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ON A SYSTEMATIC DESIGN PROCEDURE FOR SINGLE COMPONENT WATER UTILIZATION SYSTEMS IN PROCESS PLANTS

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This paper presents a robust methodology to obtain an optimal design of the single component water/wastewater allocation problem in process plants. The method uses a concentration grid water allocation procedure to obtain preliminary optimal structures. A merging procedure provides the final structures. The use of different water allocation strategies shows that the problem has several alternative solutions.

Keywords: Water management; Wastewater reuse

INTRODUCTION

Refineries, petrochemical and chemical plants intensively utilize water. Environmental laws are forcing refineries and chemical plants to use the minimum water required for their processes in order to reduce their wastewater production. The primary solution was traditionally an end-of-pipe wastewater treatment. Scarcity of water, rising energy costs and stricter regulations on industrial effluents has created a new and different view on water usage. Several procedures have been proposed to design economical

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wastewater treatment. Belhateche [1] offers a complete discussion of these technologies. In addition to the improved efficiency obtained by analyzing wastewater treatment facilities and reducing the sources of pollutants, the concept of reusing water started to be investigated systematically in the eighties. This problem has received the name of Water/Wastewater Allocation Problem (WAP).

Takama *et al.* [2] was the first to use mathematical programming and superstructures to solve the WAP problem for a refinery example. Wang and Smith [3] presented a method to perform the targeting of minimum fresh water consumption. Wang and Smith [3] also proposed a methodology that can design reuse networks. They also explored options of regenerating wastewater even when the pollutant level has not reach end-of-pipe conditions, or has not be reused throughout the entire process. Dhole *et al.* [4] popularized this methodology calling it the "water pinch". The "water pinch" approaches the WAP problem plotting the cumulative exchanged mass *vs.* composition for a set of rich and lean streams, a concept first presented by El-Halwagi and Manousiouthakis [5] for synthesizing Mass Exchanger Networks. Once all units are accounted for, a combined composite curve from all limiting profiles is created. This composite curve represents the overall behavior of the system as a single water-using unit. A fresh water supply line is then matched against the composite curve to reach a pinch point other than the origin. Once the target flowrate is obtained the authors proposed a matching method similar to the procedure followed when constructing Heat Exchanger Networks (Linnhoff and Hindmarsh [6]).

Two network design methods through water re-use have been presented by Wang and Smith [3]. Their first approach uses the *maximum driving force* available within processes. However, they show that this approach may lead to non-feasible solutions of the water network. They also proposed a second design method based on the *minimum number of water sources*. This method is based on dividing the processes in concentration intervals, and then assigning the required flowrate to each process. A rather complex loop-breaking strategy follows. In the context of a large number of too many loops are generated and there is no systematic procedure that can be applied to break them. Finally, the case where many water sources and sinks are available in the same concentration interval is not considered. In summary, the method seems to be reliable only when the number of processes is low, requiring special skills for larger systems. Moreover, there is no set of rules or algorithm that can allow implementation of these in a form of a computer program.

Attempting to ameliorate all the aforementioned difficulties, Olesen and Polley [7] presented a simplified methodology to design the water network based on the water-pinch target. They classify all processes in an elaborated way, assigning water to each one using inspection rules. Although the approach is fairly simple the authors recognized the limitation of the proposed method themselves. The procedure is only satisfactory in the design of networks with up to four or five processes. For more complex problems, is not clear how water is assigned from one operation to another. In cases where there is more then one water source, the method does not follow any rule to assign water to the following operation interval. Therefore, processes crossing the pinch can cause problems.

Another attempt to overcome the difficulties and inefficiencies of previous work was presented by Kuo and Smith [8]. They first recognized that the design procedures proposed by Wang and Smith [3] "are somewhat complex". They proposed a network design method that combines fresh water allocation and wastewater treatment introducing the concept of *water mains*. These water mains act as intermediate sinks and sources of water of certain quality. The method only offers guidelines and fails to provide a systematic procedure for the design of water utilization systems in large-scale problems. Indeed, the method is intuitive but has only been shown to be effective for small systems.

The problem is in reality a special case of mass exchanger network synthesis. It has taken a life of its own for which several especial methodologies have been proposed. This paper presents a new systematical procedure to obtain a water network that realizes the minimum water target regardless of problem size. The design is restricted to the treatment of single contaminant cases.

PROBLEM STATEMENT

Given a set of water-using/water-disposing processes, it is desired to determine a network of interconnections of water streams among the processes so that the overall fresh water consumption is minimized, while the processes receive water of adequate quality. This is what is referred to as the Water/Wastewater Allocation Planning (WAP) problem.

A more stringent version of this problem was the one presented by Takama *et al.* [2] and later used by Wang and Smith [3]. In this version, limits on inlet and an outlet concentration of pollutant are imposed *a-priori* on each process and a fixed load of contaminants is used. These inlet and outlet concentrations limits account for corrosion, fouling, maximum solubility, *etc.*

NEW DESIGN METHOD

The new procedure is based on the construction of a concentration grid, similar to the one proposed by Wang and Smith [3]. The first step requires obtaining the target, which can be performed using the same method proposed by Wang and Smith [3]. After the minimum fresh water is determined, the method requires that a concentration grid, based on maximum inlet and outlet concentrations be constructed. All processes are allocated within this grid such that they appear in as many intervals as their respective inlet and outlet maximum concentrations span through.

The second step requires assigning all the available fresh water to all fresh water users. The amount of water supplied is only the required to reach the outlet concentration of the first interval. In a third step, wastewater from these processes is assigned to processes in the subsequent intervals as required. Additional fresh water is used as needed. Figure 1 illustrates the allocation of fresh water at each interval in each of the processes.

To assign water from one process to another in any subsequent interval it is necessary to define all the sources available from previous intervals. These sources can be either fresh water, or some wastewater coming from other previous concentration intervals. All processes must reuse their own water.

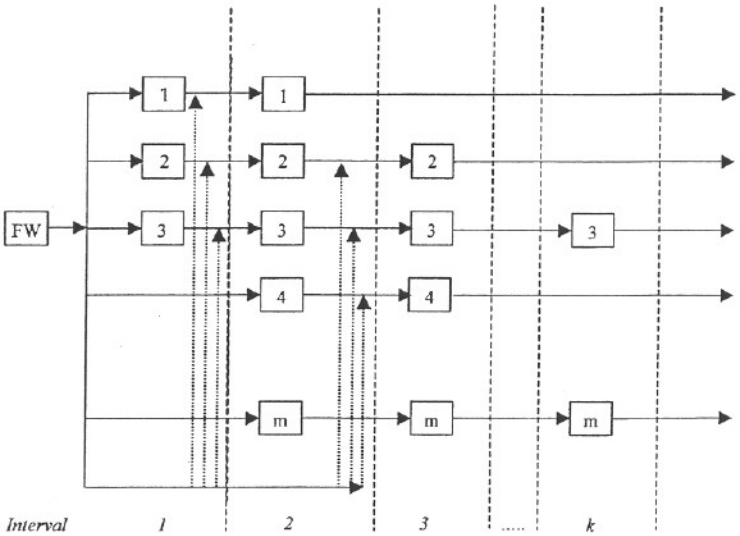

FIGURE 1 Initial allocation of fresh water in the 'm' processes involved.

Three different approaches to perform the wastewater allocation are discussed next.

Assignment Procedures

Consider a set of n wastewater users in interval k, and assume wastewater from m processes is available.

Mixers

In this first approach, all available wastewater sources from previous concentration intervals are mixed to convene into just one source. Then, wastewater is taken from this mixer to supply all the water requirements at the given concentration interval. Water moving between concentration intervals and going through the same operation would not be defined as a water source available so that unnecessary unit splitting is avoided. Figure 2 shows a schematic example where the water moves within processes 1 and 2 and a mixer is formed using the outlet streams from processes 3 through m. Water coming out from the mixer is available to feed water requirements in the next concentration interval. Operations 1 and 2 require additional water to complete the load pick-up and this water is supplied by the mixer. Process n is new in the concentration interval under study and it receives water from the mixer only. Some water in the mixer may not be required and the excess bypassed to the next concentration interval, to be reused in other downstream processes.

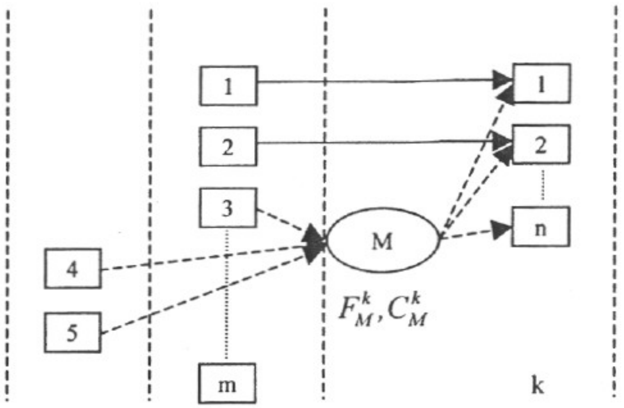

FIGURE 2 Mixing available water sources to supply water sinks.

Use of the Worst Quality Water Available First

In this approach, processes at a certain concentration interval are provided with the available wastewater at the worst possible concentration. To illustrate this approach, consider Figure 3 where process 3 and process 5 are the only available wastewater sources to provide processes 1, 2 and 4. Assume also that the outlet concentration of process 3 is larger than of process 5. In this approach, the most contaminated water, coming from process 3, must be used first. If needed, water from the other source, process 5, should be also used. Finally, any process can be the first one served. The required water for each operation can be calculated by a component mass balance performed at the receiving process. Any wastewater excess is also bypassed to the next concentration interval, to be used in another downstream process. Following this criterion, bypassed water will always be at the lowest possible concentration. As pointed out by Kuo and Smith [8], this may help obtain some wastewater streams cleaner than others.

Use of the Cleanest Water Available First

Assigning the cleanest water first maximize the driving force within the process. This approach helps reduce the size of the equipment and may also lower the number of interconnections among processes.

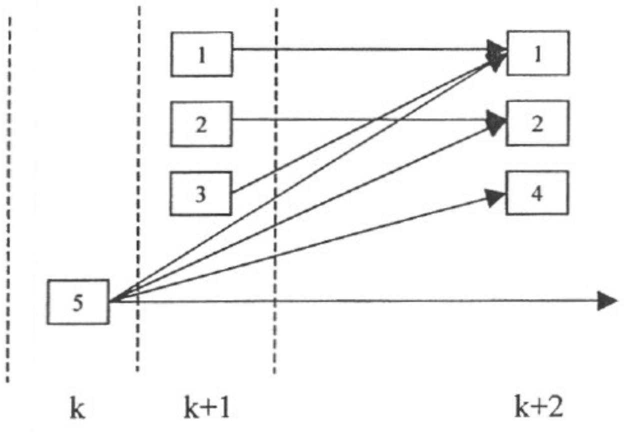

FIGURE 3 Assigning the most contaminated water first.

Advantages and Disadvantages

Mixing

The mixing approach provides with a sole wastewater source, which could be economical from a point of view of the associated piping. This facilitates calculations when assigning water to receiving processes. It also eliminates the necessity of an assignment rule to decide how to order the precursors to be used. A particular drawback of this rule is that cleaner wastewater can be mixed with others of higher contaminant concentration degrading the quality of the less polluted wastewater.

Higher Vs. Lower Polluted Wastewater Used First

The water flowrate necessary to remove a given pollutant load increases as the quality of the used wastewater decreases. A large flowrate may not be possible to handle by an already existing unit or the increase in capital investment associated with the design may not be economical. In addition, operating costs for heat and/or cooling as well as pumping could increase, as the flowrate needed for the task increases. Therefore, the utilization of cleaner wastewater may in certain cases present a greater advantage. The contaminants and the type of cleanup operations available in the wastewater treatment plant are also of vital consideration when deciding the quality of wastewater to be used. For example, concentration-difference driven processes, such as liquid–liquid extraction, may not be able to remove the contaminant to its final discharge limit. Other treatments, like those having live microorganisms, can be severely damage due to toxicity of large concentrations of certain pollutants. Therefore, favoring the bypass of large amount of wastewater at high/low concentrations of contaminant need to be thoroughly analyzed before choosing a policy.

In addition, the use of the above rules of assignment of wastewater policies varies depending on whether the pinch concentration has been reached or not. This is discussed next.

Use of the Assignment Procedures Below the Pinch

To fulfill the water requirements of each process at concentrations below the pinch, the total water in use will continuously increase because fresh water is added until the target value is completely utilized. All the wastewater exits the pinch interval at pinch concentration. For these reasons, the assignment method used will not alter the discharge concentration to the subsequent intervals and to the wastewater treatment plant.

Thus, below the pinch freshwater is assigned until it is depleted. Then a mixer can be created. When the water from this first mixture is completely consumed it is always possible to create another mixer of the sources available in that interval, this method is very useful and can always be done up to the water pinch. Alternatively, the two other policies can be used.

Occasionally, a water source is enough to feed a process close to it, therefore moving this water through a pipeline to a mixer could be unworthy. It is then possible to use a combination of the three approaches shown before in order to reduce transportation costs and simplify the water network. Figure 4 shows a combined approach.

Sometimes large distances between processes, difficulties to build by-pass pipelines, heat transfer requirements or any other limitations, can determine the design criteria rather than a fixed design method. In order to minimize costs and simplify the water network, adding more fresh water could be considered.

Use of the Assignment Procedures Above the Pinch

After the water pinch, there will be more water available than the required amount to remove the remaining loads. In other words, a surplus of wastewater is present after crossing the pinch point. Downstream requirements at the water treatment plant should be emphasized in the decision making process.

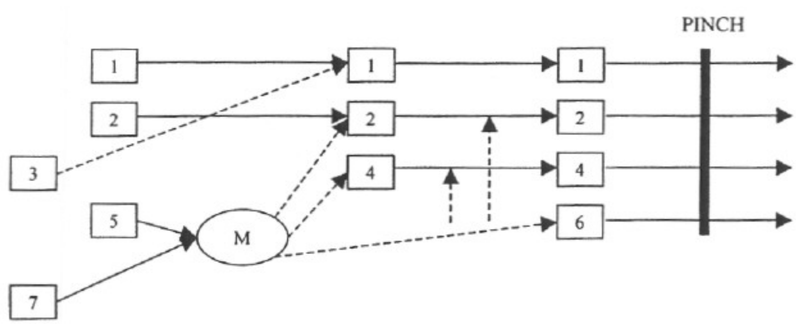

FIGURE 4 Combined design of a water network before the 'pinch'.

Determination of Flowrates

A precursor of a process can be another process or a mixer. Consider a precursor of process j in an interval i as shown in Figure 5. The pollutant concentration of the precursor is always lower ($C^i_{P_j,j} \leq C^{i-1}_j$). This is a consequence of the grid construction. The values of m^i_j, F^{i-1}_j, C^{i-1}_j, C^i_j and $C^i_{P_j,j}$ are known. Therefore, the values of $F^i_{P_j,j}$ and F^i_j need to be determined. To do this, overall and contaminant mass balances are done. When only fresh water is available, $F^i_{P_j,j}$ becomes $F^i_{w,j}$ and $C^i_{P_j,j}$ will be equal to zero. Regardless whether a precursor is another process or a mixer the mass balances can be simultaneously solved for $F^i_{P_j,j}$ and F^i_j.

$$F^i_j = F^{i-1}_j + F^i_{P_j,j} \tag{1}$$

$$F^{i-1}_j C^{i-1}_j + F^i_{P_j,j} C^i_{pj,j} + m^i_j - F^i_j C^i_j = 0 \tag{2}$$

$$F^i_{P_j,j} = \frac{F^{i-1}_j (C^i_j - C^{i-1}_j) - m^i_j}{C^i_{P_j,j} - C^i_j} \tag{3}$$

If $F^i_{P_j,j} > F_{P_j}$, then another source should be added to fulfil the water requirements of the process. This procedure is repeated until the conditions of process j have been met. In general, for m precursors providing process j in interval i, (1) and (2) can be written as follows:

$$F^i_j = F^{i-1}_j + \sum_k^m F_{P_k,j} \tag{4}$$

$$\sum_k^m F^i_{P_k,j} C^i_{P_k,j} + F^{i-1}_j C^{i-1}_j + m^i_j - F^i_j C^i_j = 0 \tag{5}$$

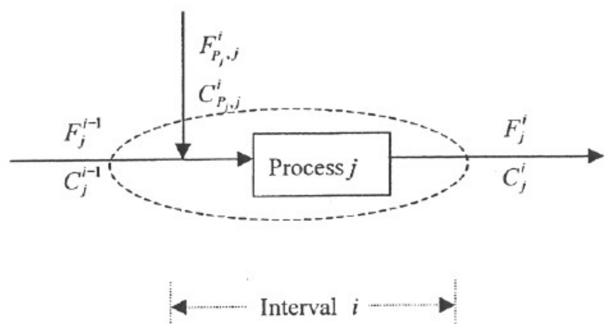

FIGURE 5 Schematic representation of process j through interval i.

Combining (4) and (5),

$$F^i_{P_m,j} = \frac{\sum_k^{m-1} F^i_{P_k,j}(C^i_j - C^i_{P_k,j}) + F^{i-1}_j(C^i_j - C^{i-1}_j) - m^i_j}{C^i_{P_m,j} - C^i_j} \tag{6}$$

The total flowrate through process j can then be calculated from (1) or (4).

As a result of these steps a preliminary grid assignment of water is obtained. This is illustrated next.

Example 1 This example is taken from Olesen and Polley [7]. It comprises 6 water-using processes. Table I provides the limiting data and Figure 6 shows the design obtained with our method.

As illustrated in Figure 6, in this problem fresh water is used to supply the water requirements of processes 1, 2, 3, 4, and 5 up to interval 2. In interval 3, fresh water is exhausted before process 5 requirements are completely fulfilled. The only wastewater available for reuse is from process 1. No other processes are completed in this interval hence it is not possible to create a mixer. Therefore, wastewater is sent from process 1 to process 5, the only process that needs additional water. In interval 4, process 3 still needs water. Wastewater is available from processes 2 and 4, both at 100 ppm. No real gain would be obtained from mixing because the resulting wastewater would have the same concentration. If either process 2 or 4 cannot fulfill process 3 requirement; then, mixing would reduce the number of interconnections. Using Eq. (3) the necessary flowrate at 100 ppm is calculated. Since this flowrate does not exceed the availability from process 2, no mixing is performed. Finally, wastewater from process 2 is used to feed process 6.

Merging

The operations are split at each concentration interval in the preliminary grid solution. The splitting is a consequence of having to remove a certain mass load at each concentration interval. These kinds of networks are not

TABLE I Limiting data for Example 1

Process number	*Mass load of contaminant (kg/h)*	C^{max}_{in} *(ppm)*	C^{max}_{out} *(ppm)*
1	2.0	25	80
2	5.0	25	100
3	4.0	25	200
4	5.0	50	100
5	30.0	50	800
6	4.0	400	800

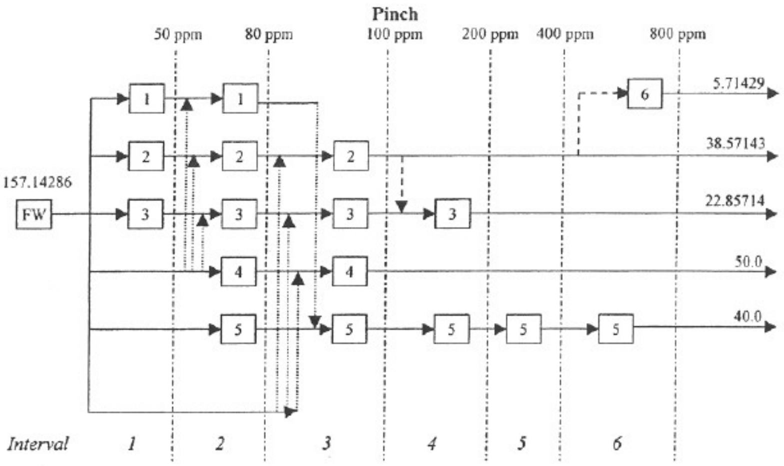

FIGURE 6 Preliminary design of the water network.

real solutions to the problem because unit operations can not be represented or built in reality as a collection of smaller processes. Therefore, as a final step, a network merging is done.

Figure 7 illustrates the merging procedure. All the individual mass loads of the process are transferred upstream and a combined feed stream at the entrance of the operation is obtained. The water sources would be added and used as new feed. This merging was proposed by Kuo and Smith [8] but a proof of its validity was not presented. Such proof is given next.

Consider a process j, which has been split into n parts throughout the concentration grid. Figure 8 shows a schematic representation of the situation. At each concentration interval i, there is a precursor, P_j^i, providing the necessary water to remove the partial load m_j^i. The proof that follows shows that the first two intervals can always be merged into one as shown in Figure 9. An overall merging can then be performed by a sequential repetition of the aforementioned basic merging process.

Proof Consider a merging of the second feed as shown in Figure 9. The merge is feasible if and only if

$$C_{j,\text{in}} \leq C_{j,\text{in}}^{\max} \tag{7}$$

$C_{j,\text{in}}$ can be obtained from a component mass balance at the inlet of (b),

$$C_{j,\text{in}} = \frac{F_{P_j,j}^1 C_{P_j,j}^1 + F_{P_j,j}^2 C_{P_j,j}^2}{F_{P_j,j}^1 + F_{P_j,j}^2} \tag{8}$$

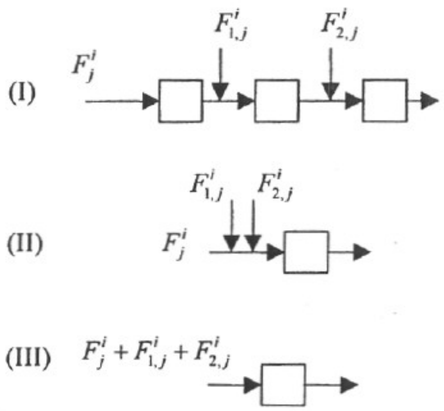

FIGURE 7 Operation merge. The breached process is recombined by adding all water sources.

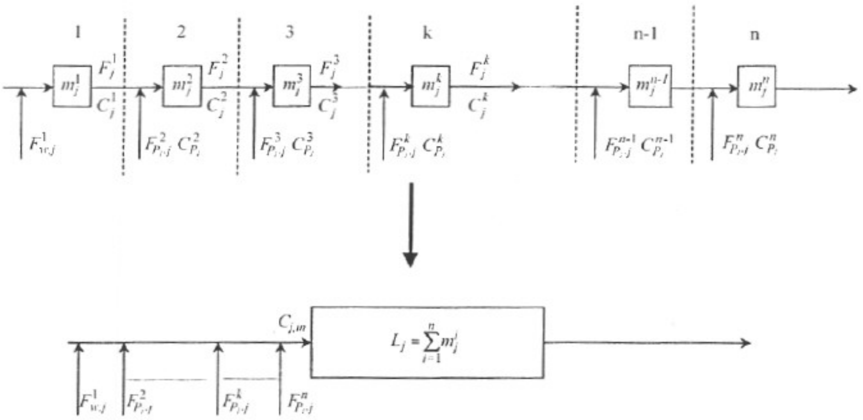

FIGURE 8 Merging of a split process.

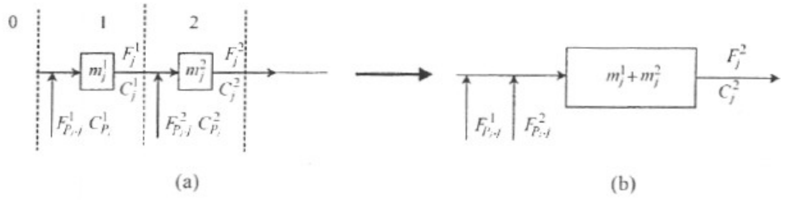

FIGURE 9 Merging of two segments of a process.

Rewriting (7) using (8) and rearranging, we obtain

$$F^1_{P_j,j}\left(C^1_{P_j,j} - C^{\max}_{j,\text{in}}\right) + F^2_{P_j,j}\left(C^2_{P_j,j} - C^{\max}_{j,\text{in}}\right) \leq 0 \tag{9}$$

which is what needs to be proven.

By grid construction,

$$m^1_j = L_j \frac{\left(C^1_j - C^{\max}_{j,\text{in}}\right)}{\left(C^{\max}_{j,\text{out}} - C^{\max}_{j,\text{in}}\right)} \tag{10}$$

and

$$m^2_j = L_j \frac{\left(C^2_j - C^1_j\right)}{\left(C^{\max}_{j,\text{out}} - C^{\max}_{j,\text{in}}\right)} \tag{11}$$

The grid construction also requires that $C^0_j = C^{\max}_{j,\text{in}}$.

Performing a component mass balance at the outlet conditions of interval 1, we get

$$F^1_{P_j,j} C^1_{P_j,j} + m^1_j = F^1_{P_j,j} C^1_j \tag{12}$$

Using (10) and (12) we obtain,

$$F^1_{P_j,j} = \frac{L_j}{\Delta C^{\max}_j} \frac{\left(C^1_j - C^{\max}_{j,\text{in}}\right)}{\left(C^1_j - C^1_{P_j,j}\right)} \tag{13}$$

where $\Delta C^{\max}_j = C^{\max}_{j,\text{out}} - C^{\max}_{j,\text{in}}$.

A component mass balance for the second interval is

$$F^1_{P_j,j} C^1_{P_j,j} + F^2_{P_j,j} C^2_{P_j,j} + m^1_j + m^2_j = \left(F^1_{P_j,j} + F^2_{P_j,j}\right) C^2_j \tag{14}$$

Replacing (10), (11) and (13) into (14), we can obtain an equation for $F^2_{P_j,j}$.

$$F^2_{P_j,j} = \frac{L_j}{\Delta C^{\max}_j} \frac{\left(C^2_j - C^1_j\right)}{\left(C^2_j - C^2_{P_j,j}\right)} \frac{\left(C^{\max}_{j,\text{in}} - C^1_{P_j,j}\right)}{\left(C^1_j - C^1_{P_j,j}\right)} \tag{15}$$

Replacing first the formula for $F^1_{P_j,j}$ (13) and for $F^2_{P_j,j}$ (15) into the l.h.s. of (9) and simplifying, we obtain

$$\begin{aligned} &F^1_{P_j,j}\left(C^1_{P_j,j} - C^{\max}_{j,\text{in}}\right) + F^2_{P_j,j}\left(C^2_{P_j,j} - C^{\max}_{j,\text{in}}\right) \\ &\quad = \frac{L_j}{\Delta C^{\max}_j} \frac{\left(C^2_j - C^{\max}_{j,\text{in}}\right)\left(C^1_{P_j,j} - C^{\max}_{j,\text{in}}\right)\left(C^1_j - C^2_{P_j,j}\right)}{\left(C^2_j - C^2_{P_j,j}\right)\left(C^1_j - C^1_{P_j,j}\right)} \end{aligned} \tag{16}$$

The left hand side of (16) is the same as the left hand side of (9). Now, by grid construction we know that,

$$C_j^2 - C_{j,\text{in}}^{\max} > 0, C_j^2 - C_{P_j,j}^2 > 0, C_j^1 - C_{P_j,j}^1 > 0,$$
$$C_j^1 - C_{P_j,j}^2 \geq 0 \text{ and } C_{P_j,j}^1 - C_{j,\text{in}}^{\max} \leq 0.$$

Then, since $(L_j/\Delta C_j^{\max}) > 0$, (9) is proven correct.

Example 1 (Continued) The final design obtained after merging is the one shown in Figure 10. Process 6 requires 5.71 ton/h of water at 100 ppm to remove the contaminants. In this case the water has been taken from process 2, but it could has also been taken from process 4, and even from process 3. Since a lot of sources can be used to supply these non-fresh water users, decisions of this type should be mainly based on geographical (distance between processes), preexisting interconnections, equipment volume limitations or any other additional constraint in the design.

Example 2 A ten water-using processes is proposed. Table II shows the corresponding limiting data for this example problem. Targeting is performed according to Wang and Smith [3] method. The minimum fresh water target is 166.26667 ton/h.

All three water assignment policies are applied to this example, and three different solution networks are obtained. The design networks and the tables of results are presented below.

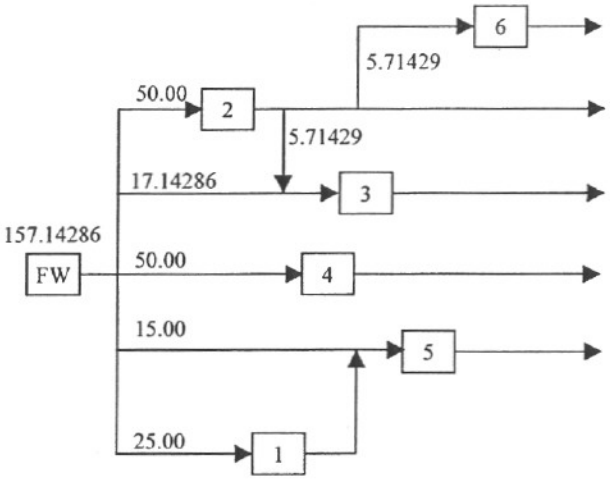

FIGURE 10 Final design of the water network for Example 1.

TABLE II Limiting data for Example 2

Process number	*Mass load of contaminant (kg/h)*	C_{in}^{max} *(ppm)*	C_{out}^{max} *(ppm)*	*Minimum fresh water flow rate without reuse (ton/h)*
1	2.0	25	80	25.0
2	2.88	25	90	32.0
3	4.0	25	200	20.0
4	3.0	50	100	30.0
5	30.0	50	800	37.5
6	5.0	400	800	6.25
7	2.0	200	600	3.3333
8	1.0	0	100	10.0
9	20.0	75	300	66.6667
10	6.5	150	300	21.6667
	Total minimum flowrate (ton/h)			252.4167

TABLE III Results of Case A

Process number	$F_{i,j}$ *(ton/h)*	C_{in} *(ppm)*	*Minimum fresh water flowrate with reuse (ton/h)*	*Wastewater flowrate (ton/h)*
1	0.00000	0.00000	25.00000	0.00000
2	0.00000	0.00000	32.00000	0.00000
3	$F_{I,3}=1.75629$	7.72845	19.04762	0.00000
4	0.00000	0.00000	30.00000	0.00000
5	$F_{I,5}=9.59446$ $F_{II,5}=3.73887$	50.00000	26.66667	40.00000
6	$F_{II,6}=10.0000$	300.00000	0.00000	10.00000
7	$F_{3,7}=5.00000$	200.00000	0.00000	5.00000
8	0.00	0.00	10.00	0.00000
9	$F_{I,9}=62.04875$	66.35823	23.55238	0.00000
10	$F_{I,10}=23.60049$ $F_{3,10}=15.80392$	135.04387	0.00000	0.00000
Mixer I	$F_{1,I}=25.00000$ $F_{2,I}=32.00000$ $F_{4,I}=30.00000$ $F_{8,I}=10.00000$	91.54639	0.00000	0.00000
Mixer II	$F_{9,II}=85.60113$ $F_{10,II}=39.40441$	300.00000	0.00000	111.26667

Case A Solution obtained using mixers.

Fresh water is available to fulfill the needs of the first six intervals and is depleted before the needs of process 9 can be fulfilled in interval 7. The total number of interconnections among processes (including the mixer) is 14. Ten of those correspond to connections below the pinch. Figures 11 and 12 show the preliminary and the final design network respectively.

TABLE IV Results of Case B

Process number	$F_{i,j}$ (ton/h)	C_{in} (ppm)	Minimum fresh water flowrate with reuse (ton/h)	Wastewater flowrate (ton/h)
1	0.00000	0.00000	25.00000	0.00000
2	0.00000	0.00000	32.00000	0.00000
3	$F_{2,3}=1.731602$	7.50000	19.04762	0.00000
4	0.00000	0.00000	30.00	0.00000
5	$F_{2,5}=6.06061$ $F_{4,5}=0.95556$ $F_{8,5}=2.68081$ $F_{9,5}=3.63636$	50.00000	26.66667	40.00000
6	$F_{9,6}=10.0000$	300.00000	0.00000	10.00000
7	$F_{3,7}=5.00000$	200.00000	0.00000	5.00000
8	0.00000	0.00000	10.00000	0.00000
9	$F_{1,9}=25.00000$ $F_{2,9}=24.20779$ $F_{4,9}=7.37778$ $F_{8,9}=4.37547$	63.35119	23.55238	70.87706
10	$F_{3,10}=15.77922$ $F_{4,10}=21.66667$ $F_{8,10}=2.94372$	139.0675	0.00000	40.38961

TABLE V Results of Case C

Process number	$F_{i,j}$ (ton/h)	C_{in} (ppm)	Minimum fresh water flowrate with reuse (ton/h)	Wastewater flowrate (ton/h)
1	0.00000	0.00000	25.00000	0.00000
2	0.00000	0.00000	32.00000	0.00000
3	$F_{2,3}=1.731602$	7.50000	19.04762	0.00000
4	0.00000	0.00000	30.00	0.00000
5	$F_{2,5}=6.06061$ $F_{3,5}=7.27273$	50.00000	26.66667	40.00000
6	$F_{9,6}=10.0000$	300.00000	0.00000	10.00000
7	$F_{1,7}=2.27273$ $F_{9,7}=2.72727$	200.00000	0.00000	5.00000
8	0.00000	0.00000	10.00000	0.00000
9	$F_{2,9}=21.82395$ $F_{3,9}=3.51255$ $F_{4,9}=30.00000$ $F_{8,9}=10.00000$	75.00000	23.55238	76.16162
10	$F_{1,10}=22.72727$ $F_{2,10}=2.38384$ $F_{3,10}=9.99394$	114.84	0.00000	35.10505

A mixer is favored in interval 7 and the water from this mixer is distributed to the rest of the processes below the pinch. A second mixer is created in interval 10 to fulfill the water needs of processes 5 and 6 above the pinch.

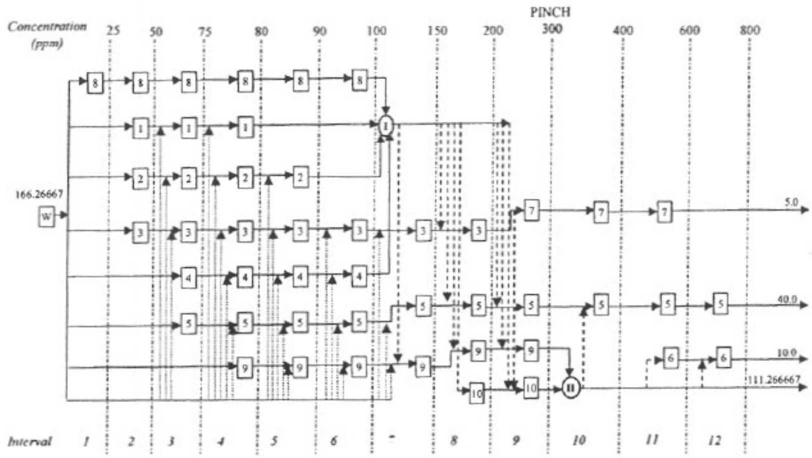

FIGURE 11 Preliminary design for Case A.

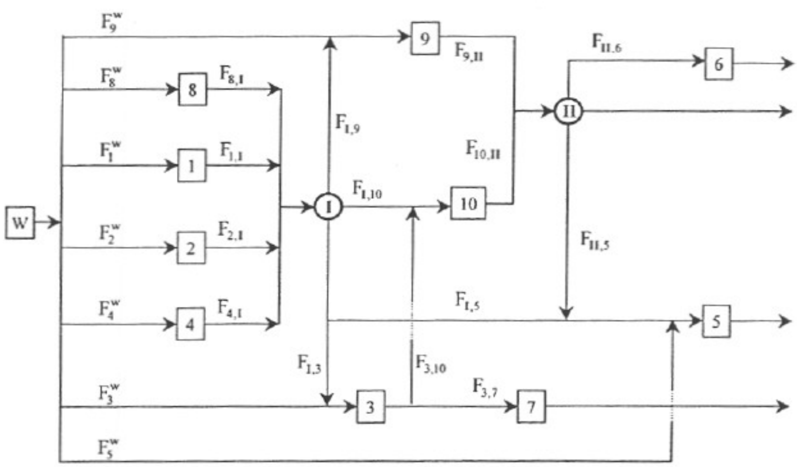

FIGURE 12 Final design for Case A.

Case B Solution obtained assigning the cleanest wastewater first.

As in Case A, fresh water is depleted before process 9 can fulfill its requirements in interval 7. Consequently, it receives wastewater from processes 1 and 2 to fulfill its needs in that interval. These precursors are the ones with the lowest concentrations available in interval 7. The total number of interconnections among processes remains the same as in Case A, but the number of them below the pinch has increased in two. Figures 13 and 14 show the preliminary and the final design network respectively.

Case C Reusing the most contaminated wastewater first.

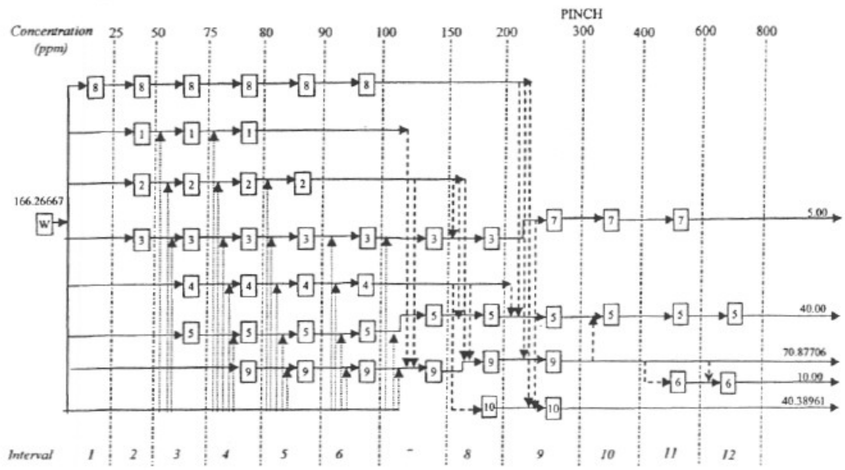

FIGURE 13 Preliminary design of Case B.

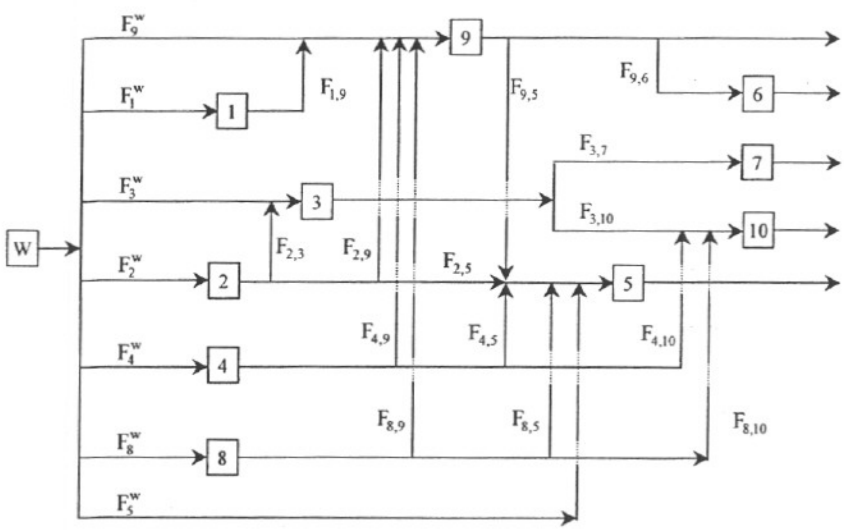

FIGURE 14 Final design for Case B.

In Case C, the total number of required interconnections has decreased to 13 comparing to the previous cases. Another important observation is that the precursors of the intensive water user, processes 5, 9 and 10, have significantly changed between Cases B and C. Figures 15 and 16 show the preliminary and the final design network respectively.

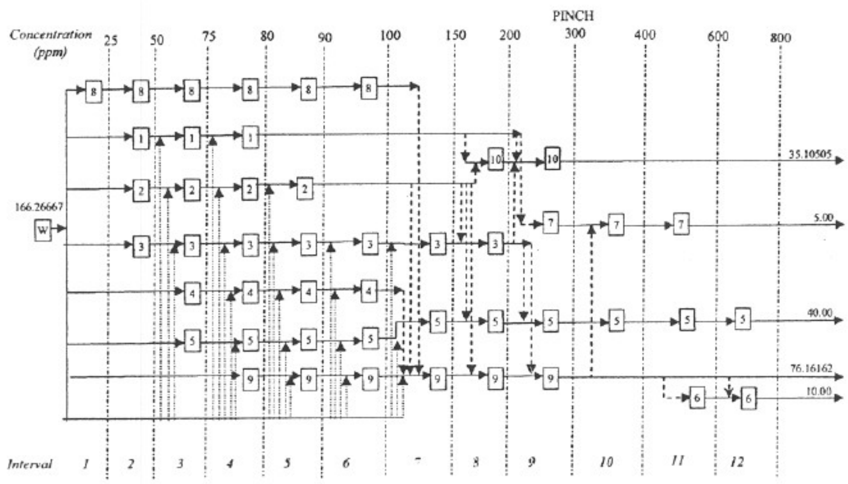

FIGURE 15 Preliminary design of Case C.

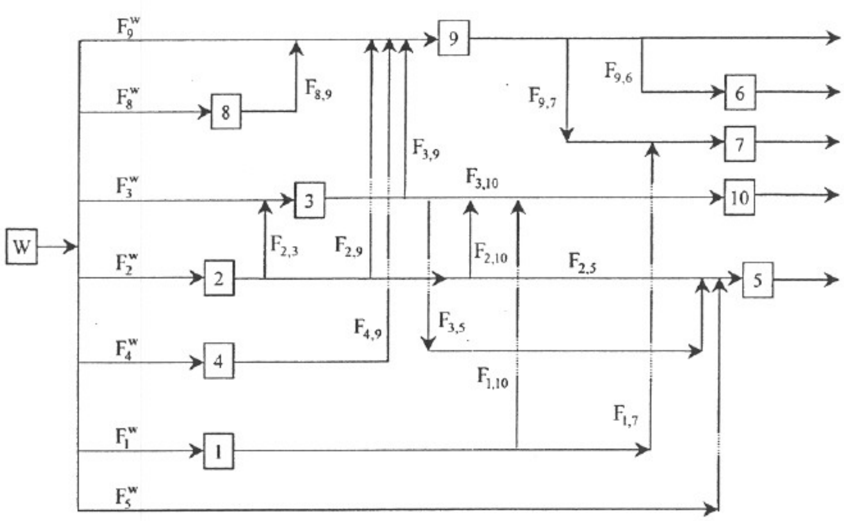

FIGURE 16 Final design for Case C.

CONCLUSIONS

A new design methodology for the solution of the single-contaminant WAP problem has been presented. Several alternatives on how to distribute water among the processes are also discussed. Finally, the application of the new procedure is illustrated through examples. The use of the different water allocation strategies shows that the problem has several alternative solutions. The existence of the above alternative solutions shows that design aspects such as distance between processes, corrosion limitations, control strategies, *etc.*, can be taken into account within the design framework presented.

Acknowledgments

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NOTATION

F_j^i	Outlet flowrate of process j in interval i
F_j^{i-1}	Inlet flowrate of process j in interval i
$F_{P_j,j}^i$	Water flowrate from precursors P_j of process j in interval i
$F_{w,j}^i$	Fresh water flowrate entering process j in interval i
F_j^w	Total fresh water usage of process j
C_j^i	Contaminant concentration of F_j^i
C_j^{i-1}	Contaminant concentration of F_j^{i-1}
$C_{P_j,j}^i$	Contaminant concentration of $F_{P_j,j}^i$
m_j^i	Mass of contaminant to be removed from process j in interval i
L_j	Total mass load of process j

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