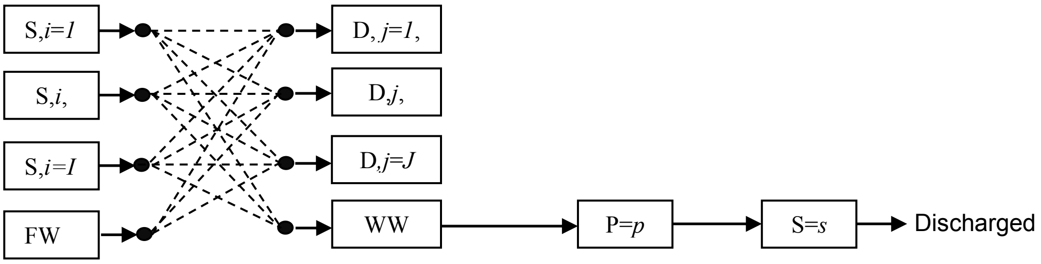

Figure 1: General water and wastewater network superstructure

The overall objective function was formulated considering four costs involving freshwater, network piping, wastewater treatment and treatment unit land area. The water reuse model follows Handani et al. (2011). In addition, the following objective function and equations were added to cater the wastewater treatment plant.

Objective function:

$$min \sum_{ww} AOH(Ftot \times TARFW) + AF(Cost_{i,j}^{fw,pipe} + Cost_{j,p}^{op,pipe} + Cost_{p,s}^{ww,pipe} + Cost_{s,o}^{out,pipe}) + AOH(OPEX^{ww,tu}) + AF(CAPEX^{ww,tu}) + Cost^{ww,land} \quad (1)$$

Subject to:

ii. Total wastewater discharge from various sources:

$$WWtot = \sum_{i} Fwp_{p} \quad (2)$$

iii. Contaminant balance of wastewater stream to primary treatment unit p:

$$WWtot * Cw_{(k)} = \sum_{p} Fwp_{p} Cwp_{(k,p)} \tag{3}$$

iv. Contaminant balance with given removal ratio for primary treatment unit p:

$$(1 - rep_{(k,p)}) * (WWtotCw_{(k)}) = \sum_{s} Fps_{(p,s)} Cps_{(k,s)} \tag{4}$$

v. Contaminant balance with given removal ratio for secondary treatment unit s:

$$(1 - rep_{(k,s)}) * \sum_{s} Fps_{(p,s)} Cps_{(k,s)} = Fso_{(s,o)} Cso_{(k,s)} \tag{5}$$

vi. Limiting concentration of wastewater in discharge pool:

$$Cso_{(k,s)} \leq cl_{(k)} \tag{6}$$

vii. Volume of primary and secondary tank:

$$V_{p} = \theta * Fwp_{p} \tag{7}$$

$$V_{s} = \theta * Fps_{p,s} \tag{8}$$

viii. Piping Cost:

$$Cost^{fw,pipe} = RM^{pipe} \times (B^{fw,pipe}) \times d^{fw,pipe} \tag{9}$$

$$Cost^{op,pipe} = RM^{pipe} \times (B^{op,pipe}) \times d^{op,pipe} \tag{10}$$

$$Cost^{ww,pipe} = RM^{pipe} \times (B^{ww,pipe}) \times d^{ww,pipe} \tag{11}$$

$$Cost^{out,pipe} = RM^{pipe} \times (B^{out,pipe}) \times d^{out,pipe} \tag{12}$$

ix. Land area:

$$A^{p,land} = V_{p} / d_{p,s}^{ww,pipe} \tag{13}$$

$$A^{s,land} = V_{s} / d_{s,o}^{ww,pipe} \tag{14}$$

$$A^{ww,land} = A^{p,land} + A^{s,land} \tag{15}$$

x. Land area cost:

$$Cost^{ww,land} = RM^{ww,land} \times A^{ww,land} \tag{16}$$

As wastewater enters the wastewater treatment network, each streams flow into a primary treatment unit at a typical detention time. Primary treatment units act as a settling tank where it removes about 60 - 70 % of suspended solids and 20 - 30 % of organic materials. In order to remove the colloidal and dissolved solids from primary treatment, the wastewater is further treated normally using biomass as an agent. This further treatment of wastewater is called secondary treatment. The final discharge from the wastewater treatment unit was set to meet the specified environmental limit as per Malaysian Acceptable Condition for Discharge of Industrial Effluent or Mixed Effluent of Standard A and B.

Mathematical model for the development of the design of optimal total water network was coded into a commercial mathematical optimisation software package GAMS (Generalized Algebraic Modelling System).

3. Industrial Case Study – Synthetic Fabric Production in Textile Industry

A synthetic fabric production in textile industry water system is analysed. The water sources and demands data for the case study is shown in Tables 1 and 2. The case study has three main wastewater streams from scouring, bleaching and rinsing, and dyeing process. Two main contaminants from this process are Biochemical Oxygen Demand and Suspended Solid. Table 3 shows the contaminant removal efficiency of each treatment unit with the cost function for treatment process taken from Kuo and Smith (1997). The treatment processes are set to reduce the concentration to the environmental limits which are 100 mg/L for SS and 50 mg/L for BOD. The tariff for freshwater in Malaysia is RM 0.45 per m^3. It is assumed that the plant operates at 8,400 h/y and a 10 % of interest rate with 3 y of annualisation is applied for the capital investment cost. The piping and land costs are 150 RM/m and 1,200 RM/m^2. Table 4 shows the distances between operations within the synthetic fabric production.

Table 1: Water demands limiting data for Synthetic Fabric Production.

Demand Description	Stream	Flowrate, D_j (t/h)	SS (mg/L)	BOD (mg/L)
Scouring	D1	50	0	0
Bleaching and rinsing	D2	100	300	45
Dyeing	D3	80	20	200

Table 2: Water sources limiting data for Synthetic Fabric Production.

Source Description	Stream	Flowrate, S_i (t/h)	SS (mg/L)	BOD (mg/L)
Scouring	S1	50	120	35
Bleaching and rinsing	S2	100	500	100
Dyeing	S3	80	45	350

Table 3: Removal ratio and cost function for treatment process

Treatment Unit	Ideal Removal Ratio (%)		Capital Cost (RM)	Operating Cost (RM)
	SS	BOD		
Primary Treatment Unit (PTU)	70	30	$16{,}800 * Fwp_p$^0.7	$1.0 * Fwp_p$
Secondary Treatment Unit (STU)	50	90	$12{,}600 * Fps_{p,s}$^0.7	$0.00067 * Fps_{p,s}$

Table 4: Distances between operations

	S1	S2	S3	PTU	STU	Discharge (m)
FW	50	50	100	150	200	500
S1	0	160	50	100	210	400
S2	40	0	60	90	150	170
S3	130	129	0	75	210	300
PTU	130	250	400	0	30	130
STU	300	210	160	100	0	120

From the developed MINLP model, the minimum freshwater flowrate for synthesis fabric production has been obtained. The initial freshwater requirement for the process is 230 t/h. Maximum water recovery (MWR) applied in this model through reuse and recycling resulted in savings of up to 43.6 % of freshwater and reduction of 43.6 % of wastewater. By solving the MINLP model, the minimum amount of freshwater consumption and wastewater generation are both 130 t/h. Both SS and BOD level have complied with the environmental limit set by the regulation.

The water and wastewater network design is shown is Figure 2.

Table 5 shows the results of optimisation when the minimum cost for overall freshwater supply, network piping, treatment unit and land cost were employed. The results were compared to the total cost without water reuse. From Table 5, it can be seen that when maximum water reuse was considered, it resulted in 33 % lower overall costs compared to the case without water reuse. A lower flowrate was obtained from the process, thus resulting in the minimum flowrate of wastewater streams.

This scenario also affects the volume of both the primary and secondary treatment units that act as a contaminant removal for both settleable solids and dissolved organic content. A larger land is required to locate the wastewater treatment unit when a higher volume of wastewater is obtained. The solution strategy introduced in this paper has proven that 44 % less land area is required when water reuse is employed within the process. Options for water reuse within the network are more economical, although it requires expensive investment in the overall piping cost. However, a different trend might be obtained, subject to current market price for freshwater and/or land price.

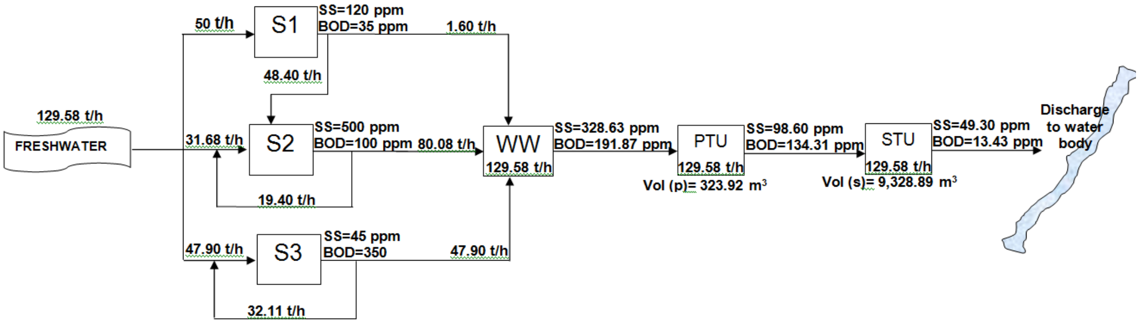

Figure 2: Synthetic fabric production water network and wastewater treatment unit using optimisation option.

Table 5: Cost comparison between maximum freshwater reuse and without reuse

Element	Cost (RM/y)-without water reuse	Cost (RM/y)-with Maximum water reuse	Percentage Difference
Freshwater	869,400	489,770	44 %
Treatment unit capital cost	4,762,800	3,187,116	33 %
Treatment unit operating cost	1,944,944	1,095,662	44 %
Overall piping cost	610,200	696,600	12 %
Land area cost	188,600	106,246	44 %
Total Cost	8,375,944	5,575,394	33 %

4. Conclusions

A model for optimal total water network (OTWN) design has been developed by considering various goal functions and economic scenarios. The consideration of other costs factor such as freshwater tariff, wastewater treatment and land price can provide an overall perspective to help industries plan a budget to start up a treatment plant. As freshwater tariff, wastewater treatment cost and land price varies from time to time, the OTWN model is able to adequately produce a dynamic cost profile and to predict the effect of total cost should any of the factors such as freshwater tariff or land cost rise. All in all, the developed model is effective to support engineers to screen design options in the integrated water network with an effective cost as well as complying with the environmental limits for wastewater discharge. Further research will focus on the consideration of power consumption cost, manpower, as well as different technologies used for wastewater treatment based on the effluent quality and different removal ratios.

Nomenclature

		Unit
$A^{p,land}$	Land area for primary treatment unit	m^2
$A^{s,land}$	Land area for secondary treatment unit	m^2
$A^{ww,land}$	Total land area for primary and secondary treatment unit	m^2
AF	Annual Factor	
AOH	Annual Operating h	h
$B^{fw,pipe}$	Connection between a freshwater source to an operation	
$B^{op,pipe}$	Connection between an operation to an operation	
$B^{ww,pipe}$	Connection between operation to wastewater stream and to treatment unit	
$B^{out,pipe}$	Connection between wastewater treatment unit to discharge point	
$CAPEX^{ww,tu}$	Capital cost of both Primary and Secondary treatment unit	RM
$Cl_{(k)}$	Environmental discharge limiting concentration	ppm
$Cost_{i,j}^{fw,pipe}$	Piping cost of freshwater source to an operation	RM
$Cost_{j,p}^{op,pipe}$	Piping cost of an operation to wastewater stream	RM
$Cost_{p,s}^{ww,pipe}$	Piping cost of wastewater stream and to wastewater treatment unit	RM
$Cost_{s,o}^{out,pipe}$	Piping cost of wastewater treatment unit to discharge point	RM
$Cost^{ww,land}$	Land area cost for wastewater treatment unit	RM
$Cps_{(k,s)}$	Wastewater concentration from primary to secondary treatment unit	ppm
$Cso_{(k,s)}$	Concentration of contaminant at secondary treatment unit	ppm
$Cw_{(k)}$	Concentration of contaminant at primary treatment unit	m
$d^{fw,pipe}$	Distance between a freshwater source to an operation	m

$d^{op,pipe}$	Distance between an operation to an operation	m
$d^{ww,pipe}$	Distance between wastewater treatment unit	m
$d^{out,pipe}$	Distance between a wastewater treatment unit to discharge point	m
$Ftot$	Total freshwater	t/h
$Fps_{(p,s)}$	Wastewater flowrate from primary to secondary treatment unit	t/h
$Fso_{(s.o)}$	Discharge flowrate of wastewater from secondary treatment unit to discharge pool	t/h
$Fwp_{(p)}$	Incoming wastewater flowrate to primary treatment unit	t/h
$OPEX^{ww,tu}$	Operating cost of both Primary and Secondary treatment unit	RM
$rep_{(k,p)}$	Contaminant concentration removal efficiency at primary treatment unit	%
$res_{(k,s)}$	Contaminant concentration removal efficiency at secondary treatment unit	%
RM^{pipe}	Cost of pipe connection per meter	RM
$RM^{ww,land}$	Cost of land area per meter square	RM
$TARFW$	Malaysian average market for freshwater tariff	RM
V_p	Volume of primary treatment unit	m^3
V_s	Volume of secondary treatment unit	m^3
$WWtot$	Total discharge of wastewater	t/h

Subscript

i	Index for water source
j	Index for water demand
k	Index for contaminants
o	Index for discharge point
p	Index for primary treatment unit
s	Index for secondary treatment unit

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