Water Minimisation by Pinch Technology – Water Cascade Table for Minimum Water and Wastewater Targeting

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ABSTRACT

Synthesis of optimal water utilisation networks for continuous processes based on Pinch Analysis has been rather well established. In contrast, less work has been done on water minimisation problem for batch processes. The development of a systematic procedure for batch water minimisation which is industrially very common as well as important is therefore required. In this work, systematic procedures involving two key steps for water minimisation, namely utility (water) targeting and network design have been conceived for batch processes. For utility targeting, a new procedure which employs the water cascade table (WCT) has been developed to establish the minimum utility (water) requirement for maximum water recovery and minimum wastewater generated. This table has been adapted from water surplus diagram for continuous processes. The WCT is a tabulated approach that avoids the tedious graphical drawings of water surplus diagram. In addition, a systematic procedure for water networks design for batch processes, which include a recent developed graphical tool called the time-water network has been introduced to allow designers to achieve the utility targets established for the problem.

INTRODUCTION

The environmental impact of industrial wastewater and much higher cost of raw water are serious challenges facing the chemical process industries nowadays. From the focus on the end-of-pipe treatment in the 1970s, chemical manufacturers have increasingly emphasised on the waste minimisation policies where pollutants are mitigated at the source. Less pollutant translates into less raw water cost as well as reduced water treatment cost.

The first attempt to minimise water usage by maximising water reuse was reported by Wang and Smith[1]. They presented a graphical approach that was adapted from heat integration using pinch technology. By plotting the limiting composite curves versus the limiting composition interval, one can locate the minimum fresh water and wastewater flowrates prior to any network design. The opportunities for regeneration-reuse and regeneration-recycling were also explored. A systematic network design procedure, which allowed the targets to be met, is also presented[1]. This is a major step in the water network design, though the assumption of water utilisation process as a mass transfer operation incurs some major drawbacks in the analysis.

Dhole *et al.*[2] correctly pointed out that some unit operations such as reactors, cooling towers and boilers may not be adequate to be modelled as mass transfer operations. They in turn proposed the use of water source and demand composite curves to locate the minimum fresh water consumption and wastewater generation. They also showed that proper mixing and bypassing could further reduce the fresh water consumption. However, it is later pointed out that unless the correct stream mixing system is identified, the apparent targets could be substantially higher than the true minimum fresh water and wastewater targets[3].

Hallale[4] recently pointed out that the water source and demand composite curves may not give a clear picture of the analysis. The targets obtained may not be a true solution, as they largely depend on the mixing patterns of the process streams. In turn, he presented a water surplus diagram in targeting the minimum fresh water and wastewater[4]. This approach was adapted from the hydrogen pinch analysis[5]. It has a similar representation to the water source and demand composite curves proposed by Dhole[2], thereby overcoming the limitations in the mass transfer-based approach[1]. Yet, this new representation does automatically build in all mixing possibilities to determine the true pinch point and reuse target.

A good review on the other existing techniques (e.g. the mathematical modeling method) in addressing the issue on water networks design in process plant was recently presented[6]. However, most of the techniques were focused on continuous processes, with very few studies conducted for the batch processes.

The only work for water minimisation for batch operation base on pinch analysis is reported by Wang and Smith[7]. By putting time as their main process constraint, the authors attempted to maximise the mass transfer driving force use in each of the concentration profile. However, they failed to come up with a good representation of the water networks[7]. The proposed water utilisation networks were conventionally represented by a water network diagram for continuous processes. The main drawback of this representation is that a designer cannot visualise how these processes are linked with time. Clearly, a better representation of the water networks is required.

More recently, the current authors present a new representation for batch water networks[8]. They showed that in order to achieve the utility targets, network design for batch process systems should be carried out independently in each time interval. A new representation called the overall time-water networks is proposed, where water-using operations are shown in the time horizon.

This paper in turn presents a novel tool for minimum utility targeting in water minimisation, i.e. the water cascade table (WCT), for both continuous and batch process systems. The WCT is adapted from water surplus diagram[4], hence the overcome the limitations in the mass transfer-based approach[1]. Moreover, WCT is tabulated in nature, which avoids the tedious exercise and trial-and-error solution in sorting out the water surplus diagram in obtaining the minimum utility targets.

We will firstly demonstrate the usefulness of WCT in determining the minimum utility targets in the continuous processes. Second part of the paper is focusing on the problem of water minimisation of batch processes. Minimum utility targets are obtained by the time-dependant WCT, a modified WCT for continuous processes. Next, a systematic water utilisation network procedure is presented, with the recent introduced time-water networks in achieving the minimum utility targets established.

THE WATER CASCADE TABLE

A general structure of WCT is shown in Table 1. First step in setting up the WCT is to list out all the contaminant concentration (C) of the water-using processes. Duplicates (if any) are to be removed and the contaminant concentration intervals are set up in an ascending order, in the first column of Table 1. This is similar in setting up the global temperature intervals in problem table analysis for heat exchange networks synthesis[9] (HENS). The first contaminant concentration is named as C_1, then C_2 until C_n.

Next, purity (P) of each contaminant concentration (column 2) is calculated. The first purity is named as P_1, then P_2 until P_n. As the concentration of pure water is one million ppm, the water purity of contaminated stream is defined as:

$$\text{Purity, } P \quad = \quad \frac{1000000 - C}{1000000} \tag{1}$$

where C = contaminant concentration in ppm.

In the third step, the purity difference (ΔP) is calculated by using equation,

$$\Delta P = P_n - P_{n+1} \tag{2}$$

Flowrate of the all water demands (F_{WD}) and sources (F_{WS}) are summed at each purity level in the column of $\sum_i F_{WD_i}$ and $\sum_j F_{WS_j}$ respectively (for simplicity, all $\sum_i$ will be presented by Σ in the following text). Note that water demands are written as negative values while the sources are positive.

Table 1. General structure of a water cascade table

C	P	ΔP	ΣF_{WDi}	ΣF_{WSj}	$\Sigma F_{WDi} + \Sigma F_{WSj}$	ΣF	ΔP x ΣF	Cumulative (ΔP x ΣF)
						F_{FW}		
1	1				$\Sigma F_{WD\,1} + \Sigma F_{WS\,1}$			
2	2				$\Sigma F_{WD\,2} + \Sigma F_{WS\,2}$			
.	.				.			
.	.				.			
.	.				.			
n	n				$(\Sigma F_{WD\,i} + \Sigma F_{WS\,j})_n$			
						F_{WW}		

We then add up the water demands and sources in the sixth column ($\Sigma F_{WDi} + \Sigma F_{WSj}$) for each different purity level. A positive value in this column designating a net surplus of water presents at its respective purity level, while a negative value designating a net deficit of water. Any water sources with higher purity are able to supply as a source for water demands with lower purity. Therefore, the set up of water "cascade" is possible.

The column of cumulative flowrate (ΣF) shows how the water cascade happens. The first row in this column represents the estimated flowrate of fresh water required for the water-using processes (F_{FW}). The estimated fresh water flowrate value will be added to the value in the second row in column ($\Sigma F_{WDi} + \Sigma F_{WSj}$) to get the cumulative water flow at its purity level. This cascade process is continued until the last value in column ($\Sigma F_{WDi} + \Sigma F_{WSj}$) is added. The total cumulative water flowrate values in the final column represent the total wastewater generated in the process (F_{WW}).

In the next column, the multiplication values between the purity difference and cumulative flowrate (ΔP x ΣF) are calculated at every purity level. These values show the pure water surplus or deficit in each region. Lastly, cumulative of (ΣF x ΔP) is obtained. It represented the situation in the water surplus diagram. With the assumed fresh water flowrate, if negative value exists, this means that there will not be sufficient water purity in the networks. Thus, more fresh water needs to be added until no value of the column is negative. The minimum fresh water target will be the flowrate that causes zero to appear at this cumulative column. The zero that appears is the pinch point.

SYSTEMATIC CLASSIFICATION OF SCENARIOS IN WATER-USING PROCESSES

Various scenarios may occur when the water-using processes are analysed globally. Systematic classification of these scenarios will help us in handling the problem easily. Generally, four different situations may occur when water-using processes are analysed in a global manner:

1. Processes where only water demands occur (hence, $\Sigma F_{WS} = 0$)
2. Processes where only water sources occur (hence, $\Sigma F_{WD} = 0$)
3. Processes with total flowrate of water demands is higher than or equal to the total flowrate of water sources ($\Sigma F_{WDi} \geq \Sigma F_{WSj}$)
4. Processes where total flowrate of water demands is lower than the total flowrate of water sources ($\Sigma F_{WDi} < \Sigma F_{WSj}$)

Targeting procedure for each of the above situation is different. In the first scenario, where only water demands occur in a process, the fresh water required is equal to the total flowrate of all the water demands ($F_{FW} = \Sigma F_{WD\,j}$). The pinch purity will occur at the demands with lowest purity level. In this situation, no wastewater is generated from the processes. Figure 1 shows the water surplus diagram of this situation, where all the water demands are located at the negative side of the *x*-axis.

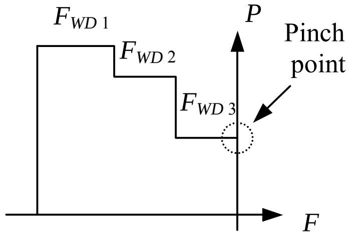

Figure 1 – Water surplus diagram with water demands only

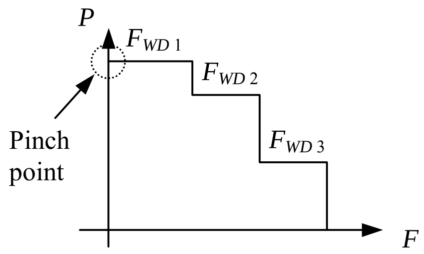

Figure 2 – Water surplus diagram with water sources only

For situation where only water sources occur, no fresh water is needed in these processes. Wastewater generated from these processes is same as the total flowrate of all the water sources ($F_{WW} = \Sigma F_{WS\,j}$). Water source with the highest purity will be the incur a pinch purity for the process (Figure 2).

In the third scenario where the total flowrate of water demands of the water-using process is more than the total flowrate of water sources ($\Sigma F_{WDi} \geq \Sigma F_{WSj}$), an estimated fresh water flowrate ($F_{FW,est}$) is needed, where,

$$F_{FW,\,est} = |\,\Sigma F_{WD\,i} + \Sigma F_{WS\,j}\,| \tag{3}$$

Column of cumulative (ΣF x ΔP) is then checked to see whether any negative value occurs. If all the values are positive, minimum fresh water needed is equal to the estimated fresh water flowrate ($F_{FW} = F_{FW,\,est}$) and the pinch purity occurs at the demand with the lowest purity level. If any negative value is observed, more fresh water is needed for the processes. A simple trial-or-error solution is needed to guess an estimated fresh water flowrate until all negative values in the column are removed. The minimum fresh water target will be the flowrate that causes zero (pinch point) to occur at the cumulative column.

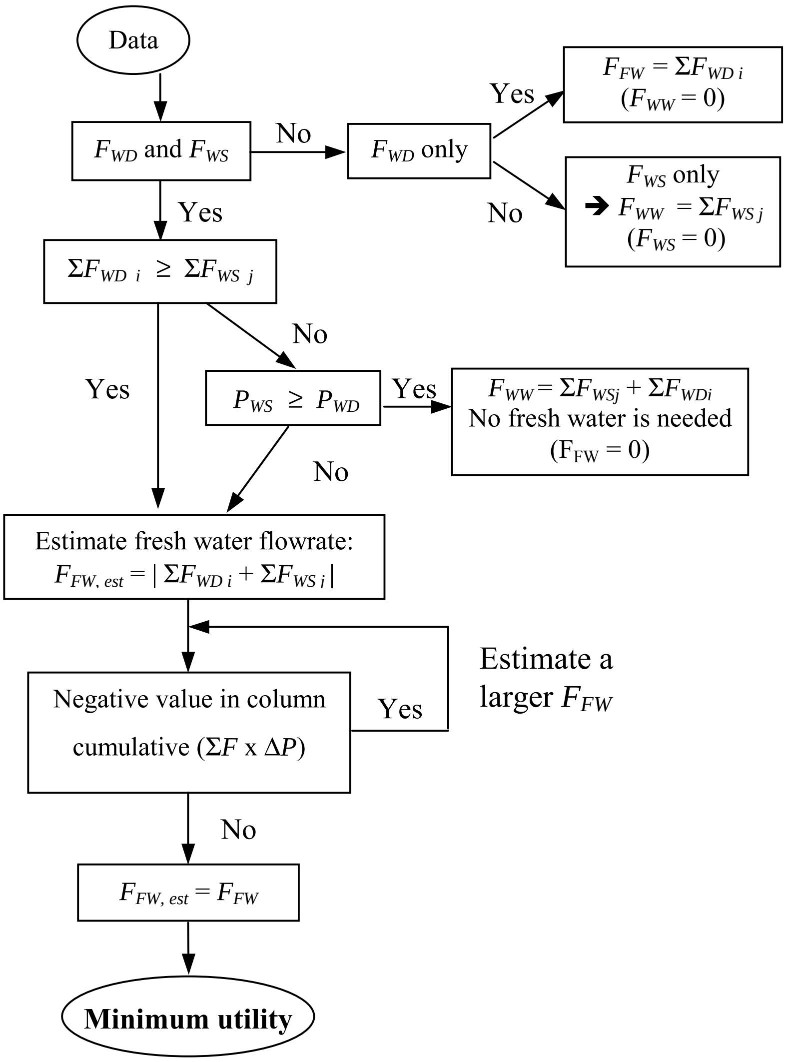

Figure 3 – Overall targeting procedure by WCT

If the total flowrate of water demands is less than the total flowrate of all the water sources ($\Sigma F_{WD\,i} < \Sigma F_{WS\,j}$), such as that in the final scenario, water demands and sources purity is taken into consideration. If the purity of water sources is higher than or equal to that of the water demands ($P_{WS} \geq P_{WD}$), no fresh water is needed. Wastewater generated is estimated to be:

$$F_{WW} = \Sigma F_{WS\,j} + \Sigma F_{WD\,i} \tag{4}$$

On the other hand, if the purity of water sources is lower than that of the water demands, fresh water are needed for the processes. Procedure of targeting the fresh water flowrate is the same as were in the third scenario, where an estimated fresh water flowrate ($F_{FW\,est}$) is needed (Eq. 3) to reach a pinch purity to occur at the cumulative column of the WCT. Figure 3 shows the summary of the overall targeting procedure by WCT.

WATER CASCADE TABLE FOR CONTINUOUS PROCESSES

We will firstly the WCT for water minimisation problem in a continuous operation. A simple example from literature[10] will be used as an illustration. This example has six water demands and five water sources. Data for the example is shown in Table 2. Minimum fresh water requirement and wastewater generated are targeted at 200 and 120 ton/h respectively[10]. Two pinch purities[4] are reported at 0.9999 and 0.99982.

Table 2. Data for continuous process

Water demand	Flowrate, $F_{WD,\,i}$ (ton/h)	Concentration, C (ppm)	Water source	Flowrate, $F_{WS,\,j}$ (ton/h)	Concentration, C (ppm)
1	120	0	1	120	100
2	80	50	2	80	140
3	80	50	3	-	-
4	140	140	4	140	180
5	80	170	5	80	230
6	195	240	6	195	250

WCT for this example is shown in Table 3. As shown, WCT has successfully predicted the minimum utility targets (minimum fresh water and wastewater) of the given example. As mentioned, much less effort is needed in obtaining these targets through the use of WCT. A simple spreadsheet calculation is by far the most needed for the calculation, as opposed to the tedious work of graphical solution through water surplus diagram.

EXTENSION INTO THE PROBLEM OF BATCH PROCESSING

We will now demonstrate how the water minimisation problem in a batch operation could be handled. The current author recently showed that both targeting and networks design should be carried out separately in each time interval[8]. WCT for continuous processes developed in this work can be extended to be used for water-using processes that operated in batch mode. Minimum water consumption as well as wastewater generation targets will be identified in each time interval. A recent developed time-water networks will then be use to design a batch water networks that achieve the established utility targets.

Minimum Utility Targeting by Water Cascade Table

In this part, we will demonstrate how WCT from continuous processes can be used for water-using batch operation. The previous example will be used for illustration. Assuming that each pair of water demand and source acts as a water-using batch operation, we have modified the duration of each operation to demonstrate a batch process. It shall be noted that the flowrate of each water-using process in continuous mode has been changed to volume for a batch operation. The data is given in Table 4.

Table 3. WCT for continuous process

C	P_n	ΔP	$\Sigma F_{WD,i}$	$\Sigma F_{WS,j}$	$\Sigma F_{WD,i}$ + $\Sigma F_{WS,j}$	ΣF	ΔP x ΣF	Cumulative (ΔP x ΔF)
						200		
0	1		-120		-120			
		0.00005				80	0.00400	
50	0.99995		-160		-160			0.00400
		0.00005				-80	-0.00400	
100	0.99990			120	120			0
		0.00004				40	0.00160	
140	0.99986		-140	80	-60			0.00160
		0.00003				-20	-0.00060	
170	0.99983		-80		-80			0.00100
		0.00001				-100	-0.00100	
180	0.99982			140	140			0
		0.00005				40	0.00200	
230	0.99977			80	80			0.00200
		0.00001				120	0.00120	
240	0.99976		-195		-195			0.00320
		0.00001				-75	-0.00075	
250	0.99975			195	195			0.00245
						120	119.9700	

Table 4. Data for batch process

Demand, D_i	Volume, V (ton)	Concentration, C (ppm)	Starting time, $t^s_{D,i}$ (h)	Ending time, $t^t_{D,i}$ (h)
1	120	0	3.5	5
2	80	50	5	7
3	80	50	9	11
4	140	140	0	1.5
5	80	170	5	6
6	195	240	8	10

Sources, S_j	Volume, V (ton)	Concentration (ppm)	Starting time, $t^s_{S,j}$ (h)	Ending time, $t^t_{S,j}$ (h)
1	120	100	8	10
2	80	140	12	14
3	-	-	-	-
4	140	180	5	7.5
5	80	230	12	13
6	195	250	13	15

The first step in the targeting stage is to divide the time intervals where the water demands and sources are found. The number of time intervals (N_{int}) is related to the number of water demands (N_{WD}) and sources (N_{WS}) via equation[8]:

$$N_{int} \leq 2(N_{WD} + N_{WS}) - 1 \tag{5}$$

with the inequality applying in cases where no water demands and sources coincide. The above equation is firstly utilised to calculate the number of composition interval in the more general problem of water minimisation, i.e. the mass exchange networks synthesis (MENS) problem[11]. Next, we proposed a Time Interval Table, where all water demands and sources at each time interval are displayed (Table 5). Volumes of water demands ($V_{D,i}$) and sources ($V_{S,j}$) at each time interval (given by a duration of Δt_k) can be calculated via the following equations:

$$V_{D,i} = F_{wWD,i} \text{ x } \frac{\Delta t_k}{t^t_{D,i} - t^s_{D,i}} \tag{6}$$

$$V_{S,j} = F_{WS,j} \text{ x } \frac{\Delta t_k}{t^t_{S,j} - t^s_{S,j}} \tag{7}$$

Table 5. Time Interval Table

Time intervals, Δt_k (hr)	Water demands, $V_{D,i}$ (ton)	Water sources, $V_{S,j}$ (ton)
0 – 1.5	$V_{D,4} = 140$	-
3.5 – 5	$V_{D,1} = 120$	-
5 – 6	$V_{D,2} = 40$; $V_{D,5} = 80$	$V_{S,4} = 56$
6 – 7	$V_{D,2} = 40$	$V_{S,4} = 56$
7 – 7.5		$V_{S,4} = 28$
8 – 9	$V_{D,6} = 97.5$	$V_{S,1} = 60$
9 – 9.5	$V_{D,3} = 20$; $V_{D,6} = 48.75$	$V_{S,1} = 30$
9.5 – 10	$V_{D,3} = 20$; $V_{D,6} = 48.75$	$V_{S,1} = 30$
10 – 11	$V_{D,3} = 40$	-
12 – 13	-	$V_{S,2} = 40$; $V_{S,5} = 80$
13 – 14	-	$V_{S,2} = 40$; $V_{S,6} = 97.5$
14 - 15	-	$V_{S,6} = 97.5$

The following procedure in utility targeting is the same with that in the continuous processes. Minimum utility targets (minimum fresh water wastewater generation) are carried out independently in each time interval. Hence, a time-dependent WCT is proposed. Time-independent WCT is conceptually similar to the time-dependent heat cascade table in the batch heat integration, where minimum utility targets (minimum heating and cooling targets) are carried out independently in each time interval.

In shall be noted that the various scenarios of water-using operations proposed previous can be seen clearly at this stage. Table 6 shows the utility targeting in four different time intervals. In time interval 3.5 – 5, only a single water demand occurs. Hence, fresh water needed in this time interval is equal to the volume of the water demand. This is the first scenario as proposed. Hence, no wastewater is generated in this interval.

In time interval 5 – 6 hr, the third scenario occurs, where total volume of water demands is larger than that of the water sources. Hence, fresh water is needed in this interval. Minimum fresh water consumption as well as wastewater generation targets are carried out in the estimated procedure that was outlined (Figure 3).

The fourth scenario of water-using processes is found in time interval 6 – 7 hr, where a larger volume of water source is found to have a lower purity than a water demand in the process. A small volume of fresh water is needed due to the water reuse is limited by the concentration profile of the water demand. Estimated procedure of the utility targets is then followed (Figure 3).

Time interval 7 – 7.5 hr, on the other hand shows that the second scenario of the water-using operation. Due to the existence of a single water source in the process, no fresh water is needed. While wastewater generated is the same amount with the volume of the water source.

Table 7 represents the overall time-dependant WCT for all the time intervals for the working example. The overall time-dependant WCT comprises the value of the total volume of water demands and sources ($\Sigma F_{WD,\ i}$ + $\Sigma F_{WS,\ j}$) (in the bracket) and the water volume that were cascaded down the concentration interval (ΣF). Number in bold represents the pinch purity of the respective time interval. The row of F_{FW} represents the fresh water volume for each independent time interval, while volume of wastewater in each time interval is represented in the row of F_{WW}. Table 7 show that the total fresh water needed in this process is 507.89 ton while wastewater generated is at a volume of 427.89 ton.

Batch Water Network Design

The current authors recently showed that in order to achieve the minimum utility targets, network design for batch processes should be carried out independently in each time interval. Hallale[4] pointed out that to achieve the utility targets, it is necessary to observe the pinch division. On the above pinch region, the pure water surplus is just equal to the total pure water deficit. This also means that the water sources above the pinch (including fresh water) should neither be fed to the water demands nor mixed with the water sources below the pinch. These guidelines must be observed during the network design to be carried out in each time interval.

Other constraints for the network design between water source *i* and demand *j* are given as follows[4]:

(a) Demands:

i. Volume

$$\sum_i V_{i,j} = V_i \tag{6}$$

where V_i is the volume required by demand *i*.

Table 6. WCT for four time intervals of the batch process example

C	*P*	Δ*P*	3.5 – 5 hr				5 – 6 hr			
			D + *S*	Δ*F*	Δ*P* x Δ*F*	Σ(Δ*P* x Δ*F*)	*D* + *S*	Δ*F*	Δ*P* x Δ*F*	Σ(Δ*P* x Δ*F*)
Total fresh water, V_{FW} (ton)				120				64		
0	1		-120				0	`		
		0.00005		0	0			64	0.00320	
50	0.99995		0			0	-40			0.00320
		0.00005		0	0			24	0.00120	
100	0.99990		0			0	0			0.00440
		0.00004		0	0			24	0.00096	
140	0.99986		0			0	0			0.00536
		0.00003		0	0			24	0.00072	
170	0.99983		0			0	-80			0.00608
		0.00001		0	0			-56	-0.00056	
180	0.99982		0			0	56			0.00552
		0.00005		0	0			0	0.00000	
230	0.99977		0			0	0			0.00552
		0.00001		0	0			0	0.00000	
240	0.99976		0			0	0			0.00552
		0.00001		0	0			0	0.00000	
250	0.99975		0			0	0			0.00552
		0.99975		0	0			0	0.00000	
						0				0.00552
Total wastewater, V_{WW} (ton)				0				0		
C	*P*	Δ*P*	6 – 7 hr				7 – 7.5 hr			
			D + *S*	Δ*F*	Δ*P* x Δ*F*	Σ(Δ*P* x Δ*F*)	*D* + *S*	Δ*F*	Δ*P* x Δ*F*	Σ(Δ*P* x Δ*F*)
Total Fresh Water, V_{FW} (ton)				28.9				0		
0	1		0				0			
		0.00005		28.9	0.00144			0	0	
50	0.99995		-40			0.00144	0			0
		0.00005		-11	-0.00056			0	0	
100	0.99990		0			0.00089	0			0
		0.00004		-11	-0.00044			0	0	
140	0.99986		0			0.00044	0			0
		0.00003		-11	-0.00033			0	0	
170	0.99983		0			0.00011	0			0
		0.00001		-11	-0.00011			0	0	
180	0.99982		56			0	28			0
		0.00005		44.9	0.00224			28	0	
230	0.99977		0			0.00224	0			0
		0.00001		44.9	0.00045			28	0	
240	0.99976		0			0.00269	0			0
		0.00001		44.9	0.00045			28	0	
250	0.99975		0			0.00314	0			0
		0.99975		44.9	44.8788			28	0	
						44.88192				0
Total wastewater, V_{WW} (ton)				44.9				28		

Table 7. Overall time-dependant WCT for all time intervals in batch water minimisation

	0-1.5	3.5-5	5-6	6-7	7-7.5	8-9	9-9.5	9.5-10	10-11	12-13	13-14	14-15
V_{FW}	140	120	64	28.89	0	37.5	38.75	38.75	40	0	0	0
1	0	**-120**	0	0	0	0	0	0	0	0	0	0
	140	0	64	28.89	0	37.5	38.75	38.75	40	0	0	0
0.99995	0	0	-40	-40	0	0	-20	-20	**-40**	0	0	0
	140	0	24	-11.11	0	37.5	18.75	18.75	0	0	0	0
0.99990	0	0	0	0	0	60	30	30	0	0	0	0
	140	0	24	-11.11	0	97.5	48.75	48.75	0	0	0	0
0.99986	**-140**	0	0	0	0	0	0	0	0	**40**	**40**	0
	0	0	24	-11.11	0	97.5	48.75	48.75	0	40	40	0
0.99983	0	0	**-80**	0	0	0	0	0	0	0	0	0
	0	0	-56	-11.11	0	97.5	48.75	48.75	0	40	40	0
0.99982	0	0	56	**56**	**28**	0	0	0	0	0	0	0
	0	0	0	44.89	28	97.5	48.75	48.75	0	40	40	0
0.99977	0	0	0	0	0	0	0	0	0	80	0	0
	0	0	0	44.89	28	97.5	48.75	48.75	0	120	40	0
0.99976	0	0	0	0	0	**-97.5**	**-48.75**	**-48.75**	0	0	0	0
	0	0	0	44.89	28	0	0	0	0	120	40	0
0.99975	0	0	0	0	0	0	0	0	0	0	97.5	**97.5**
	0	0	0	44.89	28	0	0	0	0	120	137.5	97.5
V_{WW}	0	0	0	44.89	28	0	0	0	0	120	137.5	97.5

ii. Concentration

$$\frac{\sum_i V_{i,j} C_i}{\sum_i V_{i,j}} \leq C_{\max,i} \tag{7}$$

where C_i is the contaminant concentration for source *i* and $C_{max,i}$ is the maximum accepted contaminant concentration for demand *i*. This constraint could be equally written in terms of water purity, in which the inequality would have been reversed[4].

(b) Sources

i. Volume

$$\sum_i V_{i,j} \leq V_j \tag{8}$$

where V_j is the total volume available from source *j*.

Any water from a source that is not fed to a demand will leave as a wastewater stream.

We will now start to design the water networks subjected to the rules and constraints as described above. Figure 4 shows the network design in detail for all time intervals. In the first, second and ninth time interval, i.e. from 0 – 5 hr and 10 – 11 hr, no water source is found. Thus, fresh water is fed to the water demands in these time intervals. A total of 300 ton fresh water is consumed, as had been targeted by the WCT.

We then move to time interval 5 – 7 hr and 8 – 10 hr, where direct water integration occurs. Wastewater generated from the water sources are fed to the water demands in each time interval, if the purity permits. Details of these integrations will now discuss.
In time interval 5 – 6 hr and 8 – 10 hr, purity of the water demands are lower than that of the purity of water sources, this scenario falls under the fourth scenario of the water-using operation. Amount of fresh water required is equal to the difference between the total water demands and the total water sources generated, as were predicted by the time-independent WCT (Table 7). Network designs for these time intervals are shown in Figure 4 (c) and (f). In time interval 6 – 7 hr, fresh water is required due to the purity of the water demand is higher than that of the water source (fourth scenario). Thus, 28.89 ton of fresh water is fed to the water demand (D2), while 44.89 ton of water from the source (S4) leave as wastewater (Figure 4 (d)).

Networks design in time interval 7 – 7.5 hr and 12 – 15 hr are also straightforward. Since no water demands are found in these time intervals, all the wastewater generated from the water sources leave as wastewater stream. Thus, 383 tons of wastewater is generated, as targeted by time-dependant WCT.

We feel that in a batch water network, time should be included as a variable to provide a better representation of the overall process. Thus, a recent developed time-water network diagram is utilised here. Figure 5 shows the six water-using processes as well as their water sources and demands are represented in this time-water network diagram. The total fresh water required (V_{FW}) are 507.89 tons and 427.89 tons of wastewater (V_{WW}) are generated, as has been targeted in the WCT.

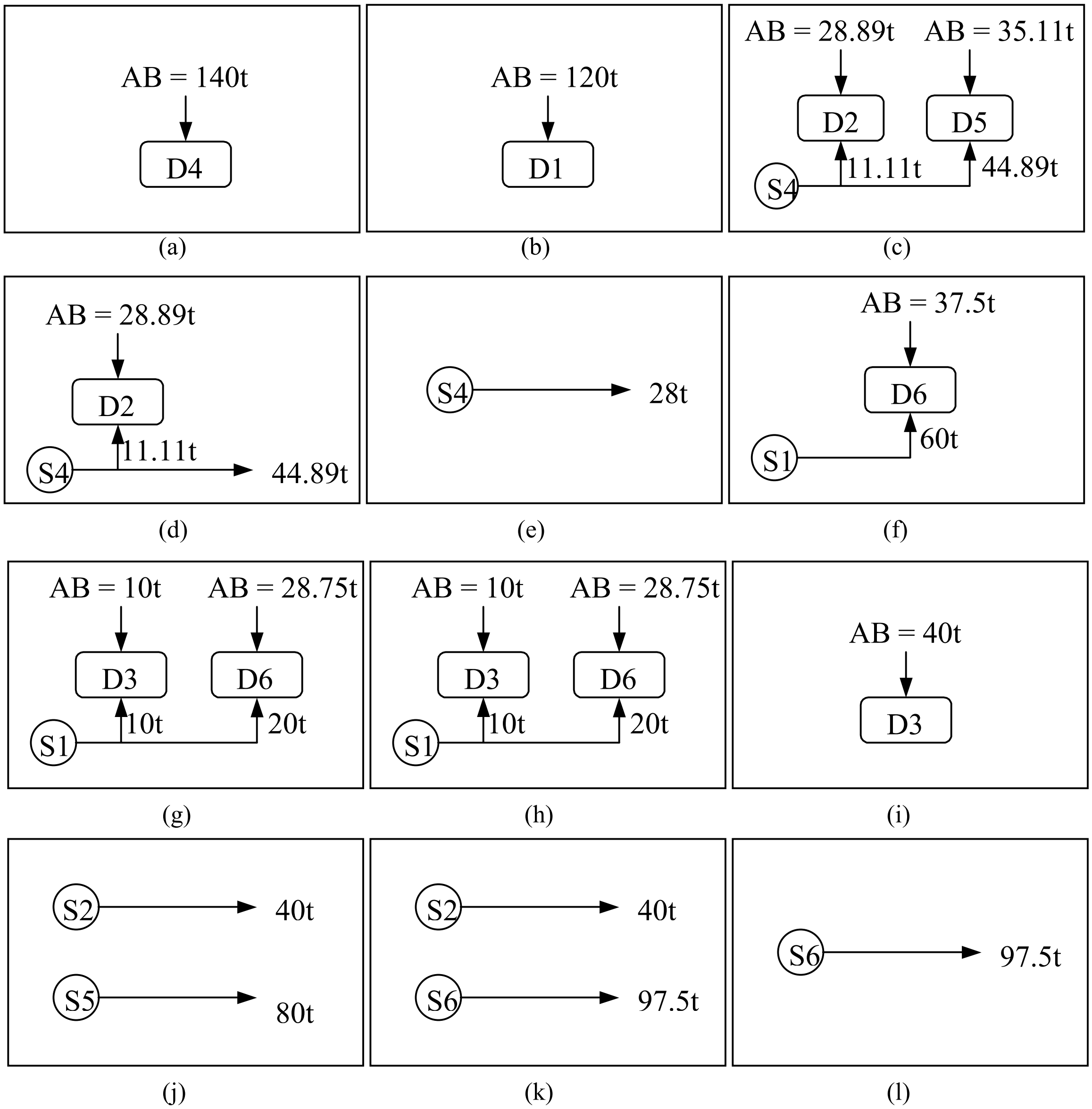

Figure 4 – Network design for all time intervals: (a) 0 – 1.5 hr; (b) 3.5 – 5 hr; (c) 5 – 6 hr; (d) 6 – 7 hr; (e) 7 – 7.5 hr; (f) 8 – 9 hr; (g) 9 – 9.5 hr; (h) 9.5 – 10 hr; (i) 10 – 11 hr; (j) 12 – 13 hr; (k) 13 – 14 hr; (l) 14 – 15 hr

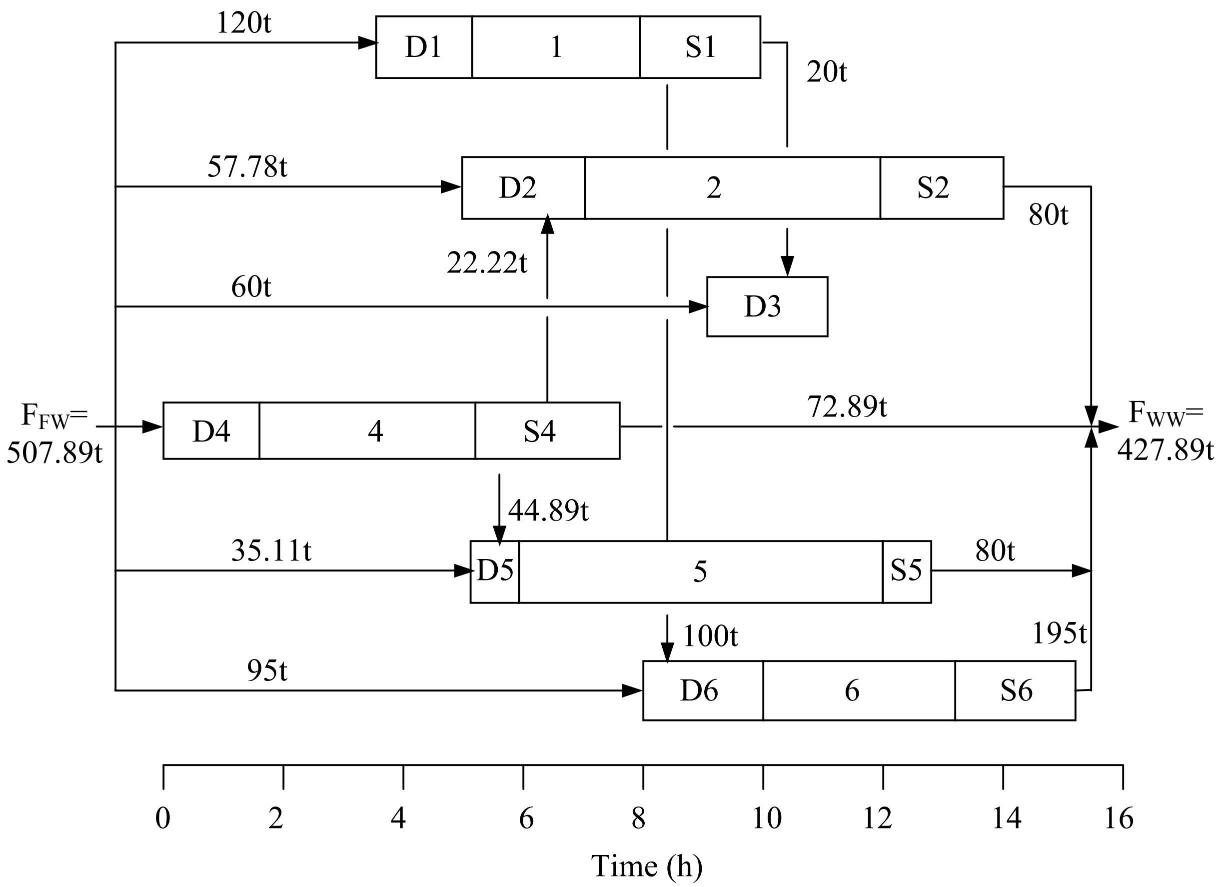

Figure 5 – The overall networks represented on the time–water networks

CONCLUSION

Water Cascade Table (WCT) is presented as a new tool for minimum utility targeting in water minimisation. WCT is tabulated in nature which avoids the tedious graphical drawings of water surplus diagram. WCT can be used for continuous and batch processes to target the minimum fresh water consumption as well as wastewater generated. Water networks for batch processes are carried out in each time interval and a time-water networks diagram is used to represent the overall networks design.

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