RETROFIT OF WATER NETWORK WITH REGENERATION USING WATER PINCH ANALYSIS

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Abstract: This paper presents the development of a new systematic technique for the retrofit of water network with regeneration based on water pinch analysis. The procedure consists of two parts: retrofit targeting and design for a water network with regeneration unit(s). In the targeting stage, retrofit targets (utility savings and capital investment) were determined for a range of process parameters (total flowrate and/or outlet concentration of the regeneration unit) to obtain a savings versus investment curve. Next, the existing water network was re-designed to meet the chosen targets. A case study on paper making process was used to demonstrate the new methodology.

Keywords: water minimization; pinch analysis; retrofit utility targeting; retrofit; network design; water regeneration.

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INTRODUCTION

Water is extensively utilized in chemical, petrochemical, pulp and paper and many other industries. Stricter environmental regulations, scarcity of quality industrial water and the rising cost of wastewater treatment have encouraged process plants to reduce water usage. Concurrently, the development of systematic techniques for water reduction, reuse and regeneration within a process plant has seen extensive progress.

The advent of water pinch analysis (WPA) as a tool for the design of optimal water network has been one of the most significant advances in the area of water minimization over the past decade. Through WPA, water use can be minimized through:

(1) *Process changes.* The inherent demand for water can be reduced through the replacement of process equipment, e.g., wet cooling towers by dry air coolers.
(2) *Reuse/recycle.* Wastewater can be directly reused in other water-using operations or recycled within an individual operation, provided that the level of contaminant does not interfere with the process.
(3) *Regeneration.* Wastewater can be purified by partial treatment to improve its quality in order to be reused or recycled in a water network. Different types of purification techniques such as filtration, activated carbon, biological treatment, membranes, and so on may be applied independently or in combination.

The power of WPA is in its ability to locate the minimum utility targets (fresh water consumption and wastewater generation) prior to detailed network design. This provides a base line for any water network to be synthesized. WPA has been relatively well established for synthesis of grassroots water networks (Wang and Smith, 1994; Polley and Polley, 2000; Hallale, 2002; Manan *et al.*, 2004) as well as for retrofit situations (Tan and Manan, 2003, 2004) particularly using the approach of reuse/recycle. However, the potential utility reduction that can be realized through direct reuse/recycle can be rather restricted. By coupling reuse/recycle strategy with regeneration, this allows further utility reductions in a water network. Nevertheless, most of the work incorporating regeneration strategy has been focused on the development of grassroots design. These approaches may not be applicable for retrofit since various constraints on an existing site including technical as well as economics needed to be taken into consideration during retrofit. To achieve larger water savings for existing processes, there is a clear need to develop a systematic technique for cost-effective water network retrofit which incorporates regeneration strategy.

PREVIOUS WORK ON WATER REGENERATION REUSE/REGENERATION RECYCLING

A number of methods related to the synthesis of grassroots water network involving regeneration have been developed. These methods can be generally classified into two main groups. The first group involves techniques based on graphical WPA while the second group involves various mathematical-based optimization approaches.

Wang and Smith (1994) proposed the first pinch-based method to maximise savings in a water network with reuse, recycling and regeneration strategies. The concept of limiting composite curves that was originally developed for utility targeting in water reuse/recycling network was extended to include targeting for network with regeneration–reuse and regeneration–recycling schemes. The minimum utility targets are located prior to detailed network design.

However, Kuo and Smith (1998) later pointed out that this approach may fail to obtain the true utility targets when the pinch points are relocated after regeneration. They proposed a new methodology where the minimum water targets are refined by migrating streams that have been classified into different water groups which include streams that are fed by fresh water and those that require regenerated water. The number of regeneration and effluent treatment units targets were also included in their approach.

Castro *et al.* (1999) later extended the regeneration–reuse approach to take into consideration multiple pinch problems. Minimum utility targets are achieved by using the water source diagram during the design stage. However, network achieved by this method mostly does not contain the minimum number of units due to the splitting of operations. To overcome this problem, additional utility is needed.

The major drawback in the abovementioned approaches is the assumption of water-using processes as mass transfer operations. Water that is used as a reactant or produced as reaction by-product; as well as water as cooling and heating media in cooling towers and boilers may not be appropriately represented as mass transfer operations. To overcome this limitation, Hallale (2002) established an alternative graphical targeting method called the water surplus diagram that is applicable to non-mass transfer-based operations. This approach locates the minimum utility targets for a grassroots water network with reuse/recycle scheme. It also provides some guidelines for the placement of regeneration units to purify water sources and further reduce in utility consumption.

A tabular approach known as water cascade analysis (WCA) technique was recently introduced by Manan *et al.* (2004) to substitute the tedious graphical approach of water surplus diagram. The WCA technique, which is based on the principles of water surplus diagram (Hallale, 2002) allows quick and accurate determination of water targets as well as assessment of options for regeneration and process changes.

The first mathematical optimization-based approach for water regeneration was introduced by Takama *et al.* (1980). They address the problem of designing optimal water recovery network for a petroleum refinery by generating a superstructure of all possible re-use and regeneration opportunities. Optimisation is then performed on the superstructure to remove uneconomic design features.

Alva-Argáez *et al.* (1998) later proposed an integrated approach for combining the insights from water pinch and mathematical programming for the synthesis of grassroots water network. All possibilities for water reuse, regeneration–reuse and regeneration–recycling are considered in the model. The generated network features the minimum total annual cost and takes into consideration process constraints such as geographical, control and safety. Other recently developed works for water network synthesis based on mathematical optimization include those of Benkó *et al.* (2000), Bagajewicz and Savelski (2001) and Xu *et al.* (2003).

PREVIOUS WORK ON HEAT, MASS AND WATER NETWORK RETROFIT

Techniques developed for the retrofit of existing water network are mainly based on the established concept of heat and mass exchange network retrofit. These techniques will be briefly reviewed here to provide basic understanding for the newly developed work presented next.

The first pinch-based retrofit approach was introduced by Tjoe and Linnhoff (1986) for heat exchange network (HEN) problems. The idea is to minimise energy consumption in a HEN by installing additional heat transfer area and by making effective use of the existing heat exchangers. In the targeting stage, an area versus energy plot for the optimum grassroots design can be constructed for a given range of minimum approach temperature, $\Delta T_{\min}$ (Figure 1). The total area efficiency, α_{Area} is next utilized to determine the appropriate retrofit profile on the plot (Tjoe and Linnhoff, 1986). The total area efficiency α_{Area} is defined as a ratio between the energy consumption for an optimum grassroots design (A_{target}) to that of an existing network (A_{existing}), as follows:

$$\alpha_{\text{Area}} = \left(\frac{A_{\text{target}}}{A_{\text{existing}}}\right)_{\text{Energy}} \tag{1}$$

From the area versus energy plot, utility reduction and new area requirement are converted into an annual utility savings versus investment plot (Figure 2). Once an acceptable investment limit is specified, a $\Delta T_{\min}$ associated with the retrofitted utility target is determined. In the retrofit design stage, cross-pinch exchangers are eliminated and existing heat exchangers are revamped to achieve better heat recovery.

Although Tjoe and Linnhoff (1986) argued that a conservative estimation is preferable for the retrofit profile with constant α_{Area} value, later works (Silangwa, 1986; Shenoy, 1995; Ahmad and Polley, 1990) show that the constant α_{Area} value may be too conservative, and hence a better estimation is needed. Silangwa (1986) pointed out that, when the

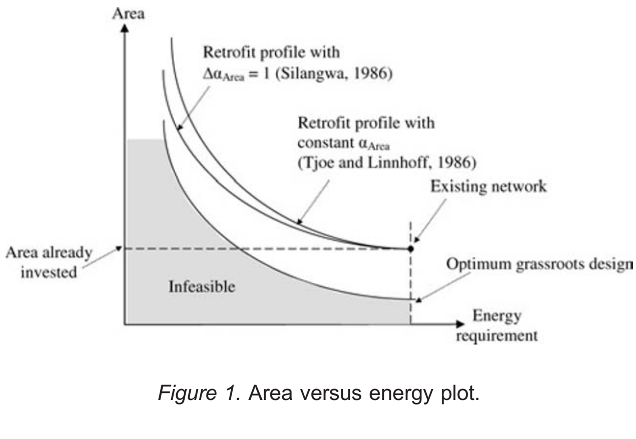

Figure 1. Area versus energy plot.

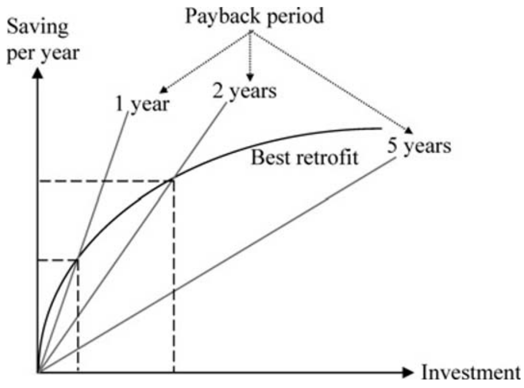

Figure 2. Savings versus investment plot.

value of α_{Area} is low (i.e., $\alpha_{\text{Area}} < 0.9$), an incremental value of $\Delta\alpha_{\text{Area}} = 1$ should be used. The incremental value of $\Delta\alpha_{\text{Area}}$ is defined as

$$\Delta\alpha_{\text{Area}} = \left(\frac{\Delta A_{\text{target}}}{\Delta A_{\text{existing}}}\right)_{\Delta\text{Energy}} \tag{2}$$

where ΔA_{target} is the minimum targeted extra area needed in a grassroots network for a reduction of ΔEnergy; while $\Delta A_{\text{existing}}$ is the newly installed area in the retrofitted network for an energy reduction of ΔEnergy. The retrofit profile plotted using $\Delta\alpha_{\text{Area}}$ is also shown in Figure 1. Note from Figure 1, the $\Delta\alpha_{\text{Area}}$ retrofit profile is moving closer to the optimum grassroots profile, as compared to the α_{Area} retrofit profile to yield a less conservative retrofit target. Both of these HEN retrofit targeting profiles will be evaluated for their adaptability in the work involving water network retrofit described in this paper.

Fraser and Hallale (2000) later extended the HEN retrofit work into mass exchange network (MEN) problem that was initiated by El-Halwagi and Manousiouthakis (1989). Their retrofit work was based on the constant α_{Area} efficiency approach of Tjoe and Linnhoff (1986). They demonstrated that pinch-based retrofit approach for HEN can be applied to the MEN problem with appropriate modifications. The area versus energy plot by Tjoe and Linnhoff (1986) was adapted to become the stage versus load plot in MEN retrofit. In this stage-load diagram, a retrofit path is chosen to allow one to determine the savings achieved for extra new stages to be added in the retrofitted MEN. This yields the same savings versus investment plot that originally developed for HEN retrofit (Figure 2). Lastly, elimination of cross-pinch mass transfer and the evaluation of driving force use are the key principles in the retrofit design stage (Fraser and Hallale, 2000).

Later development has seen the pinch-based retrofit approach that was extended for the special case of MEN, i.e., water minimization problems. The first work on this was dedicated for the retrofit of non-mass transfer-based water-using operations by Tan and Manan (2003). This approach consists of three main steps. Firstly, water network is represented by a new concentration block diagram (CBD). This diagram provides the information to diagnose the potential of retrofit in an existing water network according to a set of heuristics. Lastly, the water network will go through an evolution procedure in order to generate the final retrofit scheme.

More recently, Tan and Manan (2004) established another retrofit method for water network with mass transfer-based operations which was adapted from MEN retrofit method with constant α efficiency (Fraser and Hallale, 2000). The retrofit targets (minimum utility and number of stages for the mass exchangers) are achieved through WPA grassroots targeting and MEN capital cost techniques. These targets are then used to plot the number of stages versus fresh water flowrate diagram where a retrofit path is formed by comparing the existing design with the targets. Given an acceptable payback period or investment limit, a global minimum composition difference (ε) in accordance with these economic criteria is determined. In the retrofit design stage, elimination of cross-pinch mass exchangers is performed and retrofit of the existing water network through Wang and Smith (1994) design rules is utilised to efficiently reuse the existing number of mass transfer stages.

Alternatively, two recent water network retrofit works based on mathematical-based optimization approach are independently developed by Jödicke *et al.* (2001) and Huang *et al.* (1999). Various retrofit constraints such as process location, number and size of the holding tanks, pipe work and treatment capacity are taken into consideration by these authors to synthesize an economically feasible network.

Yet other works on mathematical programming for water network retrofit problems have also been developed (e.g., Parthasarathy and Krishnagopalan, 2001; Jacob *et al.*, 2002; Thevendiraraj *et al.*, 2003; Koppol *et al.*, 2003). However the biggest pitfall in these works is that, they were mainly based on grassroots synthesis approaches, where the main focus was aimed on the minimization of utility consumption. However, it is quite impossible to achieve an optimal retrofit without taking into consideration the various process and equipment design constraints. This may cause major modifications with long payback periods in some cases. A good retrofit approach should exploit opportunities to maximize usage of existing facilities while trying to minimize utility cost. This often makes a retrofitted network looks quite different from the optimum grassroots design (Tjoe and Linnhoff, 1986).

This paper presents a new systematic technique based on pinch analysis for the retrofit of water network with regeneration unit(s). This technique, which is applicable to mass transfer and non-mass transfer-based operations consists of two stages namely targeting and network design. In the targeting stage, the utility savings versus capital investment plot were generated for a range of the regeneration unit's flowrate or outlet concentration. An optimum regeneration flowrate and/or outlet concentration based on a maximum payback period or capital investment limit can be determined from this plot. During the network design stage, the existing water network was revamped and new regeneration unit was introduced.

PROBLEM STATEMENT AND BASIC ASSUMPTIONS

The problem statement of retrofitting water network with regeneration can generally be stated as follows:

> Given a set of mass transfer-based and non-mass transfer-based water-using processes, it is desired to retrofit an existing water network through wastewater regeneration, process stream restructuring and making effective use of existing process units to accomplish the best savings in operating costs, subject to a minimum payback period or a maximum capital expenditure.

The following assumptions were made in developing the retrofit procedure:

(1) The system operates as a single contaminant system.
(2) The system operates isothermally.
(3) Regeneration reuse/recycling are allowed in the system.
(4) Single type of regeneration treatment.

PAPER MILL CASE STUDY

Water reuse/recycling in paper mills is considered to be a universal practice for recovering valuable paper fibres from a paper machine's excess water (Wiseman and Ogden, 1996). Apart from operating cost savings and reduction in the environmental impact of a process, water reuse and recycling enables the recovery of raw materials from a water network.

A local paper mill was used as a case study to demonstrate the new methodology. The mill produces paper from old newspapers and magazines. Its raw water treatment plant treat river water with high content of suspended solids and dissolved solids at an operating cost of \$0.043 m^{-3}. The mill water system is served by a complex water network with a fresh water consumption of 1989.06 ton h^{-1} and wastewater generation of 1680.3 ton h^{-1}. A simplified version of the existing water network for the case study is illustrated in Figure 3.

In this paper mill process, used paper is fed to the pulpers where it is blended with dilution water and chemicals to form pulp slurry called stock. The paper sheet formation begins when the stock from pulpers is sent to the forming section of the paper machine. Figure 3 shows that a total of 986.52 ton h^{-1} of fresh water is fed to the paper machine via streams 1 and 2 to remove debris while wastewater is removed from the stock during paper sheet formation. Part of these water sources (streams 5 and 6) are then sent to the white water tank along with recycled water (stream 9) from other processes in the De-inking pulper (others).

To remove printing ink from the main stock, de-inking pulper (DIP) is fed with 751.32 ton h^{-1} of fresh water (stream 3) and 398.5 ton h^{-1} of reused water from white water tank (stream 8). Of the DIP source (stream 12), 54 ton h^{-1} is then mixed with 14.7 ton h^{-1} of freshwater (stream 11) to dilute the stock being pumped to the deculator in the approach flow system (AF).

Fresh water (stream 10) is also used to dilute de-inking chemicals in the chemical preparation section (CP) before the chemicals are sent to the DIP unit to assist ink removal. In addition, other process in DIP (others) also receives 201.84 ton h^{-1} of fresh water (stream 4). As for the wastewater collected from the paper machine and DIP (streams 7 and 13), it is sent to the effluent treatment plant before being discharged into the river. The effluent treatment plant operating cost is \$0.295 m^{-3} as specified by the plant personnel.

In the case study, TSS was the most dominant water quality parameter and was selected as the main contaminant upon discussion with the plant authority. TSS was monitored online and offline for the purpose of water reuse, recycling and regeneration. Table 1 summarizes the water demand and source data for this case study. *Water demand* refers to the water requirement of a water-using operation while *water source* refers to effluent stream leaving a water-using operation. Note that water sources can be considered for reuse and recycle to the water demands.

TARGETING THE MINIMUM UTILITY FOR GRASSROOTS AND RETROFITTED WATER NETWORK

One of the latest and widely used water targeting techniques known as water surplus diagram (Hallale, 2002) is limited in its ability to estimate the minimum utility targets as it implements a graphical approach that involves time-consuming trial-and-error steps. This limitation has inspired the development of a numerical technique known as WCA that eliminates the trial-and-error approach (Manan *et al.*, 2004). The main objective of the WCA is to establish the minimum utility targets, i.e., the overall fresh water requirement and wastewater generation for a process after looking at the possibility of using the available water sources within a process to meet its water demands.

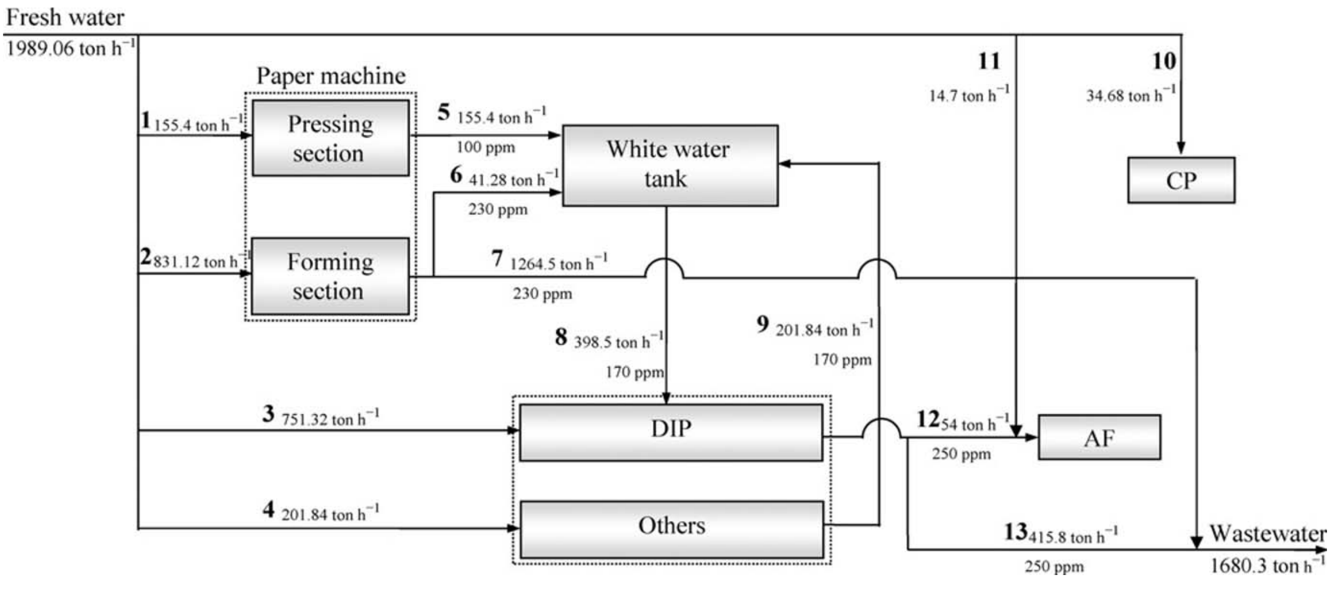

Figure 3. Existing water network for paper mill case study.

Table 1. Water demands and sources for case study.

Process description	Water demand	Flowrate, *F* (ton h^{-1})	Concentration, *C* (ppm)	Water source	Flowrate, *F* (ton h^{-1})	Concentration, *C* (ppm)
Pressing showers	1	155.40	20	1	155.40	100
Forming showers	2	831.12	80	2	1305.78	230
Others	3	201.84	100	3	201.84	170
DIP	4	1149.84	200	4	469.80	250
CP	7	34.68	20			
AF	8	68.70	200			

Manan *et al.* (2004) provides a detailed description of how WCA was used to establishe the baseline water targets for a chemical process involving mass transfer and non-mass transfer-based processes. Table 2 shows the results obtained from WCA, i.e. water cascade table (WCT) for the paper mill grassroots network before any regeneration placement. Note that the plant consumed 848.12 ton h^{-1} of minimum fresh water and generated 539.36 ton h^{-1} of wastewater when no regeneration is involved. On the other hand, if one were to retrofit the water network using the conventional retrofit technique for non-mass transfer-based process (Tan and Manan, 2003), one will achieve a saving of 1140.94 ton h^{-1} fresh water. Further reduction of utility targets can only be achieved with the introduction of water regeneration units. This will be described in the following section.

RETROFIT TARGETING OF WATER NETWORK WITH REGENERATION

In this section, a new technique to incorporate regeneration units into water network retrofit is presented. Two types of regeneration units were considered and the one giving the best savings was selected. Dissolved air flotation (DAF) tank and saveall disc filter (SDF) were two typical physical treatments suggested to purify water by recovering fibre from the excess water of paper machines. Note that these regenerators were the types actually used in the sections of the paper mill under study and therefore appropriate for the purpose of partial upgrading of white water to meet the quality required for the relevant processes. Table 3 shows the economic data for DAF tank and SDF that was extracted from various literature sources (Arundel, 2000; Koppol *et al.*, 2003; Perry and Green, 1997; Peter and Timmerhaus, 1980; Tchobanoglaus and Burton, 1991; Wiseman and Ogden, 1996).

DAF tank is an equipment that removes suspended solids (TSS) from wastewater and other industrial process streams. DAF tank is commonly used for wastewater pre-treatment, product recovery and thickening of biological solids in food processing, pulp and paper as well as petrochemical industries. This separation process is operated by introducing fine gas (usually air) bubbles into wastewater to attach and lift the particles to the water surface to be removed. Hence, wastewater leaves the unit at higher purity. A portion of the DAF tank effluent is recycled, pressurised and semi-saturated with air before re-entering the tank.

On the other hand, SDF is widely used as thickening device in the pulp and paper industry to remove solids from wastewater. It is operated by passing wastewater stream through filter mediums supported by disks. The solid content of the wastewater will be trapped by the filter mediums and finally disposed off. This leaves the wastewater at higher quality. Both regeneration units will be assessed in the retrofit situation.

Consider a generic model of a regeneration unit shown in Figure 4. Water produced or discharged from a water-using operation is treated in the regeneration unit to a higher purity. Water source leaving the regeneration unit is then

Table 2. WCT without regeneration.

Interval, *n*	Concentration, C_n (ppm)	Purity, P_n	$\Sigma F_{D,j}$ (ton h^{-1})	$\Sigma F_{S,i}$ (ton h^{-1})	$\Sigma F_{D,j} + \Sigma F_{S,i}$ (ton h^{-1})	F_C, (ton h^{-1})	Pure water surplus (ton h^{-1})	Cumulative pure water surplus (ton h^{-1})
						848.12		
0	1				0			
		0.00002				848.12	0.016962	
20	0.99998		−190.08		−190.08			0.016962
		0.00006				658.04	0.039482	
80	0.99992		−831.12		−831.12			0.056445
		0.00002				−173.08	−0.003462	
100	0.9999		−201.84	155.4	−46.44			0.052983
		0.00007				−219.52	−0.015366	
170	0.99983			201.84	201.84			0.037617
		0.00003				−17.68	−0.000530	
200	0.9998		−1218.54		−1218.54			0.037087
		0.00003				−1236.22	−0.037087	
230	0.99977			1305.78	1305.78			0
		0.00002				69.56	0.001391	
250	0.99975			469.8	469.8			0.001391
		0.99975				539.36	539.22603	
								539.22742

Table 3. Economic data for regeneration unit.

	Dissolved air flotation	Saveall disc filter
$C_{out,min}$	30 ppm	30 ppm
Hydraulic loading rate	20 $m^3\ m^{-2}\ day^{-1}$	6 $m^3\ m^{-2}\ day^{-1}$
Operating cost	\$0.150 ton^{-1}	\$0.179 ton^{-1}
Costing equation	$C = 2310.6$ Area $+ 260\,292$	$C = 63\,300^*(\text{Area } 9.3)^{0.48}$
Maximum area per unit	400 m^2	140 m^2
% Recycle flowrate	50%	—
Piping estimation	16% of capital investment	16% of capital investment

allocated for further reuse or recycle in the water network. Hence, regeneration is performed such that

$$C_{in} > C_{out} \qquad (3)$$

Feng and Chu (2004) states that the capital and operating costs of a regeneration unit are normally a function of regeneration flowrate (F_{reg}) and the outlet concentration of the regeneration stream (C_{out}). By studying the effects of these variables on the added regeneration unit, several retrofit cases can be explored in combination to target the optimum retrofit design with the addition of regeneration unit. Three cases considered in this work include:

(1) varying F_{reg} with C_{out} fixed;
(2) varying C_{out} with F_{reg} fixed;
(3) varying both F_{reg} and C_{out}

Case (1) involves a situation where a fixed C_{out} is required from a regeneration unit. Case (2) applies for situations where a fixed amount of regenerated water is needed in certain processes. Case (3) applies when there are no preferable C_{out} and F_{reg} values during retrofit. To yield a specific retrofit target, it is necessary to select a reasonable payback period for investment for each of the cases mentioned.

For the paper mill case study, the minimum achievable outlet composition, $C_{out,min}$ for both types of regeneration units (DAF tank and SDF) was set at 30 ppm (Wiseman and Ogden, 1996). There is virtually no limitation for the value of F_{reg} for each regeneration unit since this value will only affect the number of newly installed regeneration unit(s) in the network. For economic analysis, the maximum payback period was set at 2 years. Application of these cases on the paper mill case study is described next.

Case 1: Varying F_{reg} with C_{out} Fixed

For Case 1, the minimum outlet concentration for the regeneration unit, $C_{out,min}$ was fixed at 30 ppm while the regeneration flowrate, F_{reg} was varied. The objective of this case was to search for the optimum regeneration flowrate, $F_{reg,optimum}$ for the newly added regeneration unit(s). When a new regeneration unit was installed in an existing water network, F_{reg} amount of water at lower quality was regenerated to a higher quality for reuse and recycle, thereby reducing the utility targets of the network. Consequently, a bigger regeneration unit with a higher F_{reg} enabled further utility savings. However, it will be shown in the later section that the utility savings for a network will remain constant at the maximum regeneration flowrate value. We define the maximum regeneration flowrate to be $F_{reg,max}$. Hence, the optimum regeneration flowrate, $F_{reg,optimum}$ will fall in the range of $0 \leq F_{reg,optimum} \leq F_{reg,max}$.

To obtain the value of $F_{reg,\ max}$, a plot of fresh water flowrate (F_{FW}) target versus F_{reg} shown in Figure 5 was generated for a grassroots design of the paper mill water network. This yields a $F_{reg,\ max}$ of 620.27 ton h^{-1} at $C_{out,min}$ of 30 ppm (see WCT in Table 4). As shown in Figure 5, the fresh water target starts to level off at the $F_{reg,max}$ of 620.27 ton h^{-1}. Note that at this point of $F_{reg,\ max}$, the regenerated water cannot be further reused since the water network had reached its limitation in terms of reusing/recycling of the regenerated.

Ideally, it is desirable to retrofit an existing network to achieve the minimum utility targets identified in a grassroots design. Nevertheless, this is usually not possible during retrofit due to various process constraints and the need to minimize changes on the existing process structure. To consider these constraint, we have adapted a retrofit targeting procedure parallel to those developed for HEN and MEN problems as a basis for the newly proposed water network retrofit technique. However, instead of adding more exchanger areas/stages (such as in the case of HEN and MEN retrofit works), capital investments were allocated on new regeneration units installation to further reduce the utility targets, apart from modifications of existing network structure.

Figure 6 shows a few possible water network retrofit profiles for this case. As compared to the retrofit profiles for HEN and MEN problems shown in Figure 1, the retrofit profile for water network is indeed unique. For water network retrofit, the

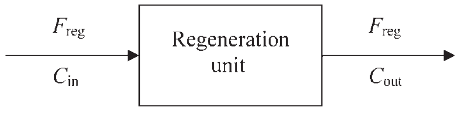

Figure 4. A regeneration unit.

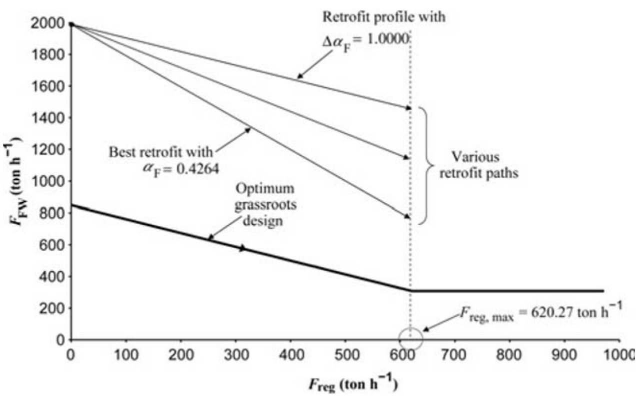

Figure 5. F_{FW} versus F_{reg} (Case 1).

Table 4. WCT with 620.27 ton h^{-1} of F_{reg} with 30 ppm C_{out}.

Interval, n	Concentration, C_n (ppm)	Purity, P_n	$\Sigma F_{D,j}$ (ton h^{-1})	$\Sigma F_{S,i}$ (ton h^{-1})	$\Sigma F_{D,j} + \Sigma F_{S,i}$ (ton h^{-1})	F_C, (ton h^{-1})	Pure water surplus (ton h^{-1})	Cumulative pure water surplus (ton h^{-1})
						308.76		
0	1				0			
		0.00002				308.76	0.00618	
20	0.99998		−190.08		−190.08			0.00618
		0.00001				118.68	0.00119	
30	0.99997			620.27	620.27			0.00736
		0.00005				738.95	0.03695	
80	0.99992		−831.12		−831.12			0.04431
		0.00002				−92.17	−0.0018	
100	0.9999		−201.84	155.4	−46.44			0.04247
		0.00007				−138.61	−0.0097	
170	0.99983			201.84	201.84			0.03276
		0.00003				63.23	0.0019	
200	0.9998		−1218.5		−1218.5			0.03466
		0.00003				−1155.3	−0.0347	
230	0.99977			1155.31	1155.31			0
		0.99977				0	0	
								0

profiles originate from the utility consumption (fresh water flowrate) of the existing network at 1989.06 ton h^{-1} at the upper left portion of the F_{FW} versus F_{reg} plot and moves towards the lower right portion of the plot. The best retrofit curve is typically the curve that approaches the utility targets of the grassroots network. Note that fresh water reduction (represented by y-axis) also led to the reduction of wastewater flowrate.

We next define a new retrofit parameter called the 'fresh water efficiency', α_F. For a fixed regeneration flowrate (F_{reg}), α_F is defined as the ratio between fresh water target for a grassroots design ($F_{FW,target}$) to the fresh water consumption of an existing network ($F_{FW,existing}$) as given in equation (4):

$$\alpha_F = \left(\frac{F_{FW,\ target}}{F_{FW,\ existing}}\right)_{F_{reg}} \tag{4}$$

The α_F value indicates how close the fresh water consumption in an existing network as compared to that in a grassroots design. A value of unity for α_F means that the existing water network has achieved the utility targets of a grassroots design. This is however almost impossible for most retrofit cases.

We have also defined the 'incremental value of fresh water efficiency', $\Delta\alpha_F$ for an increment of regeneration flowrate, ΔF_{reg} by taking the analogy from the $\Delta\alpha_{Area}$ (Silangwa, 1986; Shenoy, 1995; Polley and Polley, 2000). $\Delta\alpha_F$ was defined as the ratio between the decrease in fresh water target in grassroots design ($\Delta F_{FW,target}$) to the decrease in fresh water consumption of an existing network ($\Delta F_{FW,existing}$) as given by equation (5):

$$\Delta\alpha_F = \left(\frac{\Delta F_{FW,\ target}}{\Delta F_{FW,\ existing}}\right)_{\Delta F_{reg}} \tag{5}$$

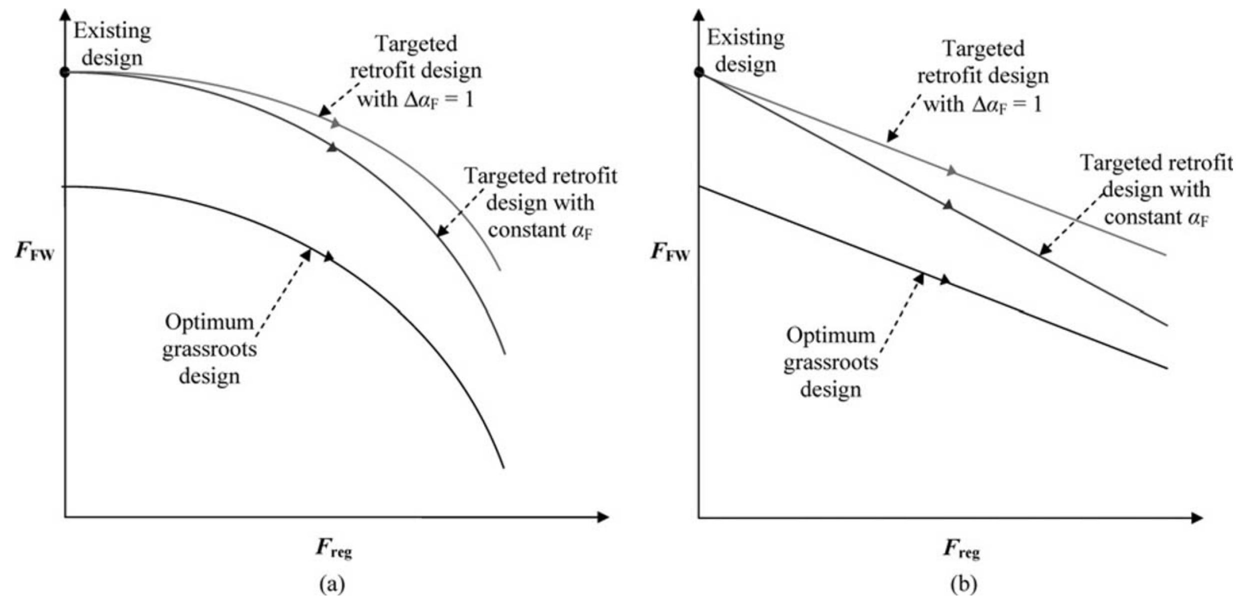

Figure 6. Two kinds of retrofit profiles (Case 1): (a) curve paths; (b) straight paths.

α_F and $\Delta\alpha_F$ values for this case study were calculated at 0.4264 and 1.0000 respectively using equations (4) and (5). α_F and $\Delta\alpha_F$ values yielded two possible retrofit paths for the water network as shown in Figure 5. The retrofit path with the constant α_F value of 0.4264 to which it approached the utility targets of an ideal grassroots design is the better choice.

For the retrofit of water networks, two types of retrofit profiles may exist The first is a curved path similar to the conventional profiles for heat and mass integration [Figure 6(a)] and the second is a linear retrofit path [Figure 6(b)]. The curved path occurs for problems with multiple pinches while the linear profile is found in water network problems involving a single pinch point (Tan and Manan, 2004). Since the paper mill case study involves a single pinch point, we will focus our discussion to the linear retrofit profile for the remainder of the text.

Figure 7 focuses on the left portion of Figure 5, i.e., portion where the F_{FW} versus F_{reg} plot levels off at $F_{reg,max} = 620.27$ ton h^{-1}. For the ease of demonstration, only the retrofit profile of $\alpha_F = 0.4264$ was shown. The plot consists of three main regions. We termed the area below the optimum grassroots design as the infeasible region since it was impossible to achieve utility reduction lower than that for the optimum grassroots design. The region in between the optimum grassroots design and the retrofit profile was termed as the economical design region where the desired retrofit targets will possibly fall. Finally, it was uneconomical to achieve retrofit targets in the region above the retrofit profile since no savings could be achieved.

We next determined the economic performance of this retrofit case using a savings versus investment plot. This included the fresh water and wastewater savings as well as the capital investment for retrofit work. Utility savings achieved during retrofit was defined as the total water utility cost savings minus the increment in operating cost for F_{reg}. On the other hand, the capital investment for network retrofit covered the costs of newly installed regeneration units as well as piping modifications. The size of a regeneration unit was estimated based on the following equation (Tchobanoglaus and Burton, 1991):

$$\text{Size of regeneration unit} = \frac{\text{Total regeneration flowrate}}{\text{Hydraulic loading rate}} \quad (6)$$

Due to the difference in capital and operating costs, different savings versus investment plots were needed to assess the two proposed regeneration units, i.e., DAF tank and SDF. Figures 8 and 9 illustrate the savings versus investment plot for the DAF tank and SDF respectively. Figure 8 shows three different segments of savings versus investment plot for the DAF tank. Each of these segments represented the desired number of units based on the size calculated at different F_{reg} value. Payback period lines were also identified in the diagram to enable designer to choose the optimum retrofit targets. A targeted investment limit of 1.68 years (below 2 years with maximum utility savings) was identified for a capital investment \$3.91M and savings of \$2.30M. Three DAF tanks were required to achieve this target.

The savings versus investment plot for SDF is shown in Figure 9. A targeted investment limit of 1.92 years (below 2 years with maximum utility savings) was identified for a capital investment and savings of \$4.83 M and \$2.52 M respectively. However, the installation of 18 units of SDF was required to achieve this target.

It is also worth to point out that Figures 8 and 9 are unlike the retrofit situation in heat and mass integration where the total area or number of stages was the only parameter to decide the retrofit option. There were more factors to consider in this work. For instance, installing 18 units of SDF may not be a practical retrofit option for the case study, since a large area was required for all of these regeneration units. Hence, it was up to the designer to decide which regeneration units were to be chosen during network retrofit. In any case, $F_{reg,optimum}$ for both retrofit options was 620.27 ton h^{-1}.

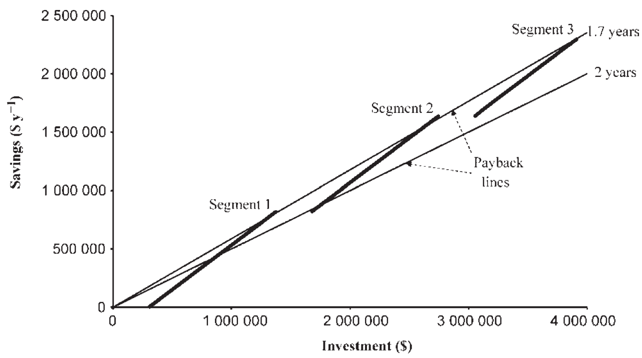

Figure 8. Savings versus investment plot for DAF (Case 1).

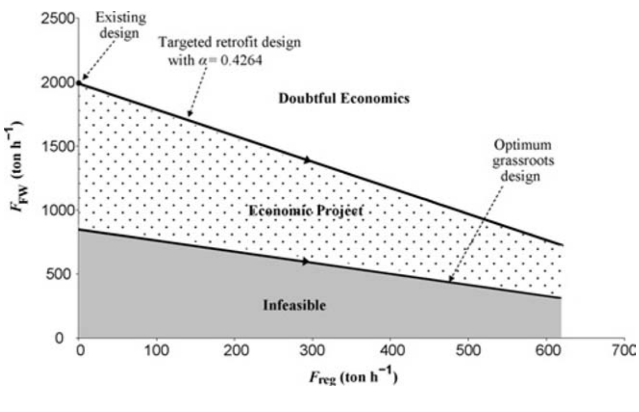

Figure 7. F_{FW} versus F_{reg}plot with constant α (Case 1).

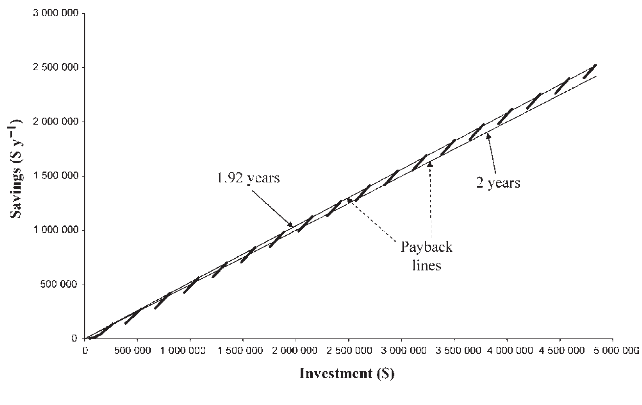

Figure 9. Savings versus investment plot for SDF (Case 1).

Case 2: Varying C_{out} at a Fixed F_{reg}

For the second case of network retrofit, F_{reg} was fixed at $F_{reg,max}$ while the outlet concentration of the regeneration unit, C_{out} was varied. The objective of this case was to determine the optimum outlet concentration of the regeneration unit, $C_{out,optimum}$, which fell between $C_{out,min}$ and $C_{out,max}$. Table 3 indicates that the $C_{out,min}$ for both regeneration units in this case study was fixed at 30 ppm. On the other hand, $C_{out,max}$ was based on the highest concentration among the available sources in the water network. This is a reasonable basis since no water shall be regenerated 'dirtier' than the available water sources in an existing network. From Table 1, the concentration of source 4 at 250 ppm was identified as $C_{out,max}$.

The next step in this case involved the determination of $F_{reg,max}$ for the water network, as done for Case 1. While C_{out} was varied, $F_{reg,max}$ was fixed at 620.27 ton h^{-1}. Recall that this value was the optimal regeneration flowrate ($F_{reg,optimum}$) found at a fixed $C_{out,min}$ for Case 1.

Next, WCA technique was used to locate the various targets for the grassroots water network when a regeneration unit with fixed $F_{reg,max}$ and various C_{out} was added. Figure 10 shows two different kinds of $F_{FW,min}$ versus C_{out} plot, i.e., a curved path similiar to the conventional heat and mass integration profile [Figure 10(a)] or a straight retrofit path [Figure 10(b)]. These plots revealed that for an optimum grassroots design, a regeneration unit with lower C_{out} would consume less fresh water as a result of cleaner regenerated water that could be reused or recycled A similar trend could be expected for an existing water network. However, during retrofit, some capital investments would be needed for newly installed regeneration unit as well as for existing network modifications. We hence defined another retrofit parameter called 'fresh water efficiency', α_C as given by equation (7):

$$\alpha_C = \left(\frac{F_{FW,\,target}}{F_{FW,\,existing}}\right)_{C_{out}} \quad (7)$$

where $F_{FW,target}$ and $F_{FW,existing}$ are the fresh water targets for grassroots network and the existing network respectively for a given regeneration C_{out} value. The α_C value provided a comparison of the minimum fresh water targets in a grassroots design with the existing fresh water consumption. An α_C of unity means that the existing water network had achieved the grassroots utility targets. This is impractical for most retrofit cases.

An 'incremental value of fresh water efficiency', $\Delta\alpha_C$ on the other hand was defined as the ratio between a decrease of fresh water target in grassroots design, $\Delta F_{FW,target}$ to that of the decrease in fresh water consumption in an existing network, $\Delta F_{FW,existing}$ for a given decrease in outlet concentration of regeneration unit, ΔC_{out} [equation (8)]:

$$\Delta\alpha_C = \left(\frac{\Delta F_{FW,\,target}}{F_{FW,\,existing}}\right)_{\Delta C_{out}} \quad (8)$$

Figure 11 represents the two retrofit profiles for Case 2, which was plotted using the fresh water efficiency values calculated using equations (7) and (8). These profiles corresponds to the values of $\alpha_C = 0.4264$ and $\Delta\alpha_C = 1$. Note from Figure 11 that these retrofit profiles originated from the utility target of the existing network at the upper right portion of the $F_{FW,min}$ versus C_{out} plot. Fresh water usage was reduced with a decrease in outlet concentration of the regeneration unit. A feasible retrofit path is the one leading to the optimum grassroots design, i.e., towards the lower left portion of the graph. As shown in Figure 11, a retrofit path with a constant α value would be a better choice. This represents the situation in Case 1. Figure 11 also shows that this retrofit diagram consists of three main regions, namely an infeasible design region, an economical design region and an uneconomic design region.

Next, the savings achieved and the capital investment (due to new regeneration unit placement) at each point in Figure 11 was calculated based on the economics data in Table 1. The savings versus investment plot for DAF tank and SDF are shown in Figures 12 and 13 respectively. Figure 12 shows that an investment of \$3.91 M is needed

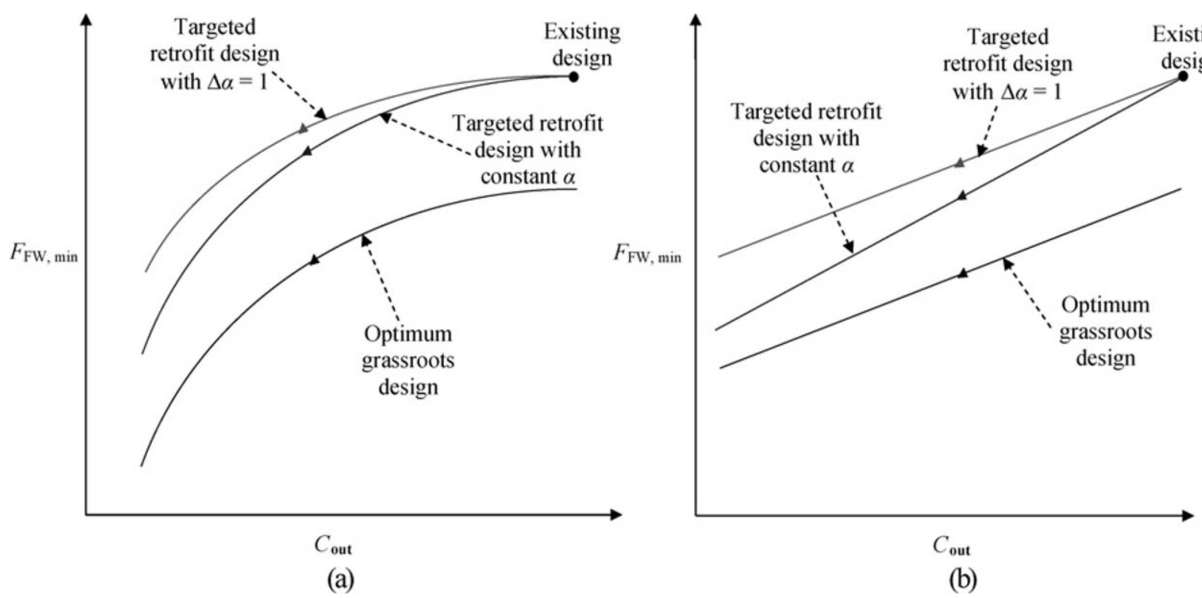

Figure 10. Two kinds of retrofit profiles (Case 2): (a) curve paths; (b) straight paths.

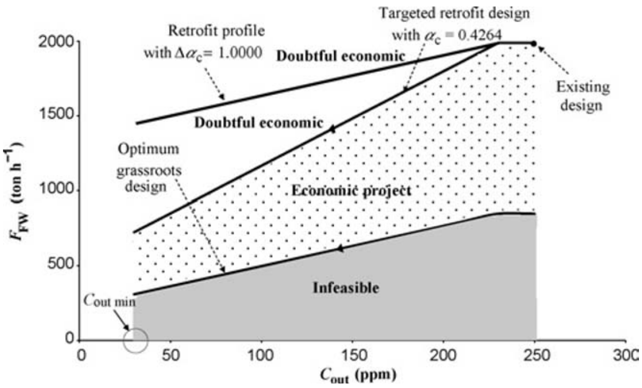

Figure 11. F_{FW} versus C_{out} plot with constant α (Case 2).

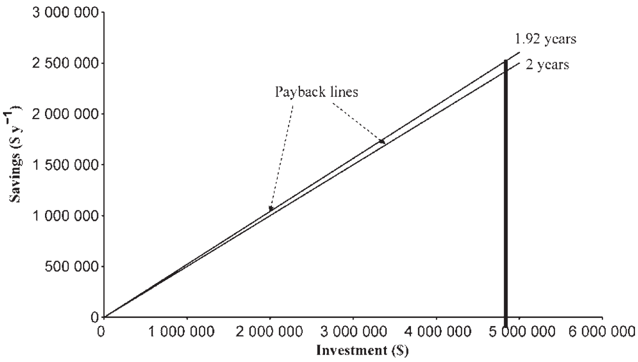

Figure 13. Savings versus investment plot for SDF (Case 2).

for the installation of three new DAF tanks to achieve an annual savings of \$2.30 M. This corresponds to the payback period of 1.7 years. On the other hand, capital investment of \$4.83 M is needed for the installation of 18 new SDF units. The targeted annual savings achieved for this alternative was at \$2.52 M. This led to a payback period of 1.92 years. Note also that due to the fixed value of F_{reg} in this case, both savings versus investment diagrams in Figures 12 and 13 appeared to be a vertical straight line at a fixed capital investment. The capital investment was independent of C_{out} because the selected regeneration unit mainly depended on the operating conditions. Finally, $C_{out,optimum}$ corresponding to both regeneration units were determined at 30 ppm.

Case 3: Varying C_{out} and F_{reg}

For Case 3, both F_{reg} and C_{out} were varied. The objective of this case was to search for $F_{reg,optimum}$ and $C_{out,optimum}$ for the added regeneration units. The first step in this case was to identify the boundary for $C_{out,optimum}$. Since the same case study and regeneration units were used, $C_{out,min}$ of 30 ppm and $C_{out,max}$ of 250 ppm were chosen. Next, the value of $F_{reg,max}$ was determined at various C_{out}.

Figure 14 shows the F_{FW} versus C_{out} plot for a grassroots network, calculated using the WCA technique. Note that the fresh water consumption remained constant at 308.76 ton h^{-1} when the regeneration unit produced regenerated water at concentration lower than the C_{out} of 95 ppm. However, beyond the C_{out} of 95 ppm, a larger amount of fresh water was required in the network due to the lower quality of regenerated water. Increased fresh water led to higher wastewater generated from the network.

Our objective was to target the utility reduction when regeneration units were installed in an existing water network. It was therefore necessary to focus on the constant fresh water region of the grassroots F_{FW} versus C_{out} plot (i.e., $C_{out} \leq 95$ ppm) where the minimum utility targets were achieved. As a result, the boundary of $C_{out,max}$ was shifted from 250 ppm to 95 ppm.

Figure 15 focuses the F_{FW} versus C_{out} plot with the newly defined C_{out} boundary at 95 ppm (from Figure 14). This plot consists of the optimum grassroots design and a newly added retrofit profile for the existing network, with α calculated at 0.4264 [following equation (8)]. Note also that α was selected instead of $\Delta\alpha$ in this case. This was due to the optimum grassroots plot being a horizontal straight line, and hence no profile of $\Delta\alpha$ can be plotted. Similar to the previous cases, regions of infeasible design, economical design and an uneconomic design exist in this case.

The operating cost savings and the required capital investment were calculated next to assess the economics of this case. Figures 16 and 17 illustrate the savings versus investment plot for DAF tank and SDF respectively. Note from Figures 16 and 17 that the savings decreased as investment increased when the regeneration flowrate (F_{reg}) and regeneration outlet concentration (C_{out}) were simultaneously varied. As C_{out} increased, the maximum regeneration flowrate ($F_{reg,max}$) also increased. This resulted in a lower fresh water retrofit profile. Increased $F_{reg,max}$ also led to higher capital

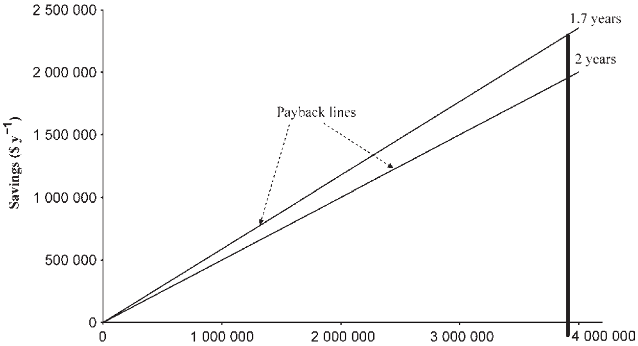

Figure 12. Savings versus investment plot for DAF (Case 2).

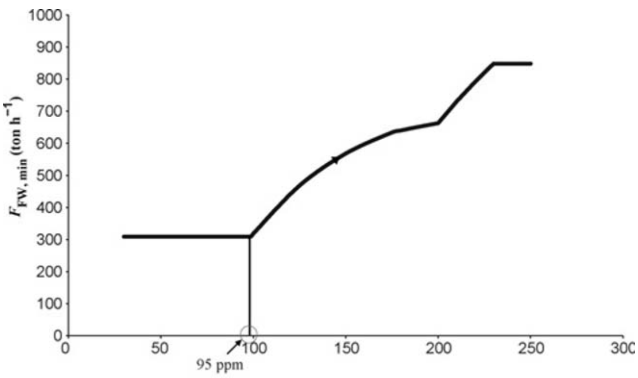

Figure 14. $F_{FW, min}$ versus C_{out} (Case 3).

investment. The savings also decreased due to increased (F_{reg}) and reduced fresh water as well as wastewater savings. A targeted investment limit of 1.7 years (below 2 years with maximum utility savings) was identified for DAF tank for a capital investment of \$3.91 M and savings of \$2.30 M. Three DAF tanks were required to achieve this target. On the other hand, 18 units of SDF were needed to achieve the same targets. This corresponded to a capital investment of \$4.83 M, an annual savings of \$2.52 M and a payback period of 1.92 years. The $C_{out,optimum}$ and $F_{reg\ optimum}$ for both regeneration units were 30 ppm and 620.27 ton h^{-1}.

DISCUSSION

It was shown that three cases achieved the same retrofit targets ($C_{out,optimum}$ and $F_{reg,optimum}$) for the paper mill case study. This was mainly due to the selection of fixed C_{out} and F_{reg} variables in the first two cases. If a different C_{out} and/or F_{reg} and different payback period were specified for Case 1 and Case 2, different retrofit targets would have emerged. Therefore, it could be concluded that retrofit targets depended on C_{out} and F_{reg} as well as on the payback period specifications.

Although $C_{out,optimum}$ and/or $F_{reg,optimum}$ attained for both regeneration units were 30 ppm and 620.27 ton h^{-1} respectively, selection of DAF tanks as the new regeneration units was the better retrofit option for all three cases. This was due to the more reasonable targeted number of DAF tanks as compared to SDF. Nevertheless, one can still consider installing SDF in this case study if the maximum water savings constraint was neglected. Installing five units of SDF, for instance, gave a total F_{reg} of 139 ton h^{-1}, C_{out} of 30 ppm and a payback period of 1.91 years.

All the retrofit targets achieved in this section were merely based on the limiting data for the case study and was independent of any particular network design. In order for these targets to be meaningful and effective, a network design technique leading to the retrofit targets is needed. The procedure for network design is described in the next section.

RETROFIT DESIGN OF WATER NETWORK WITH REGENERATION

In the grassroots design of a maximum water recovery network, the pinch point plays an important role to ensure the established utility targets are realized. Water network is normally divided into regions above and below the pinch during the design stage. Network design is then carried out

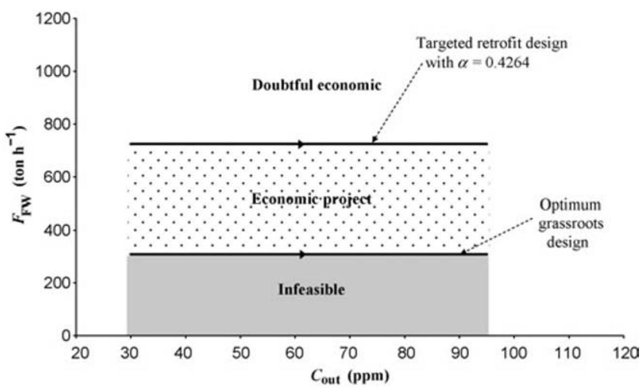

Figure 15. F_{FW} versus C_{out} plot with new C_{out} boundary (Case 3).

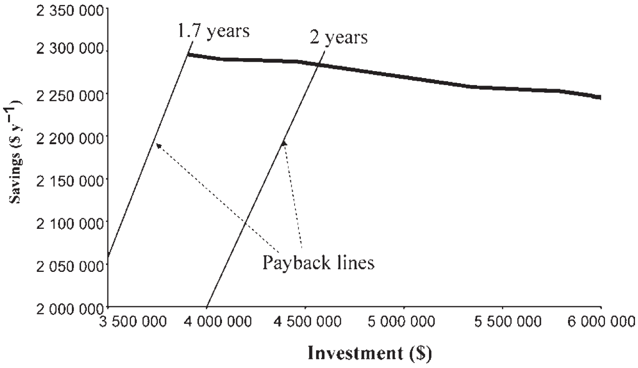

Figure 16. Savings versus investment plot for DAF (Case 3).

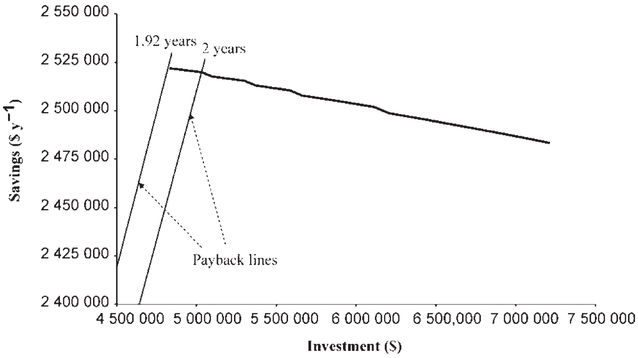

Figure 17. Savings versus investment plot for SDF (Case 3).

independently in these regions using various network design procedures (e.g., Wang and Smith, 1994; Feng and Seider, 2001; Prakash and Shenoy, 2005). Similarly, getting the pinch location(s) for an existing water network is also essential before any retrofit design is carried out.

To determine the pinch points, we rely again on the WCA technique. Utility targeting was performed for a grassroots network based on the water demands and sources data (Table 1) along with the $F_{reg,optimum}$ and $C_{out,optimum}$ of the regeneration unit(s) identified earlier. Table 4 shows the resulting WCT for the grassroots network. The water pinch for this grassroots network existed at the lowest concentration level (230 ppm) where there was zero cumulative pure water surplus (Table 4). Water pinch at this location indicated that all sources and demands appear at the region above the pinch, and hence, a zero discharge process (no wastewater generation) was achieved. However, in revamping an existing water network, achieving the targets as in the grassroots design is not always possible.

For retrofitting water network involving non-mass transfer processes, such as for the paper mill case study, many network design techniques may be used. These include the source sink mapping diagram (El-Halwagi, 1997; Dunn and Wenzel, 2001), sink-source allocation (Prakash and Shenoy, 2004) or concentration block diagram (Tan and Manan, 2003). In this work, we utilized the concentration block diagram (CBD) to represent the existing water network. CBD provides a clear representation of the existing water network in terms of the water flowrate as well as contaminant concentration.

CBD of the paper making case study is presented in Figure 18. The vertical dashed lines represent the concentration-interval boundaries which correspond to a distinct limiting inlet or outlet concentration. The water-using operations are represented by rectangles corresponding to their inlet and outlet concentrations. The arrows in the diagram indicate the water streams of the existing water network with the stream flowrate in ton h^{-1} and contaminant concentration in ppm (figures in parentheses).

The next step in the retrofit design stage was to identify the streams for regeneration. Sources at the highest concentration were always preferred as this reduced the mass load accumulated in wastewater produced. One noticed from Figure 1 that, at the highest concentration of 250 ppm, 469.8 ton h^{-1} of wastewater is available from the source 4, i.e., the water source of DIP. However, the targeted $F_{\mathrm{reg,max}}$ that was identified in the earlier stage amounts to 620.27 ton h^{-1}. This means that part of the wastewater discharged from Forming Showers (at second highest concentration) was chosen to satisfy the remaining F_{reg} amounted fed to the DAF tanks. The dotted lines in Figure 18 show the streams which are identified for regeneration. 54 ton h^{-1} of water produced from DIP was originally sent to DAF tanks instead of being reused in AF.

The existing water network was next redesigned to meet the established retrofit targets. This involved sending the identified streams to the regeneration unit (DAF tanks) and feeding the purified source to the water-using operations to reduce fresh water intake. The preliminary retrofit design is presented in Figure 19. As shown, 54 ton h^{-1} of water source was sent to AF unit from the DAF tanks instead of feeding from the DIP unit directly in the existing water network (refer to Figure 3). The remaining regenerated water from the DAF tanks were also sent to the Pressing Showers, Forming Showers and for Chemical Preparation.

The final step of the retrofit design stage involves optimisation of the preliminary retrofitted network for further utility reduction. To achieve this, opportunity for further reuse and/or recycle of wastewater sources in the preliminary retrofit design was explored. One option in this effort is to reuse and recycle the effluent from Forming Showers back to its own water demands as well as to other water-using processes. The final retrofit design for the paper making case study is shown in Figure 20. It is shown that after retrofit, the fresh water consumption has been reduced by 80% to 401.82 ton h^{-1} while the wastewater generation has been reduced by 95% to 92.52 ton h^{-1}.

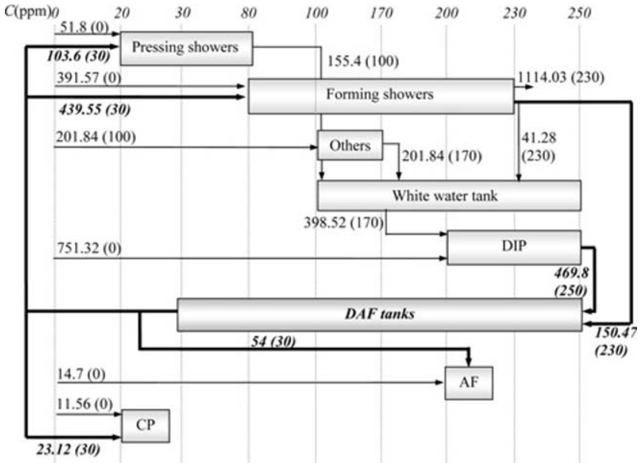

Figure 19. Preliminary retrofit design.

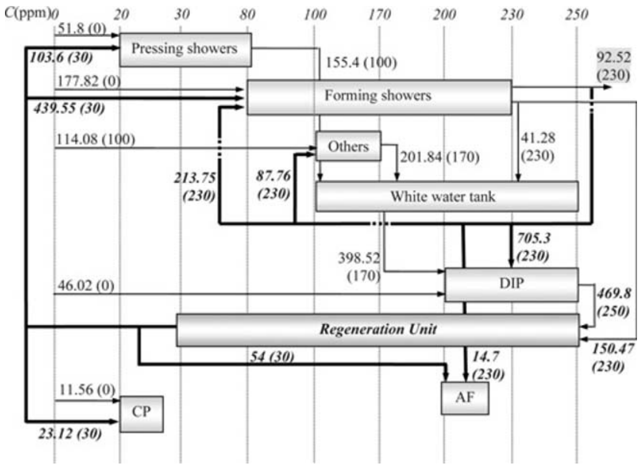

Figure 20. Final retrofit design.

Economic calculations show that a total savings of \$3.16 M has been achieved with this final network, with the installation of three new DAF tanks. Though the savings had slightly surpassed the targeted value (\$0.86M), however the capital investment of \$3.91M remained within target. The resulting payback period of 1.24 years is slightly better as compared to the targeted value of 1.7 years. Finally, note that the retrofit design presented above is one of the many possible solutions that can achieve the retrofit target. Often, different network design configurations can be achieved with the use of different network design techniques (El-Halwagi, 1997; Dunn and Wenzel, 2001; Prakash and Shenoy, 2005).

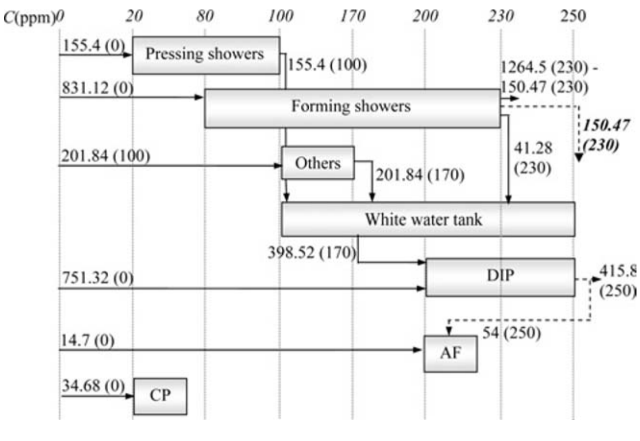

Figure 18. Existing water network in CBD with identified streams for regeneration.

CONCLUSIONS

A new systematic procedure for the retrofit of water network with regeneration has been developed. This procedure enables further reduction of the utility targets to be achieved in an existing water network via water reuse, recycling and regeneration. The optimum design of the regeneration unit was based on two process parameters, i.e., regeneration flowrate and the outlet concentration. The methodology consists of two stages namely, retrofit targeting and design. In the targeting stage, fresh water versus regeration flowrate and outlet concentration diagrams were introduced, and a feasible retrofit path was identified to establish various retrofit targets. Given a fixed payback period or capital expenditure, the retrofit targets were determined from the savings versus investment diagram. During network design, the existing water network was revamped according to pinch design rules to meet the established retrofit targets. This methodology has successfully achieved the retrofit targets prior to design, and further minimized fresh water consumption and wastewater generation in an existing water network.

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