Targeting and Design Procedure for Water-using Networks with Single Contaminant

Mai Mohamed Refaat, Said Ali , Mustafa Awad

***Abstract**: Minimizing of wastewater has become a focus of research as the reduction of wastewater discharge and water conservation has great importance. Wastewater discharge and fresh water consumption can significantly be reduced by Integration of the water system. The integration is done by reuse, regeneration reuse/recycling of waste wastewater appropriately. This work shows the development of a systematic technique which target freshwater consumption and wastewater discharge to achieve the maximum water recovery for systems involving a single contaminant. A generic linear programming model has been used based on water network superstructure to generate the maximum water recovery targets and design minimum water network .It has been used in this work water path analysis and improved source shift algorithm to evolve a preliminary water network to reduce number of interconnections by incurring a penalty on both wastewater and freshwater flow rates. This method has been tested for one problem reported in the literature. It is cleared from the illustrated problems that the proposed procedure needs much less computation compared with methods taken from other literatures.*

***Keyword:** Water minimization, mathematical modeling, maximum water recover, optimization, single contaminant.*

I. INTRODUCTION

Rising costs of freshwater, effluent treatment and the current drive toward environmental sustainability have encouraged the industry to find new ways to decrease wastewater generation and freshwater consumption. The most important ways to reduce water are as follows, Olson de Souza [1]:

1. Reuse: means that the wastewater from a unit is used as fresh water for another unit in case of the wastewater does not violate the restrictions on consumer unit.

2. Regeneration reuse: it resembles the former, but firstly the wastewater is transferred to an infiltration unit before using by the consumer unit.

3. Regeneration recycling: here, each unit uses its produced wastewater as fresh water after infiltration process to the wastewater. The synthesis of the industrial water network (Mann and Liu [2], Jezowski [3]) has been an active area of research in process systems engineering for more than a decade. The available design methods are categorized into three types, the pinch based, mathematical programming based and graphical based approaches. A complete review on the previous approach is given by Foo [4], while Faria and Bagajewicz [5] gave through survey of the latter. Further the evolutionary approach is carried out through modifying the basic case solution. Obtaining desirable alternative solutions is the goal of evolution with minimum total throughput, minimal fresh water use and minimum number of interconnections. To evolve from a preliminary design to network structures with fewer matches, Prakash and Shenoy [6] proposed first, the so-called source conversion algorithm (SSA). Later, Ng and Foo [7] discussed that the source shift strategy original version was iterative as it could only be used in trial and error fashion. To circumvent this drawback, two guiding rules were therefore introduced in the improved Source shift Algorithm (SSA). Linnhoff and Hindmarsh [8] was also proposed The idea of a water path, which resembles the well-establish concept of heat load path in HEN design, to relax the upper bound of freshwater consumption rate so as to simplify network configuration. Recently, four additional evolution techniques were proposed by Das et al. [9] according to path relaxation for deriving simple designs from a preliminary resource allocation network (RAN) and the loop breaking concepts. The total number of alternative configurations was not targeted although successful applications have been reported and the resource penalty cannot always be avoided during evolution. WPA Water Path Analysis and SSA the improved Source shift Algorithm are used in this study to develop a preliminary water network to reduce number of interconnections by penalizing both wastewater flow rate and freshwater. The method has been tested for one problem reported in the literature.

II. PROBLEM STATEMENT

The problem is stated as follows: a set of water sources and sinks are given. The flow rate and concentration of contaminants are the parameters that determine the water characteristics of the sink sources and requirements. The objective is to design the optimal water using network and systematic evolve to generate desirable alternative solutions with minimum total throughput, minimum fresh water consumption and minimum interconnection.

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* Correspondence Author
Mai Mohamed Refaat*, Chemical Engineering and petroleum refining department, Suez University, Suez, Egypt. Email: engmemeceko@gmail.com.
Said Ali, Chemical Engineering and Petroleum Refining department, Suez University, Suez, Egypt. Email: engmemeceko@gmail.com.
Mustafa Awad, Chemical Engineering and Petroleum Refining department, Suez University, Suez, Egypt. Email: engmemeceko@gmail.com.

III. DESIGN PROCEDURE

Design procedure consists of three main steps;

Step1: Limiting Water Data Extraction

To identify water demands and water sources those have potential for integration. The water demand reflects the actual requirements of different water use processes while water sources are water available for reuse while. Water sources and demand are the limiting water data and were listed in terms of quantity (contaminant concentration) and quality (flow rate). Suppose that the concentration of contaminant for each the source and demand is fixed at its maximum values.

Step 2: Mathematic formulation

The second step is to generate the superstructure in which all possible configurations of flow are embedded. For each process that uses water, the inlet water stream can be freshwater, wastewater from the same or different processes, whereas in the outlet stream, the resulting wastewater may be discharged or reused directly in the same or different processes. All possible links between water sources, demands and wastewater discharges are represented by the superstructure. Fig. 1 shows general water network superstructure.

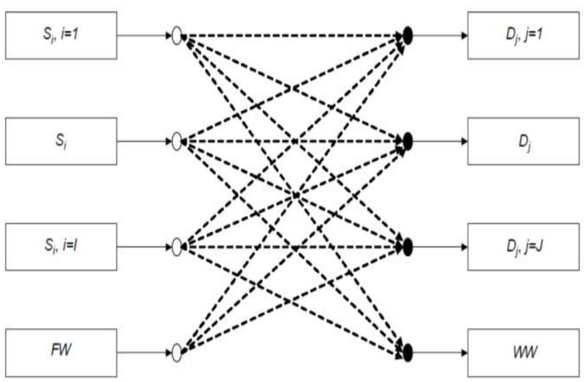

Fig. 1. General Superstructure for Maximum Water Recovery Network.

Determining the minimum freshwater that leads to the maximum total reuse of water in the system and the minimum wastewater generation is the objective of this mathematic model. Si is the source i water flow rate and Dj is the demand j water flow rate with a maximum contaminant concentration Csi for the source and Cdj for the demand. WWi refers to the flow from source i to waste without any quality limit. FWj denotes the flow transferred from freshwater to demand j, with a quality Cw. Fi,j represents the flow transmitted from source i to demand j. The objective function is to reduce the used freshwater amount, FW_j.

$$\text{Min } \Sigma\, FW_j \qquad (1)$$

Equation (1) represents the minimization of the objective function and it is subjected to the following constraints:

(1) Water balance for each source i: is given by

$$WW_i + \Sigma\, F_{i,j} = S_i \qquad (2)$$

As the available water source Si must be equal to the generated wastewater, WW_i and reused water from source i to demand j, $F_{i,j.}$

(2) Water balance for each demand j: is given by

$$FW_j + \Sigma F_{i,j} = D_j \qquad (3)$$

As the desired water demand, D_j must be equal to the water used supply from fresh water, FW_j and the reused water, $F_{i,j}$.

(3) The contaminant load from all sources must satisfy the contaminant load for demand j.

$$FW_j{*}C_w + \Sigma F_{i,j}{*}C_{si} < D_j * C_{dj} \quad (4)$$

As the contaminant mass load for demand j is applied from a mixed of contaminant mass load from different sources (e.g fresh water, Fwj*Cw and potential reused water, Fi,j*Csi).

(4) Non-negativity constraints:

$$FW_j,\ WW_i,\ F_{i,j} \quad 0 \qquad (5)$$

As all the variables are positive/non-negativity. The fresh water supply, wastewater generation and reused water flow rate must be greater than zero.

Step 3: Evolution step:

In this step, the water network can be simplified. Simplification achieved by reducing the number of interconnections including primary water network. Evolution is achieved in two stages. The first stage is implemented through the Displacement Source Algorithm (SSA) and the network developed can be simplified by WPA, Ng and Foo [7]. If the primary network cannot be developed by SSA; i.e. Not compliant with SSA standards, then we can use WPA which applies to network evolution as an available solution only.

IV. EXAMPLE

One example is presented to demonstrate the procedure for implementing the proposed method and its efficacy to generate water-using network for single contaminant.

Example 1

The problem involves four sources and four sinks and the example is taken from Polley and Polley [10].

The example consists of combination of mass transfer based operations and non-mass transfer based operations.

Table- I: The Limiting data.

	Flow rate	Concentration	Load	Cumulative load
	(Ton/h)	(ppm)	(Kg/h)	(Kg/h)
Water demand Dj				
1	50	20	1	1
2	100	50	5	6
3	80	100	8	14
4	70	200	14	28
Water source Si				
1	50	50	2.5	2.5
2	100	100	10	12.5

3	70	150	10.5	23
4	60	250	15	38

Step1: The mathematic problem can be solved by using the commercial software LINGO program. The result of the minimum fresh water and wastewater flow rates are 70 ton/h and 50 ton/h respectively. Besides, the targets of wastewater and minimum freshwater found above are identical to S. Aly et. al [11] and Polley and Polley [10] using their methods.

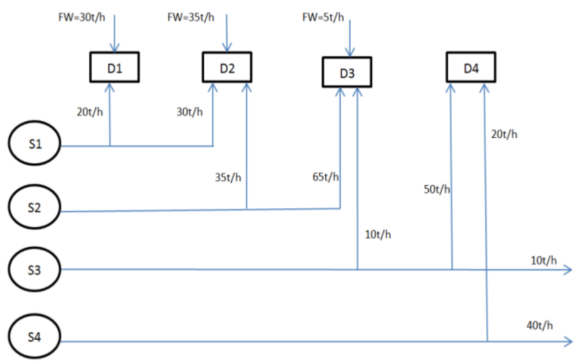

Fig. 2. The network design for the example

Step 2: The network is represented as a matching matrix shown in the table 2. S1, S2, S3 and S4 are the water sources appear as rows and D1, D2, D3 and D4 are the demands and appear as columns that arranged according to the increasing in the concentration. As shown in this water network, 12 interconnections among the water demands and sources that fulfill the minimum water flow rates features.

Table- II: Network design represented as matching matrix.

		F_j(t/h)	50	100	80	70	50
		C_j(ppm)	20	50	100	200	
F_j(t/h)	C_j(ppm)		D1	D2	D3	D4	WW
70	0	FW	30	35	$\xleftarrow{5}$ 5		
50	50	S1	20	30			
100	100	S2		35	$\xrightarrow{15}$ 65		
70	150	S3			$\xleftarrow{10}$ 10	50	10
60	250	S4				20	40

Step 3: In order to apply SSA, both criteria of the SSA should be checked. The two main criteria are:
1. Both demand and source must have the same concentration level.
2. The source flow rate must be equal or higher than the demand flow rate.
It is notice that, two demand-source pairs with the same level of concentration are firstly identified, i.e. S1 with D2 (50ppm) and S2 with D3 (100ppm). However only the S2-D3 match complies with the second criteria, where S2 has higher flow rate (100 t/h) than D3 (80 t/h).As a start, demand D3 which required 80 t/h of water will be fully supplied by source S2. An equal amount of water flow rate is shifted from D3 to D2 via FW-D2 (5t/h) and S3-D2 (10t/h) matches. Therefore, two interconnection D3-FW and D3-S3 matches are eliminated and new match emerges for D2-S3 match. The result is evolved network with 11 matches. Hence a simpler network is produced as shown in table 3.

Table- III: Design of network represented as matching matrix after shifts of the source.

		F_j(t/h)	50	100	80	70	50
		C_j(ppm)	20	50	100	200	
F_j(t/h)	C_j(ppm)		D1	D2	D3	D4	WW
70	0	FW	30	40			
50	50	S1	20	30			
100	100	S2		20	80		
70	150	S3		10		50 $\xleftarrow{10}$	10
60	250	S4				20 $\xrightarrow{10}$	40

If we assumed that the WW has the maximum allowable contaminate of 250 ppm so SSA technique can apply once more between WW-S4 match, where both of them has the same concentration(as we assumed) and S4 has higher flow rate (60 t/h) than WW (50 t/h). Equal amount of water is shifted via S3-D4 from WW to D4. Evolved network is shown in table 4 with one interconnection less than the preliminary network, only 10 matches exist.

Table- IV: Design of network represented as matching matrix after shifts of the source.

		F_j(t/h)	50	100	80	70	50
		C_j(ppm)	20	50	100	200	
F_j(t/h)	C_j(ppm)		D1	D2	D3	D4	WW
70	0	FW	30	40			
50	50	S1	20	30			
100	100	S2		20	80		
70	150	S3		10		60	
60	250	S4				10	50

It is clear that we can't proceed in evolution using SSA method, and then it is valid now to use the WPA technique for more evolution of the network. As show in table 5, when applying WPA technique, two water paths are identified in the network.

Table- V: Network evolution with water path analysis

		F_j(t/h)	50	100	80	70	50
		C_j(ppm)	20	50	100	200	
F_j(t/h)	C_j(ppm)		D1	D2	D3	D4	WW
70	0	FW	30	40			
50	50	S1	20	30			
100	100	S2		20	80		
70	150	S3		10	$\xrightarrow{10}$	60	
60	250	S4				10 $\xrightarrow{10}$	50

Path 1 which is solid line, consists of 2 L-kinks ,D2-S3 with 10 t/h and D4-S4 with 10 t/h, and path 2 is the dashed line which has 3 L-kinks,D1-S1 with 20t/h , D2-S3 with 10 t/h and D4-S4 with 10 t/h. so path 1 is chosen to be eliminated to evolve the network since the two L-kinks of the path contain the smallest flow rate among all the connections of L-kink. Thus 10 t/h of fresh water is added into D2 in the row of FW. Then D2-S3 match is removed and 10 t/h of water shifted along path 1 to D4, also the match D4-S4 is eliminated and 10t/h of water from S4 is sent to wastewater discharge WW. In table 6, the evolved network is shown with the penalty of 10t/h of fresh water and only 7 matches are eliminated from the original design. It is clear that no more evolution, neither by SSA nor WPA can be achieved, since there aren't any conditions of evolution available. The final network design is shown in Fig. 3.

Table- VI: Final network after water path analysis (10t/h fresh water penalty)

		F_j(t/h)	50	100	80	70	50
		C_j(ppm)	20	50	100	200	
F_i(t/h)	C_i(ppm)		D1	D2	D3	D4	WW
70	0	FW	30	50			
50	50	S1	20	30			
100	100	S2		20	80		
70	150	S3				70	
60	250	S4					60

V. CONCLUSIONS

The mathematical modeling has been tested for one problem reported in the literature. It is clear that the procedure proposed in the illustrated problem needs much less computation in comparison with methods taken from literatures. The proposed LP model has been successfully implemented in the example.

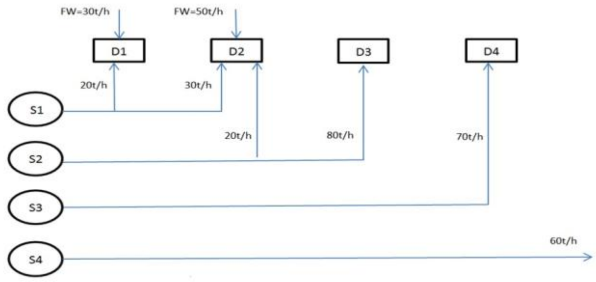

Fig. 3. The final evolved network design

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AUTHORS PROFILE

Mai Mohamed Refaat was born in Egypt. She got his BSc in Chemical Engineering and Petroleum Refining, Suez, Egypt in 2005. She has a Diploma in Petroleum Refining. She is working in Suez Oil Processing Company in Egypt as a refining Engineer.

Said Ali was born in Suez city, Egypt. He got his BSc in the Chemical Engineering and Petroleum Refining from the Faculty of Petroleum and Mining Engineering (Suez University), Suez, Egypt. He is a professor in the chemical Engineering, specialist in the optimization, modeling and simulation. He is a faculty member in the faculty of petroleum and mining engineering, chemical engineering and petroleum refining department. He taught in several universities in Egypt such as AUC, BUC and Al pharos. He has taught several courses in chemical engineering such as control, optimization, safety, computer applications, phase equilibrium, process synthesis and operational research. He supervised many scientific theses (Master and Doctorate).

Mustafa Awad was born in Egypt. he got his BSc in Chemical Engineering and Petroleum Refining from the Faculty of Petroleum and Mining Engineering (Suez University), Suez, Egypt. he has PhD in the refinery engineering from Suez University, specialist in the lube oil treatment. he is a faculty member in faculty of petroleum and mining engineering, chemical engineering and petroleum refining department. he has taught several courses in chemical engineering such as specifications of petroleum products and test methods, petroleum refinery engineering, plant design and pollution control. She supervised many scientific theses such as enhancing produced water in oil fields using alternative treatment technologies, flared gas recovery and optimum operating conditions of gas dehydration.