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A Systematic Method to Minimize Freshwater Utilization by Multiple Contaminants Network

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***Abstract:** A systematic procedure is developed to design and evaluate water by using networks with multiple contaminants. The proposed algorithm contain two sequential steps, in the first step the total, the total possibilities of matching source flows to demand flows were evaluated and a heuristic design technique is proposed based on the results. In the second step, three strategies are suggested to reach high level of operability, two source shift, path relaxation and loop breakage are applied in order to improve the network and minimize interconnections.*

The proposed approach was evaluated and assessed through a case study. The results are in match with the available data in the literature. In the meantime the computational time to reach confluence was significantly reduced.

***Keywords:** Water minimization, water using network, multiple contaminants, evolution process design.*

I. INTRODUCTION

Nowadays strict environmental laws are being enforced on the quality of the industrial waste water discharge. Hence, more attention is required to minimize waste water discharge through water system integration.

There are many methods which have been suggested in the literature. Takma et al [1] used a superstructure based method to discuss the design of water networks. Wang and Smith [2] minimized wastewater by using a graphical method. Kuo and Smith [3] design wastewater treatment by using a graphical method which depends on the work of Wang and Smith [2].

Doyle and Smith [4] applied linear and nonlinear programming methods to minimize fresh water utilization with the aid of networks with multiple contaminants. Huang et al [5] used a nonlinear programming method for the design of the water distribution networks.

Alva- Argaez et al [6] combined insights from water pinch with mathematical programming to design the water employ systems with multiple contaminants. In the research conducted by Cao et al [7] a pinch multi agent genetic algorithm was applied to optimize water consumption .four techniques were proposed by Das et al [8] to design water networks. They used loop breaking and path relaxation concepts to establish their design. A preliminary resource allocation network (RAN) was built without significant penalties.

In this research a two-step methodology are introduced as a new approach to design water networks. The first step is the allocation of the process and the second step is the evolution of preliminary design to reach the desired solution that will achieve minimum fresh water consumption, lowest number of interconnections and lower overall throughput.

The proposed method will be illustrated using case study which the results obtained by using our proposed approach were compared with the results obtained by other approaches available in the literature.

II. PROBLEM STATEMENT

We can describe the structure problem of a water employ network as follows: a group of water- using units with multiple contaminants. It is required to determine a network of interconnections of water flow through the unit so that the total consumption of fresh water decreased and few interconnection.

III. DESIGN PROCEDURE OF WATER-USING NETWORKS

A. Arrange all unit processes

The outlet concentration will be considered as the major factor to determine the performing order of the processes.
The maximum outlet concentration for each contaminant from the unit processes arranged in increasing order.

B. Allocation of sources and demands

- The process with lowest order will performed first and they often use fresh water as follows

$$F_{fresh}^{min} = max\left[\frac{m_k}{C_k^{out}}\right] \qquad (2)$$

$$m_k = F\left(C^{out} - C^{in}\right) \qquad (3)$$

F_{fresh}^{min} *is the minimum fresh water amount,*
m_k *[mass load of contaminant k removed in the process],*

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C_k^{out} *[outlet concentration of contaminant k],* C_k^{in} *[inlet concentration of contaminant k] and F[flow rate of water].*

-if there are a lot of source flows available, we must choose which source should be reused first. The source which has the highest value of the quasi-allocation amount should be used first

$$R_{ij} = min_{k=1,2,\ldots NC}\left[\frac{C_{j,k}^{in}}{C_{i,k}^{out}}\right] \qquad (4)$$

Where Ri,j is the quasi- allocation amount , $C_{j,k}^{in}$ [inlet concentration of contaminant k in demand stream j] , $C_{i,k}^{out}$ [outlet concentration of contaminant k in source stream I] and NC [number of contaminants].

-Distribution of source stream S_i to demand stream D_j as (S_i,D_j).

-When the contaminant concentration of S_i which is allocation to D_j, is reached the limiting value first we called it as reuse key contaminant RKC for (S_i,D_j) which corresponding to R_{ij}

-we should be used another source which have next highest the quasi- allocation amount (R_{IJ}) value when one source cannot be enough for the demand

C. Calculate the mass load of source and demand

$$M_s = FxC_{out} \qquad (5)$$

$$M_D = FxC_{in} \qquad (6)$$

Where M_s [mass load of source], F [flow rate of process], c_{out} [outlet concentration of source], M_D [mass load of demand] and C_{in} [inlet concentration of demand].

It should be pointed that there are three cases for mass load:

First - If the mass load of RKC for source (M_{RKCS}) is equal to the mass load of RKC for demand (M_{RKCD}). In this situation the source gives all water in it to demand.

Second- If the mass load of RKC for source (M_{RKCS}) is higher than the mass load of RKC for demand (M_{RKCD}). In this situation the source gives only the amount of water as follows

$$W_R = \left[\frac{M_D}{C_S^{out}}\right] \qquad (7)$$

Where W_R is the water required, M_D [mass load demand] and C_S^{out} [Outlet concentration of source] and the other needed water is taken from fresh water.

Third - If the mass load of RKC for source (M_{RKCS}) is lower than the mass load of RKC for demand (M_{RKCD}). In this situation the source gives all water in it to demand, and the other needed water is taken from the source which have next highest R_{ij} value.

D. Calculate new inlet and outlet concentration

Calculate new inlet and outlet concentration for each process after allocation as follows

$$C_{in}^{new} = \frac{\left(C_{in}^{old} x M_N\right)}{M_O} \qquad (8)$$

$$C_{out}^{new} = C_{out}^{old} - \left(C_{in}^{old} - C_{in}^{new}\right) \qquad (9)$$

Where C_{in}^{new} [new inlet concentration], C_{out}^{new} [new outlet concentration] , C_{in}^{old} [old inlet concentration], C_{out}^{old} [old outlet concentration], M_N [new mass load] and M_O [old mass load].

- *Allocation of source streams to demand streams*

E. Repeat step 2 until all the processes are completed

Example (1):

Table- I: Process data of Example (1)

Process number	contaminant	Outlet Concentration ppm	degree	Order
P 1	A	15	1	2
	B	400	2	
	C	35	1	1
P 2	A	120	2	12
	B	12500	3	
	C	180	2	3
P 3	A	220	3	9
	B	45	1	
	C	9500	3	2

Step (1)

Table- II: The order of processes

Process	contaminant	F^{max} (t/h)	$C^{max,\ in}$ (ppm)	$C^{max,\ out}$ (ppm)
1	A	45	0	15
	B		0	400
	C		0	35
2	A	34	20	120
	B		300	12500
	C		45	180
3	A	56	120	220
	B		20	45
	C		200	9500

The result of order process is

P_1-------- P_3------- P_2

Step (2)

Process 1 will be performed first which use fresh water consumption by using equation 2, 3

$$M_A = 45x15x10^{-3} = 0.675 \quad kg/h$$

$$M_A = 45x15x10^{-3} = 0.675 \quad kg/h$$

$$M_C = 45x35x10^{-3} = 1.575 \quad kg/h$$

$$F_{fresh}^{min} = max\left(\frac{0.675}{15}, \frac{18}{400}, \frac{1.575}{35}\right)$$

Then minimum fresh water = 45 T/h.

The calculation of process P_3 depends on the stream of the available sources: S_0 (fresh water) and S_1 (process P_1).

Table- III: The allocation of process P_3

Source (S_1)		Demand (D_3)		Quasi allocation by using equation (4)
S_1	C_{OUT} (ppm)	D_3	C_{in} (ppm)	
A	15	A	120	$R_A = \frac{120}{15} = 8$
B	400	B	20	$R_B = \frac{20}{400} = 0.05$
C	35	C	200	$R_C = \frac{200}{35} = 5.7$
				$R_{(S1)}$=min=0.05
				RKC = B

Step (3):

Calculate the mass load of RKC (B) for the source and demand by using equation5, 6

Mass of S_1 (MS_1) = $45x400x10^{-3}$= 18 Kg/h

Mass of D_3 (MD_3) = $56x20x10^{-3}$ = 1.12 Kg/h

The mass load of source is greater than that of demand

The reuse amount of S_1 is calculate with equation (7)

$$W_R = \frac{1.12}{400} x\ 10^3 = 2.8\ T/h$$

The amount of fresh water consumption = 56-2.8 = 53.2 T/h

Step (4):

Calculate the new inlet and outlet concentration of process (P_3) by using equation (8) and (9) as shown in the following table.

Table- IV: The new inlet and outlet concentration of process P_3

Contaminant	New mass load Kg/h	New inlet concentration (ppm)	New outlet concentration (ppm)
A	0.042	0.75	100.75
B	1.12	20	45
C	0.098	1.75	9301.75

Step (5):

The next performed process is process (P_2), the current available sources:

S_0 (Fresh water), S_1 (process P_1), S_3 (process P_3)

Table- V: The allocation of process (S_1, S_3, P_2)

	Source (S_1)	Source (S_3)	Demand (D_2)	allocation (S_1 , D_2)	allocation (S_3 , D_2)
Contaminant	C_{out}	C_{out}	C_{in}		
A	15	100.75	20	1.33	0.198
B	400	45	300	0.75	6.67
C	35	9301.75	45	1.286	0.005
				R_{S1}=min=0.75	R_{S3}=min=0.005
				RKC is B	RKC is C

To select the source should be reused first

R= max (R_{S1} ,R_{S3})= max(0.75, 0.005) = 0.75 , Then select S_1 with RKC is B

- Calculate the mass load of RKC (B) for the source and demand by using equation (5 ,6)

Mass of S_1 (MS_1) = $42.2x400x10^{-3}$= 16.88 T/h

Mass of D_2 (MD_2) = $34x300x10^{-3}$ = 10.2 T/h

The mass load of source is greater than that of demand

The reuse amount of S_1 is calculate with equation (7)

$$W_R = \frac{10.2}{400} x\ 10^3 = 25.5\ T/h$$

The amount of fresh water consumption = 34-25.5 = 8.5 T/h

Calculate the new inlet and outlet concentration of process (P_2) by using equation (8) and (9) in the following table

Table- VI: The new inlet and outlet of process P_2

Contaminant	New mass load Kg/h	New inlet concentration (ppm)	New outlet concentration (ppm)
A	0.383	11.26	111.26
B	10.2	300	12500
C	0.893	26.26	161.26

Table- VII: The Final concentration of processes

Process	Inlet concentration			Outlet concentration		
	A	B	C	A	B	C
P_1	0	0	0	15	400	35
P_2	0.75	20	1.75	100.75	45	9301.75
P_3	11.26	300	26.26	111.26	12500	161.26

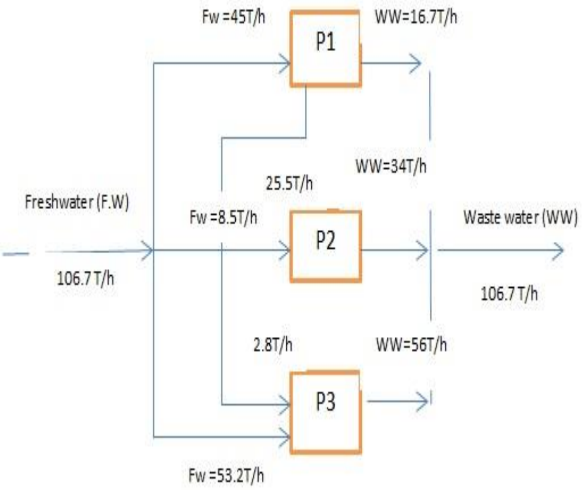
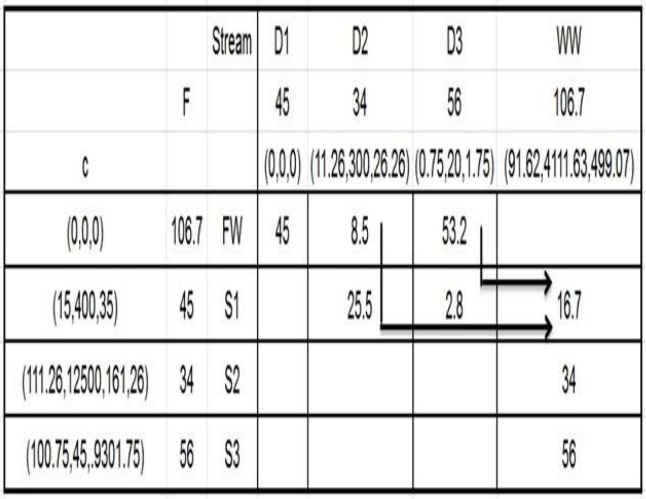


Fig. 1. Primary design network for example

Step (6):

To obtain simpler configuration from a preliminary one, we must be first calculated the minimum number of interconnections by applying Eq. (10)

Table- VIII: Network evolution with water path example (1)



		Stream	D1	D2	D3	WW
	F		45	34	56	106.7
c			(0,0,0)	(11.26,300,26.26)	(0.75,20,1.75)	(91.62,4111.63,499.07)
(0,0,0)	106.7	FW	45	8.5	53.2	
(15,400,35)	45	S1		25.5	2.8	16.7
(111.26,12500,161,26)	34	S2				34
(100.75,45,.9301.75)	56	S3				56

$$N_M^{Target} = N_S + N_D + 1 \qquad (10)$$

The number of matches = 8

The target of match number is

$$N_M^{Target} = 4 + 4 - 1 = 7$$

We found that there are two paths in the primary network:

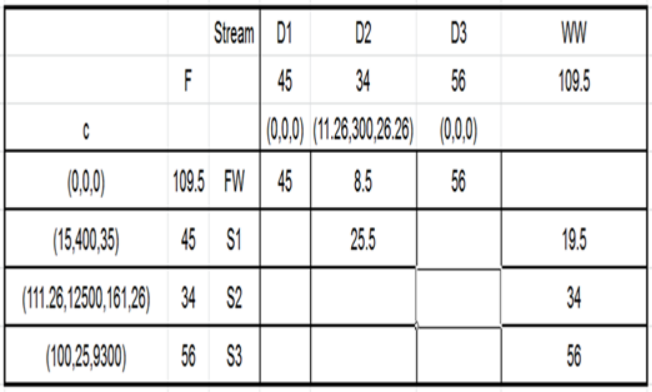
Path 1: FW- D_3, S_1-D_3, S_1-WW

Path 2: FW-D_2, S_1-D_2, S_1-WW

We choose to eliminate matches S_1- D_3 by path 1 relaxation to save the usage of fresh water in a minimum level.

The total fresh water usage in this design should be increased by 2.8 T/h

Table- IX: alternative network for example 1 with a fresh water penalty 2.8 T/h



		Stream	D1	D2	D3	WW
	F		45	34	56	109.5
c			(0,0,0)	(11.26,300,26.26)	(0,0,0)	
(0,0,0)	109.5	FW	45	8.5	56	
(15,400,35)	45	S1		25.5		19.5
(111.26,12500,161,26)	34	S2				34
(100,25,9300)	56	S3				56

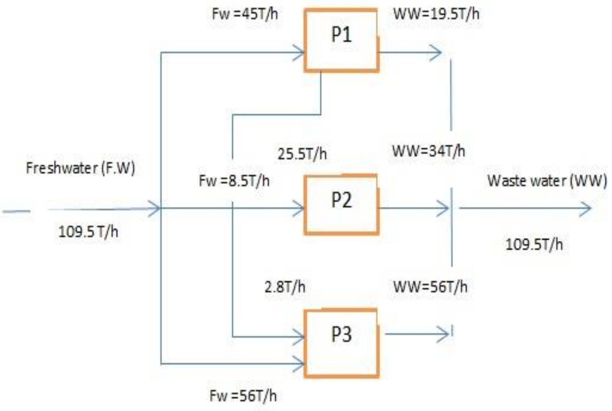


Fig. 2. Final design network for example 1

Table- X: The comparison between the results obtained in this search and that obtained in the literature methods

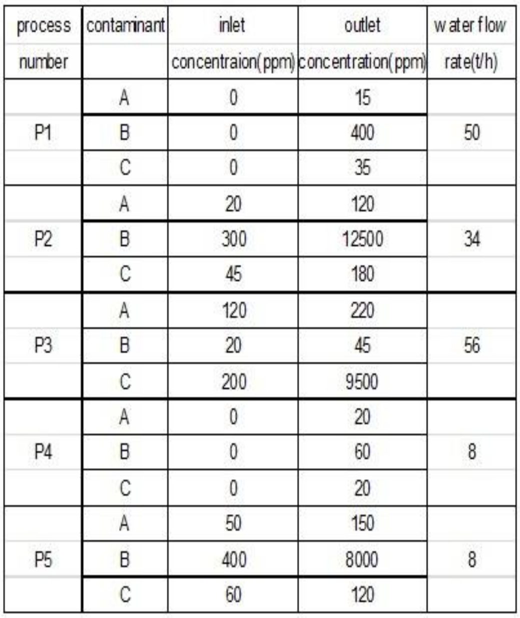
Literature	Method	Number of interconnection
Wang and Smith(1994)	Pinch technology	9
Li and Chang(2007)	Heuristic method	7
Zheng et al(2011)	Combining the concentration potential concepts with LP approach	9
Doyle and Smith(1997)	Linear and nonlinear optimization	8
Present work	Evolution method	7

We can see that the minimum number of interconnection of the designs which obtained in this work is comparable to or better than that obtained in the literature.

Example (2)

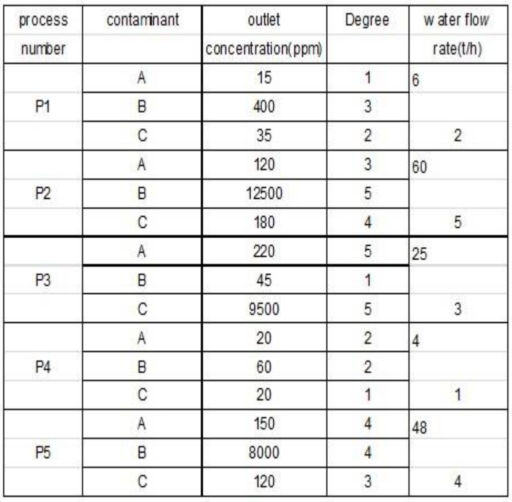
This example consider five processes (P_1, P_2, P_3, P_4 and P_5) involving three contaminants (A, B and C) with the following limiting water data

Table- XI: limiting process data of example (2)



process number	contaminant	inlet concentraion(ppm)	outlet concentration(ppm)	water flow rate(t/h)
P1	A	0	15	50
	B	0	400	
	C	0	35	
P2	A	20	120	34
	B	300	12500	
	C	45	180	
P3	A	120	220	56
	B	20	45	
	C	200	9500	
P4	A	0	20	8
	B	0	60	
	C	0	20	
P5	A	50	150	8
	B	400	8000	
	C	60	120	

Table- XII: The order of processes



process number	contaminant	outlet concentration(ppm)	Degree	water flow rate(t/h)
P1	A	15	1	6
	B	400	3	
	C	35	2	2
P2	A	120	3	60
	B	12500	5	
	C	180	4	5
P3	A	220	5	25
	B	45	1	
	C	9500	5	3
P4	A	20	2	4
	B	60	2	
	C	20	1	1
P5	A	150	4	48
	B	8000	4	
	C	120	3	4

The result of order process is

P_4------P_1-----P_3-----P_5-----P_2

Process (P_4)

Take fresh water = 8 T/h

Process (P_1)

Take fresh water = 50 T/h

Process (P_3)

The current available sources: So (Fresh water), S_4 (process P_4) and S_1 (process P_1)

Table- XIII: the allocation of process (S_1, S_3, P_2)

	Source (S_1)	Source (S_4)	Demand (D_3)	allocation (S_4 , D_3)	allocation (S_1 , D_3)
Conta-minant	C_{out}	C_{out}	C_{in}		
A	15	20	120	6	8
B	400	60	20	0.33	0.05
C	35	20	200	10	5.71
				R_{S1}=min=0.33	R_{S3}=min=0.05
				RKC is B	RKC is B

To select the source should be reused first

R= max (R_{S1} ,R_{S4})= max(0.33, 0.05) = 0.33 Then select S_4 with RKC is B

- Calculate the mass load of RKC (B) for the source and demand by using equation (5, 6)

Mass of S_4 (MS_4) = 8x60x10^{-3}= 0.48 Kg/h

Mass of D_3 (MD_3) = 56x20x10^{-3} = 1.12 Kg/h

The mass load of source is smaller than that of demand so S4 give all water to D_3=8 T/h

D_3 take water from other source S_1

-Calculate the mass load of RKC (B) for the source and demand by using equation

Mass of S_1 (MS_1) = 50x4000x10^{-3}= 20 Kg/h

Mass of D_3 (MD_3) = 1.12-(5x60x10^{-3}) = 0.64 kg/h

The mass load of source is greater than that of demand

The reuse amount of S_1 is calculate with equation (7)

$$W_R = \frac{0.64}{400} \text{x } 10^3 = 1.6 \text{ T/h}$$

The amount of fresh water consumption = 56-8-1.6 = 46.4 T/h

- Calculate the new inlet and outlet concentration of process (P3) by using equation (8) and (9) as shown in the following table

Table- XIV: New inlet and outlet concentration of P3

Contaminant	New mass load Kg/h	New inlet concentration (ppm)	New outlet concentration (ppm)
A	0.184	3.29	103.3
B	1.12	20	45
C	0.216	3.86	9303.9

Process (P_5)

The current available sources: So (Fresh water), S_3 (process P_3) and S_1 (process P_1)

Table- XV: The allocation of process (S1, S3, and D5)

	Source (S_1)	Source (S_3)	Demand (D_5)	allocation (S_1 , D_5)	allocation (S_3 , D_5)
Conta-minant	C_{out}	C_{out}	C_{in}		
A	15	103.29	50	3.33	0.48
B	400	45	400	1	8.89
C	35	9303.9	60	1.71	0.006
				R_{S1}=min =1	R_{S3}=min = 0.006
				RKC is B	RKC is C

To select the source should be reused first

R= max (R_{S1} ,R_{S3})= max(1, 0.006) = 1 Then select S_1 with RKC is B

- Calculate the mass load of RKC (B) for the source and demand by using equation (5, 6)

Mass of S1 (MS_1) = 48.4x400x10^{-3}=19.4 Kg/h

Mass of D_5 (MD_5) = 8x400x10^{-3} = 3.2 kg/h

The mass load of source is greater than that of demand

The reuse amount of S_1 is calculate with equation (7)

$$W_R = \frac{3.2}{400} \text{x } 10^3 = 8 \text{ T/h}$$

- Calculate the new inlet and outlet concentration of process (P_5) by using equation (8) and (9) in the following table

Table- XVI: New inlet and outlet Concentration of P_5

Contaminant	New mass load Kg/h	New inlet concentration (ppm)	New outlet concentration (ppm)
A	0.12	15	115
B	3.2	400	8000
C	0.28	35	95

Process P_2

The current available sources: So (Fresh water), S_1 (process P_1), S_3 (process P_3) and S_5 (process P_5)

Table- XVII: The allocation of process (S_1, S_3, S_5, and D_2)

	Source (S_1)	Source (S_3)	Source (S_5)	Demand (D_2)	allocation (S_1 , D_2)	Allocation (S_3, D_2)	Allocation (S_5, D_2)
Contaminant	Cout (ppm)	Cout (ppm)	Cout (ppm)	C_{in} (ppm)			
A	15	103.3	115	20	1.33	0.19	0.174
B	400	45	8000	300	0.75	6.67	0.037
C	35	9303.9	95	45	1.28	0.0048	0.47
					$R_{S1=}$min= 0.75	R_{S3}=min=0.0048	R_{S3}=min= 0.037
					RKC is B	RKC is C	RKC is B

To select the source should be reused first

R= max (R_{S1}, R_{S3}, R_{S5}) = max (0.75, 0.0048, 0.037) = 0.75

Then select S_1 with RKC is B

- Calculate the mass load of RKC (B) for the source and demand by using equation (5, 6)

Mass of S1 (MS_1) = $40.4 \times 400 \times 10^{-3} = 16.2$ Kg/h

Mass of D_2 (MD_2) = $34 \times 300 \times 10^{-3} = 10.2$ Kg/h

-The mass load of source is Greater than that of demand

-The reuse amount of S_1 is calculate with equation (7)

$$W_R = \frac{10.2}{400} \times 10^3 = 25.5 \text{ T/h}$$

The amount of fresh water consumption = 34-25.5 = 8.5 T/h

- Calculate the new inlet and outlet concentration of process (P_2) by using equation (8) and (9) as shown in the following table

Table- XVIII: New inlet and outlet Concentration of P_2

Contaminant	New mass load Kg/h	New inlet concentration (ppm)	New outlet concentration (ppm)
A	0.382	11.23	111.23
B	10.2	300	12500
C	0.892	26.25	161.25

Table- XIX: The Final concentration of processes

Process	Inlet concentration			Outlet concentration		
	A	B	C	A	B	C
P_4	0	0	0	20	60	20
P_1	0	0	0	15	400	35

P_3	3.29	20	3.86	103.29	45	9303.9
P5	15	400	35	115	8000	95
P5	11.23	300	26.25	111.23	12500	161.25

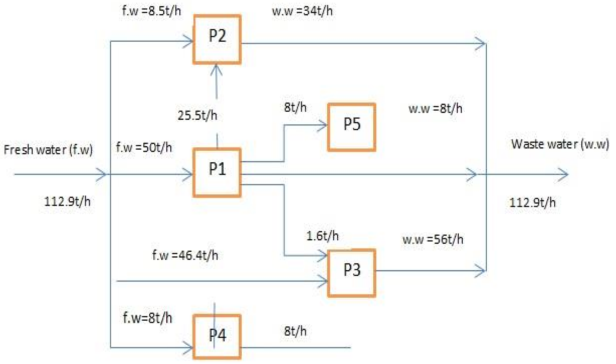


Fig. 3. Primary design network for example 2

To obtain simpler configuration from a preliminary one, we must first calculated the minimum number of interconnections as a design target by applying Eq. (10)

$$N_M^{Target} = N_S + N_D - 1 \qquad (10)$$

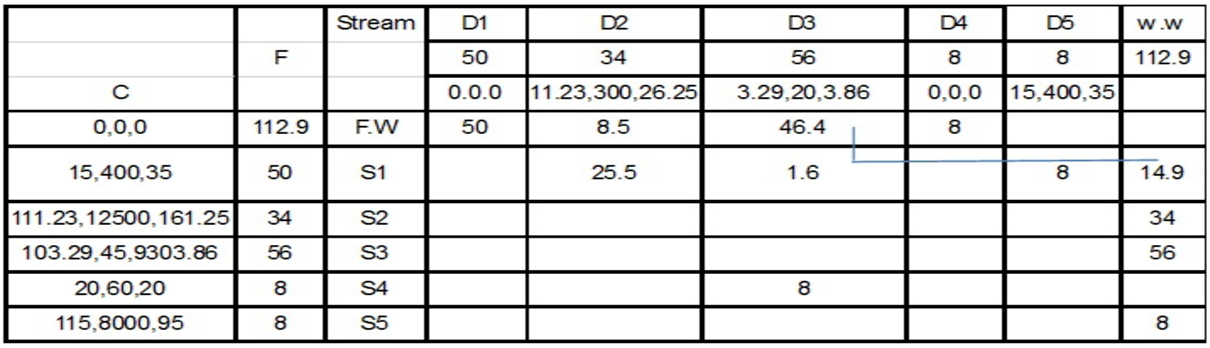
The number of matches = 12

The target of match number is

$$N_M^{Target} = 6 + 6 - 1 = 11$$

Only one path relaxation (F.W-D_3, S_1-D_3, S_1-W.W)

Table- XX: Network evolution with water path



		Stream	D1	D2	D3	D4	D5	w.w
	F		50	34	56	8	8	112.9
C			0.0.0	11.23,300,26.25	3.29,20,3.86	0,0,0	15,400,35	
0,0,0	112.9	F.W	50	8.5	46.4	8		
15,400,35	50	S1		25.5	1.6		8	14.9
111.23,12500,161.25	34	S2						34
103.29,45,9303.86	56	S3						56
20,60,20	8	S4			8			
115,8000,95	8	S5						8

Table- XXI: alternative network for example 2 with a fresh water penalty 1.6 T/h

C	F	Stream	D_1	D_2	D_3	D_4	D_5	w.w
			50	34	56	8	8	115
			0.0.0	11.23,300,26.25	2.86,8.57,2.86	0,0,0	15,400,35	
0,0,0	114.5	F.W	50	8.5	48	8		
15,400,35	50	S1		25.5			8	16.5
111.23,12500,161.25	34	S2						34
102.86,33.57,9302.86	56	S3						56
20,60,20	8	S4			8			
115,8000,95	8	S5						8

Number of matches = 11

The total fresh water usage in this design should be increased by 1.6 T/h.

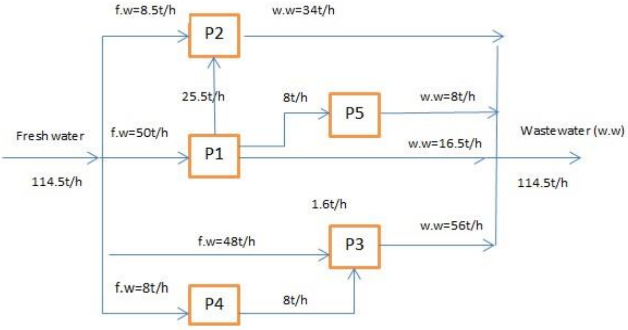


Fig. 4. Final design network for example 2

IV. CONCLUSION

The proposed method is demonstrated for the design of the water using network in two steps. Step (1) the allocation of process for water using network, step (2) is evolution of primary design to obtain a minimum number of interconnections.

The solution obtained from the presented method compare favorably with those in the literature and the results well demonstrate the effectiveness of proposed approach.

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