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An Optimal Water-Waste Nexus for an Eco-Industrial Park

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Resource sustainability is a top priority agenda nowadays which is extensively discussed in the circular economy concept. Reduction of water consumption, as well as final waste generation can be achieved by implementation of process integration and optimisation techniques. Promotion of eco-industrial park (EIP) as an option to improve conventional industrial park will enable the symbiotic participation of all parties, including the nearby domestic community. In this paper, a mathematical model is developed to maximise profit generation from simultaneous resource recovery and water integration from the wastewater. The novelty lies on consideration of multiples sources from industrial and domestic streams, while performing simultaneous regeneration, recycle, and reuse of water and resource recovery works. A superstructure and the associated mathematical equations are developed. Five types of contaminants i.e Chemical Oxygen Demand (COD), Total Dissolved Solid (TDS), Total Suspended Solid (TSS), Chromium (Cr), and Zinc (Zn) will be considered in the model. Generic Algorithm Modelling System (GAMS) is used as the optimisation tool. The case study result shows that a total annual profit of 200,788 USD/y could be generated by the centralized wastewater utility service provider and the payback period is less than 3 y. As a result, 37 % of freshwater could be minimized and 0.02 dry t/h of waste metal precipitate can be recovered from the wastewater. The demand side is also economically benefitted as the cost of supplied water is 10 % lower than the typical cost. The model provides insight on how the domestic and industrial sources can be symbiotically integrated, while retaining economic benefits to the centralized wastewater utility service provider and the demands.

1. Introduction

The circular economy emphasizes on the 3R strategies i.e reduce, reuse, and recycle in order to replace the current linear economy practice. The Eco-Industrial Park (EIP) offers a medium to perform industrial symbiosis and material exchange with the industries within the nearby communities. Water integration and resource recovery from the wastewater can be conducted to obtain an optimal water-waste nexus. Numerous researches have been done on the development of optimal water network for industrial or domestic usage. These include the concept of one-way centralised water reuse header (CWRH) for application at Total Site (Fadzil et al., 2018), heuristic method considering multiple contaminants for usage of batch networks (Li et al., 2019), multi-period water network management considering predictable variations (Liu et al., 2017), direct and mixed integration for water allocation across individual plants (Liu et al., 2017). Fan et al. (2019) presented a mathematical method which considers simultaneous reuse, regeneration reuse/recycling and treatment of the wastewater. A multi-objective optimization model regarding optimal water-energy-nexus for a residential complex has been studied by Núñez-López et al. (2018). The model incorporates water network synthesis and it also incorporates wastewater reclamation and harvesting of the rainwater. They did not consider water regeneration and/or outsourcing. As the wastewater can be regenerated for subsequent reuse, a resource recovery step can also be conducted simultaneously to recover or extract any valuable elements or compounds in it. The recovery work can be considered as an indirect regeneration or treatment of the wastewater as the contaminant content may be removed during such process. O'Dwyer et al. (2020) developed an optimisation framework that perform wastewater treatment/recovery in an eco-industrial park. It considers pipeline cost and the spatial aspects

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regarding the sources' location. The same main author presented a mixed integer linear non-integer programming (MINLP) that can generate a set of treated output streams based on a combination of different treatment recovery technologies (O'Dwyer et al., 2018). There is also a mathematical model developed to use industrial wastewater sludge to resources (Sujak et al., 2017). However, there is a research gap that requires attention; an optimal water network combining both domestic and industrial sources based on water integration, and resource recovery activities are yet to be developed. Some of the wastewaters from the domestic source e.g. ablution water from mosque and households' greywater can be applicable for regeneration and reuse for industrial usage. In this study, a mathematical model that could provide optimal water regeneration and reuse network that is also capable to perform metal recovery from the selected wastewater streams is developed. The main objective is to maximize profit from the network established.

2. Method

In this study, given a set of wastewater source streams and a set of water and demand streams from different process industries and domestic sources, it is desired to design a centralized water-waste recovery network. The wastewater is assumed to have certain water flowrate and contaminant concentrations which can be reused directly or with regeneration. The wastewater may also have valuable metal content that can be recovered. The system economics will be considered to maximize total profit of the system. A proposed superstructure regarding the model is shown in Section 2.1. The process description is provided subsequently. Section 2.2 will provide the mathematical formulations used in the model.

2.1 Superstructure

The superstructure of the study is shown as in Figure 1. It consists of the sources (h), regeneration (r), membrane treatment (m), outsource (os), and the demand (i). The membrane treatment consists of ultrafiltration (UF) with double stage reverse osmosis (RO) filtration. The filtrate from it and the regeneration will be considered for chemical precipitation in order to recover the heavy metals. The permeate will be sent to the mixer for subsequent usage. Some main assumptions of the model: (i) the pH is neutral or within the workable limit of the regeneration and/or the membrane filtration (ii) the chemistry of reaction between the chelating agent in the households' greywater with the industrial wastewater is not considered (iii) the recovered heavy metal sludge moisture content is 70 % (iv) selling price of the recovered metal is 100 USD/t.

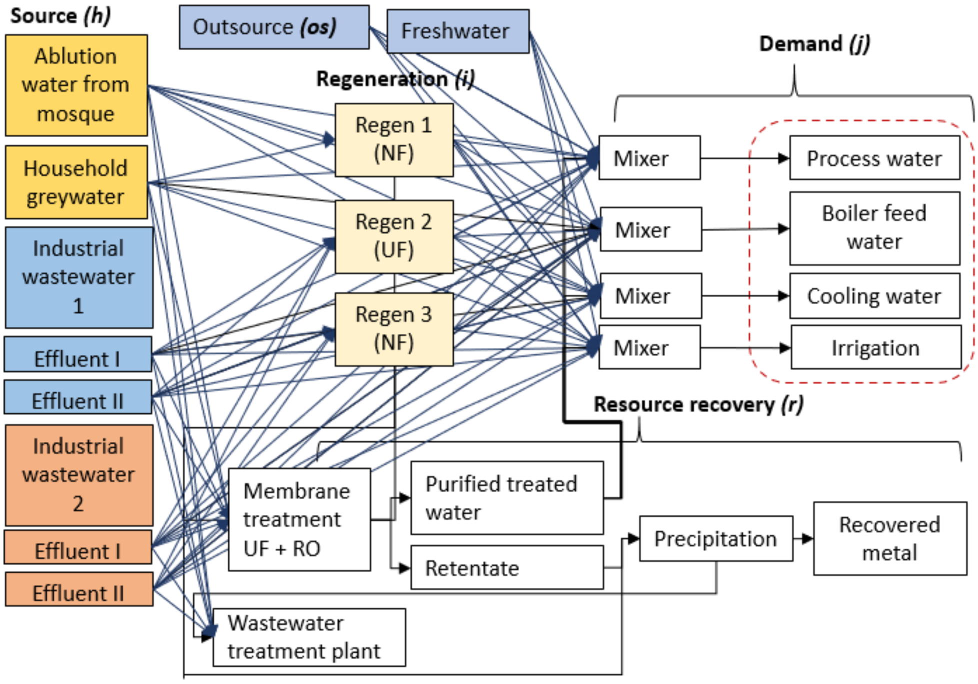

Figure 1: The superstructure of the study

Each demand has respective contaminant content limits that need to be adhered. Selling price of each type of supplied water is (i) Process water 1.35 USD/m^3; (ii) Boiler feed water 1.35 USD/m^3; and (iii) Cooling water and irrigation water 0.68 USD/m^3. These are 10 % lower than the typical cost. It is assumed that the water for irrigation usage is the freshwater or tap water prior to the optimization. The precipitation equipment cost calculation is not in the scope of this study. The economics benefits are mainly on the profit obtained by the centralized wastewater utility service provider via supplying water to the demands and selling of the precipitated metals.

2.2 Mathematical Formulation

The main objective of the model is to obtain maximum profit Pr from selling of water based on the acceptable demand's contaminant content and selling of the metal precipitate; both act as the sources of revenue Rv. That said, the incurred annualized investment cost IC, operating and maintenance cost OMC, and total freshwater used during the mixing to meet the demand F_i^{fw} needs to be considered. P^{fw} is cost of freshwater. AWH is annual working hour. It is shown as per Eq(1).

$$Pr = Rv - IC - OMC - \sum_i (F_i^{fw} \times P^{fw} \times AWH) \tag{1}$$

The sources F_h^h constraints to the regeneration units F_r^r, the membrane filtration systems F_m^m and the wastewater treatment plant F_h^{wwt} are given in Eqs(2) – (10). $F_{h,r}^{hr}$ is the individual flow rate from the source to the regeneration unit and $F_{h,m}^{hm}$ is the individual flow rate from the source to the membrane filtration systems.K is a large value to be multiplied with $B_{h,r}^{hr}$, which is a binary parameter to assign the sources h to the regeneration unit. A_r^{Regen} is the parameter regarding percentage recovery of regenerated stream and $A_{r,p}^{CRegen}$ is the parameter regarding contaminant removal percentage of the inlet stream. $C_{h,p}^h$, $C_{r,p}^r$, $C_{r,p}^{regen}$, and $C_{m,p}^m$ is the contaminant content of the source, regeneration inlet stream, the regenerated stream and the systems membrane filtration inlet.

$$F_h^h = F_h^{wwt} + \sum_r F_{h,r}^{hr} + \sum_m F_{h,m}^{hm} + \sum_i F_{h,i}^{hi} \qquad \forall h \tag{2}$$

$$F_h^h \times C_{h,p}^h = (F_h^{wwt} \times C_{h,p}^h) + \sum_r (F_{h,r}^{hr} \times C_{h,p}^h) + \sum_m (F_{h,m}^{hm} \times C_{h,p}^h) + \sum_i (F_{h,i}^{hi} \times C_{h,p}^h) \qquad \forall h,p \tag{3}$$

$$K \times B_{h,r}^{hr} = F_{h,r}^{hr} \qquad \forall h,r \tag{4}$$

$$F_r^r = \sum_h F_{h,r}^{hr} \qquad \forall r \tag{5}$$

$$F_r^r \times C_{r,p}^r = \sum_h (F_{h,r}^{hr} \times C_{h,p}^h) \qquad \forall r,p \tag{6}$$

$$F_r^r \times A_r^{Regen} = F_r^{regen} \qquad \forall r \tag{7}$$

$$C_{r,p}^r \times A_{r,p}^{CRegen} = C_{r,p}^{regen} \qquad \forall r,p \tag{8}$$

$$F_m^m = \sum_h F_{h,m}^{hm} \qquad \forall m \tag{9}$$

$$F_m^m \times C_{m,p}^m = \sum_h (F_{h,m}^{hm} \times C_{h,p}^h) \qquad \forall m,p \tag{10}$$

The demands' constraints are provided as the following Eqs(11) – (12). F_i^i is the flow rate of the demand and $C_{i,p}^i$ is its contaminant content. F_i^{fw} is the flow rate of freshwater. $F_{os,i}^{osi}$, $F_{r,i}^{regeni}$ and $F_{m,i}^{pmti}$ is the individual flow rate of the outsource, regenerated streams, and the purified treated water to the mixers. C_p^{fw} is the freshwater contaminant content. C_p^{pmt} is the purified treated water contaminant content. Total contaminant load of the demand should be the same or lower than the supply stream.

$$F_r^{regen} = \sum_i F_{r,i}^{regeni} \qquad \forall r \tag{11}$$

$$(F_i^i \times C_{i,p}^i) \geq (F_i^{fw} \times C_p^{fw}) + \sum_{os} (F_{os,i}^{osi} \times C_p^{fw}) + \sum_r (F_{r,i}^{regeni} \times C_{r,p}^{regen}) + \sum_m (F_{m,i}^{pmti} \times C_{m,p}^{pmt}) \qquad \forall h,p \tag{12}$$

Eqs(13) – (16) provide formulations regarding mass balance at the membrane systems. A_m^m is the recovery percentage of water in the membrane systems. F_m^{pmt} is flow rate of purified treated water. $A_{m,p}^{Cm}$ is the contaminant removal percentage of the inlet stream. The resulting contaminant concentration for F_m^{pmt} is $C_{m,p}^{pmt}$. F_m^{rtt} and $C_{m,p}^{rtt}$ is the flow rate and contaminant content of the retentate. It is assumed that pH of retentate is 7. The chemical precipitation equations are referred from Metcalf & Eddy (2014).

$$F_m^m \times A_m^m = F_m^{pmt} \qquad \forall m \qquad (13)$$

$$C_{m,p}^m \times A_{m,p}^{Cm} = C_{m,p}^{pmt} \qquad \forall h,p \qquad (14)$$

$$F_m^m = F_m^{pmt} + F_m^{rtt} \qquad \forall m \qquad (15)$$

$$F_m^m \times C_{m,p}^m = \left(F_m^{pmt} \times C_{m,p}^{pmt}\right) + \left(F_m^{rtt} \times C_{m,p}^{rtt}\right) \qquad \forall m,p \qquad (16)$$

The generic equation regarding the revenue or cost saving generation, annualised investment cost, and operating and maintenance cost are provided as per Eqs(17) – (19). P_i^{water} is the selling price of supplied water to the demand. $ICR.ICM$, and ICP are the investment cost of regeneration unit, the membrane systems, and the incurred pump and motor. Total operating and maintenance cost OMC is a combination of OM of the regeneration unit $OMCR$, pump $OMCP$, and motor $OMCM$. The detailed cost estimation for each equipment/unit/systems are provided in Section 3. Estimation of the membrane units/systems is based on steps mentioned by Woods (2007). The latest cost index is based on the 2018 CEPCI value.

$$Rev = \sum_i (F_i^i \times P_i^{water} \times AWH) \qquad (17)$$

$$IC = (ICR + ICM + ICP)af \qquad (18)$$

$$OMC = (OMCR + OMCP + OMCM) \qquad (19)$$

3. Case Study

A case study is conducted with usage of parameters in Tables 1 to 3. The industrial effluents are set to be fully utilized in the optimization step. Upper bound for each demand is set at 100 m^3/h.

Table 1: Properties of the sources and the demands

Source/Demand	Flow rate (m^3/h)	COD (mg/L)	TDS (mg/L)	TSS (mg/L)	Cr (mg/L)	Zn (mg/L)	Reference
Ablution water from mosque	1	31	20	31	0	0	(Mohamed et al., 2017)
Households' greywater	50	250	100	200	0	0	
Alkaline Cleaning effluent from Porcelain Enamelling Industry	1.25	500	700	140	0.05	0.59	(Wang et al., 2009)
Acid Etch from Porcelain Enamelling Industry	1	300	500	32	0.1	0.1	
Steel Operating effluent from Coil Coating Industry	10	9,000	3,400	130	320	54	
Galvanized Steel effluent from Coil Coating Industry	10	8,900	2,400	250	290	220	
Process water	100*	5	1,000	5	<0.1	<0.1	(Metcalf & Eddy Inc, 2014)
Boiler feed water	100*	5	700	10	<0.1	<0.1	
Cooling water	100*	75	500	100	1	1	
Irrigation	100*	100	4,000	300	<0.1	2	

*upper bound

Table 2: Filtration performance of each type of membrane

Type of Membrane Filtration	Membrane flux rate (m^3/m^{2}h)	Recovery Efficiency (%)	COD Removal Efficiency (%)	TDS Removal Efficiency (%)	TSS Removal Efficiency (%)	Cr Removal Efficiency (%)	Zn Removal Efficiency (%)	Reference
UF	0.050		85	1	98	0	0	(Metcalf & Eddy Inc, 2014)
NF	0.017		95	50	99	80	80	
RO	0.017		95	95	99	99	99	

Table 3: Investment, operating and maintenance cost of the membranes

Type of Membrane Filtration	Reference Cost (USD)	Operating Pressure (kPa)	Energy Consumption (kWh/m^3)	Membrane Replacement Cost (USD/m^2)	Maintenance Cost (USD)	Labour and Cleaning Cost (USD)
UF	USD 42,217 for 2.88 m^3/h inlet flow rate[a]	200[b]	0.25[b]	35	5 % of Investment Cost	2.25 times of membrane replacement cost[c]
NF	USD 42,217 for 2.88 m^3/h inlet flow rate[a]	1,050[b]	0.45[b]	35	5 % of Investment Cost	2.25 times of membrane replacement cost[c]
RO	USD 132,682 for membrane area 1,600m^2[a]	1,350 [b]	0.60[b]	40	5 % of Investment Cost	2.25 times of membrane replacement cost[c]

[a](Woods, 2007), [b](Metcalf and Eddy Inc, 2014), [c](Samhaber and Nguyen, 2014)

Table 4: Other items/parameters value used in this study

Items/Parameters	Value
Annual working hour	8,000 h
Price of freshwater	USD 0.75/m^3
Outsource flow rate	1.1 m^3/h
Lime cost	120 USD/t
Electricity cost	0.084 USD/kWh
Membrane replacement frequency	Once in 5 y
Pump and motor investment cost	Referred to (Sinnott and Towler, 2020) O&M cost is 5 % of investment cost

4. Results and Discussion

The multi integer non-linear program (MINLP) model is run via GAMS version 24.7.4 in a computer with processor capacity of IntelCore i3-8130U 2.2GHz. It was solved using BARON solver. Execution time takes less than 5 s. The optimal network selected is shown in Figure 2.

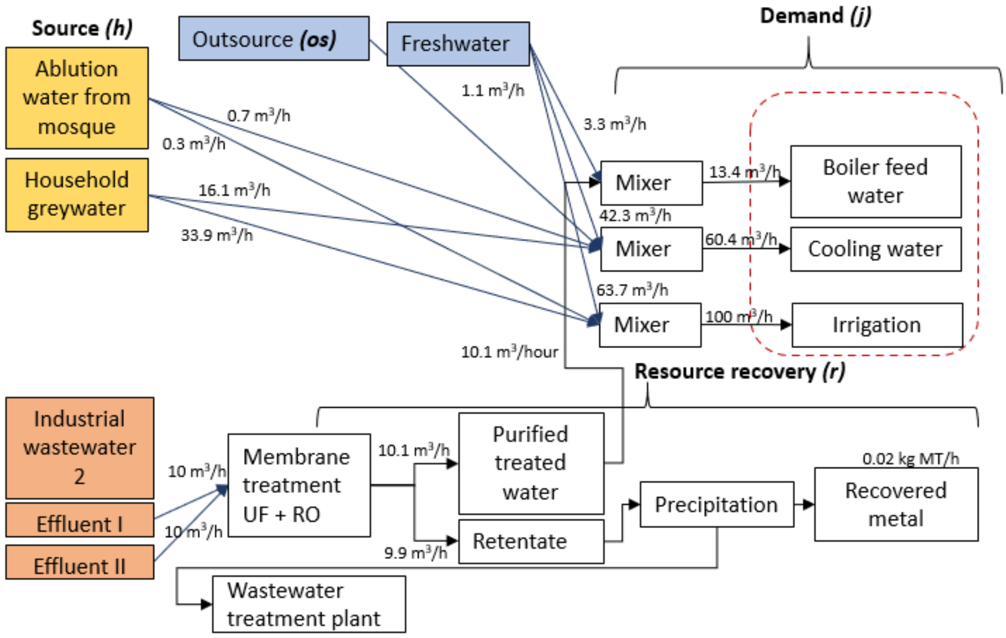

Figure 2: The proposed optimization solution

From the proposed solutions, freshwater with amount of 3.3 m^3/h and 10.1 m^3/h of permeate are combined to form 13.4 m^3/h supply of boiler feed water. 0.7 m^3/h of the ablution water, 16.1 m^3/h of households greywater, 0.05 m^3/h of alkaline cleansing effluent, 0.1 m^3/h of acid etch effluent, 1.1 m^3/h of outsourced water, and 42.3 m^3/h of freshwater are mixed together to make supply of 60.4 m^3/h of industrial cooling water. 33.9 m^3/h of households greywater, 1.2 m^3/h of alkaline cleansing effluent, 0.9 m^3/h of acid each effluent, and 63.7 m^3/h of freshwater are combined to supply 100 m^3/h for irrigation application. The effluents from steel and galvanized steel operations are sent to the membrane filtration. It generates 10.1 m^3/h of permeate and 9.9 m^3/h of retentate. The permeate is used for boiler feed water supply as mentioned earlier and the retentate will be chemically treated to precipitate the Zn and Cr. The process generates 0.02 dry t/h of metal precipitate. A net profit of USD 200,788 for the centralized wastewater utility service provider is obtained from the optimized water network. TIC is USD 28,067 and OMC is USD 139,164. The mixing performed is able to reduce 37 % of freshwater consumption. The annual revenue from the recovered metal is USD 12,800. That said, this study is yet to consider piping cost of transporting the sources to the centralised facility. The cost estimation range, at best, is assumed at ±30 % (Woods, 2007). Ultimately, this study provides an insight in how the wastewater streams from both domestic and industrial sources could be symbiotically optimized in the EIP.

5. Conclusion

In this study, an optimal water-waste nexus is developed for usage within the EIP context. Wastewater sources from the domestic and industrials sectors are considered for potential water integration and resource recovery. In this study, all parties obtain economics benefits as (i) the sources do not need to pay processing fee to the centralized facility (ii) the centralized facility is able to generate profit, and (iii) the demand is able to buy the supply water at 10 % lower cost. The EIP acts as an important medium to apply the circular economy practice. Moving forward, a more detailed study is suggested in order to evaluate the solution’s practicality in the real world.

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References

Fadzil A. F. A., Wan Alwi S.R., Manan Z., Klemeš J.J., 2018, Industrial site water minimisation via one-way centralised water reuse header, Journal of Cleaner Production, 200, 174–187.

Fan X.-Y., Klemeš J.J., Jia X., Liu Z.-Y., 2019, An iterative method for design of total water networks with multiple contaminants, Journal of Cleaner Production, 240, 118098.

Li A., Liu C., Liu Z.,2019, A heuristic design method for batch water-using networks of multiple contaminants with regeneration unit, Chinese Journal of Chemical Engineering, 27(5), 1103–1112.

Liu L., Wang J., Song H., Du J., Yang F., 2017, Multi-period water network management for industrial parks considering predictable variations, Computers & Chemical Engineering, 104, 172–184.

Liu L., Wang J., Song H., Du J., Yang F., 2016, Synthesis of water networks for industrial parks considering inter-plant allocation, Computers & Chemical Engineering, 91, 307–317.

Metcalf & Eddy, Inc, 2014, Wastewater Engineering: Treatment and Resource Recovery, McGraw-Hill Education, New York, United States of America.

Mohamed R.M., Al-Gheethi A.A., Aznin S.S., Hasila A.H., Wurochekke A.A., Kassim A.H., 2017, Removal of nutrients and organic pollutants from household greywater by phycoremediation for safe disposal, International Journal of Energy and Environmental Engineering, 8(3), 259–272.

Núñez-López J.M., Rubio-Castro E., El-Halwagi M.M., Ponce-Ortega J.M., 2018, Optimal design of total integrated residential complexes involving water-energy-waste nexus, Clean Technologies and Environmental Policy, 20(5), 1061–1085.

O’Dwyer E., Chen K., Wang H., Wang A., Shah N., Guo M., 2020, Optimisation of wastewater treatment strategies in eco-industrial parks: technology, location and transport, Chemical Engineering Journal, 381, 122643.

O’Dwyer E., Wang H., Wang A., Shah N., Guo M., 2018, Optimisation of wastewater treatment and recovery solutions in industrial parks, Computer Aided Chemical Engineering, 43, 1407–1412.

Samhaber W.M., Nguyen M.T., 2014, Applicability and costs of nanofiltration in combination with photocatalysis for the treatment of dye house effluents, Beilstein Journal of Nanotechnology, 5(1), 476–484.

Sujak S., Wan Alwi S. R., Lim J. S., Manan Z., 2017, A mathematical model for techno-economic evaluation of industrial wastewater sludge to resources, Chemical Engineering Transactions, 56, 115–120.

Sinnott R., Towler G., 2020, Chemical Engineering Design, Butterworth-Heinemann, Oxford, United Kingdom.

Wang L.K., Shammas N.K., Hung Y.T., 2009, Waste treatment in the metal manufacturing, forming, coating, and finishing industries, CRC Press, Florida, United States of America.

Woods D.R, 2007, Rules of thumb in engineering practice, Wiley-VCH Verlag, Weinheim, Germany.