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Abstract

Material reuse/recycle has gained much attention in recent years for both economic and environmental reasons. Process integration techniques for water network synthesis have evolved rapidly in the past decade. With in-plant water reuse/recycle, fresh water and wastewater flowrates are reduced simultaneously. In this work, linear programming and mixed integer linear programming models that include piping cost and process constraints are developed to retrofit an existing water network in a paper mill that was not originally designed with process integration techniques. Five scenarios are presented, each representing different aspects of decision-making in real process integration projects. The fifth scenario makes use of fuzzy optimisation to achieve a compromise solution that considers the inherent conflict between maximising water recovery and minimising capital cost for retrofit.

KEYWORDS: water integration, retrofit, optimisation, fuzzy programming

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INTRODUCTION

Development of cleaner technology has been a recent trend in the process industries. Although end-of-pipe effluent treatment is still used to ensure compliance to discharge regulations, some works have now shifted towards waste minimisation practices which are more environmentally sustainable. In addition, the other factor that encouraged this trend has been of economics associated with water supply and treatment cost. In responding to this shift, the development of process integration techniques has been one of the most significant advances in waste minimisation in the past decade. One of the active areas has been that of resource conservation, with one of the most active area being water network synthesis. Via in-plant material reuse/recycle, both raw material consumption and waste generation are reduced significantly.

The seminal work for water network synthesis was initiated by Wang and Smith (1994) who presented the two-stage pinch analysis approach based on the more general mass exchange network synthesis problem (El-Halwagi and Manousiouthakis, 1989; El-Halwagi, 1997). Following the conventional pinch analysis approach, targeting tool is first used to identify the minimum fresh water and wastewater flowrates, which is then followed by detailed network design guided by heuristics. Many other flowrate targeting and network synthesis tools were also developed thereafter (e.g. Wang and Smith, 1995; Kuo and Smith, 1998; Hallale, 2002; El-Halwagi *et al.*, 2003; Manan *et al.*, 2004; Prakash and Shenoy, 2005a, b; Agrawal and Shenoy, 2006; Foo *et al.*, 2006; Ng and Foo, 2006; Bandyopadhyay *et al.*, 2006; Bandyopadhyay, 2006; Shenoy and Bandyopadhyay, 2007; Ng *et al.*, 2007a; Ng *et al.*, 2007b). However, most of these works have only addressed water network synthesis problems in grassroots design (i.e. when process plants have not been built) during which stage there is significant flexibility. Less work has been dedicated to the more realistic problems where existing water network in an operational plant is to be retrofitted to save water (Tan and Manan, 2006; Tan *et al.*, 2007; Chiang and Foo, 2006). In such cases, there are physical constraints to be considered – for example, the locations of the water sources and sinks may already be fixed, and the plant layout may allow new piping to be installed only in certain locations. The optimality of the pinch-based solution may not be guaranteed as retrofit cases often require detailed costing for the changes to be made. Hence, of the mathematical programming approach to process integration is preferred in handling a retrofit problem.

Early work on mathematical-based optimisation approach for water network synthesis was reported by Takama and co-workers (Takama *et al.*, 1980a, 1980b, 1981). Much later, Alva-Argáez and co-authors developed the integrated approach combining the insights from water pinch and mathematical programming in handing the mass transfer-based water network problems (Alva-

Argáez *et al.*, 1998, 1999). The combined use of pinch and linear programming (LP) techniques was later presented by Jacob *et al.* (2002). Optimisation approaches based on non-linear programming (NLP) were later presented for mass transfer-based processes (Rossiter and Nath, 1995; Yang *et al.*, 2000; Abebe *et al.*, 2003) and for non-mass transfer-based processes (Dunn *et al.*, 2001). Huang *et al.* (1999) and Benko *et al.* (1999, 2000) individually developed the mathematical-based approach to include water treatment in the total water network synthesis. Bagajewicz and co-workers utilised linear programming and algorithmic procedures for the design of water network, for both single (Bagajewicz and Savelski, 2001; Savelski and Bagajewicz, 2000a, 2000b, 2001, Gómez *et al.*, 2001) and multiple impurities (Bagajewicz *et al.*, 2000; Savelski and Bagajewicz, 2003). More recent work in this area uses advanced mathematical optimisation approaches, such as fuzzy linear programming (Tan, 2002; Tan and Cruz, 2004), genetic algorithm (Tsai and Chang, 2001; Li ***et al.***, 2003; Prakotpol and Srinophakun, 2004; Shafiei *et al.*, 2004; Lavric *et al.*, 2005), adaptive random search optimisation approaches (Poplewski *et al.*, 2002; Jeżowski *et al.*, 2003; Poplewsk and Jeżowski, 2005) and particle swarm optimisation (Hul *et al.*, 2006; Luo *et al.*, 2006). As in the case of pinch-based approaches, most of these mathematical approaches are also dedicated to grassroots design rather than retrofit cases. It is hence necessary to develop a simple and yet practical mathematical model to handle water network retrofit. This is the subject of this paper. Linear programming (LP) and mixed integer linear programming (MILP) models have been developed in this work to cater for water network retrofit cases for an operational plant. LP and MILP models are used as they guarantee global optimality and can be easily executed with the aid of commercial optimisation software.

In the following section, the developed model will be described. A paper milling process plant with an existing water network is next utilised to illustrate the developed model. Five different scenarios are considered in this case to show the wide applicability of the models, namely:

- Design for maximum water recovery
- Design for water recovery with capital investment limits
- Design to meet wastewater reduction percentage targets
- Design with forbidden reuse or recycle matches
- Design considering the conflicting objectives of maximum water recovery and minimum capital investment

WATER NETWORK RETROFIT MODELS

In this section, the development of the LP and MILP models for water network retrofit is presented. The formulation makes use of the source-sink allocation approach, which is also the basis of the techniques developed by Hallale (2002), El-Halwagi *et al*. (2003) and Prakash and Shenoy (2005 a, b). This approach assumes fixed flowrates for all inlet and outlet streams (hence it is often known as the *fixed flowrate problem*), fixed concentrations for the outlet streams, and well-defined concentration limits for the inlet streams. In contrast, most mathematical models in the literature consider water-using processes as a type of mass exchange network (often known as the *fixed load problem*, e.g., Alva-Argaez *et al*., 1998, 1999; Bagajewicz *et al*., 2000; Bagajewicz and Savelski, 2001; Savelski and Bagajewicz, 2000a, 2000b, 2001, 2003). The main limitation of this model is that, many water-using processes which are essentially not mass transfer operations will have to be converted into mass transfer operations. This in turn makes the model more complicated unnecessarily. The recent works in water network synthesis has mainly based on the fixed flowrate problems, which is believe to handle the fixed load problem equally well (e.g. see discussion in Hallale, 2002; Manan *et al*., 2004).

Model parameters

A and B = piping cost constant on an hourly basis
$C_{\mathrm{out},\,i}$ = outlet concentration of source i
$C_{\mathrm{in},\,j}$ = inlet concentration limit of sink j
CAP = capital cost limit for retrofit
$D_{i,\,j}$ = Manhattan distance for source i to sink j
EFF = effluent volume target
F_i = outlet flowrate of source i
F_j = inlet flowrate of sink j

Decision variables

$b_{i,\,j}$ = binary variable for connection of source i to sink j
$F_{\mathrm{FW},\,j}$ = freshwater flow rate of sink j
$F_{i,\,j}$ = water reused/recycled from source i to sink j

Different objective functions may be used for the optimisation model. To minimise fresh water flowrate sent to water sinks j, Equation 1 shall be used:

$$\text{Minimise } \Sigma_j\, F_{\mathrm{FW},\,j} \tag{1}$$

The material balance around each source is:

$$\Sigma_j\, F_{i,\,j} \le F_i \qquad\qquad \forall i \tag{2}$$

The water balance around each sink is based on the total flowrate of the streams comprising the mixed flow:

$$\Sigma_i F_{i,j} + F_{\mathrm{FW},j} = F_j \qquad \forall j \qquad (3)$$

The material balance for component *k* of the mixture of source(s) *i* that is fed to each sink *j* is subject to the specified concentration limit of the process:

$$\Sigma_i F_{i,j}\,\mathrm{C}_{\mathrm{out},\,i,k} \leq F_j\,\mathrm{C}_{\mathrm{in},\,j,k} \qquad \forall j,\ k \qquad (4)$$

In addition, an upper limit to piping cost can be specified:

$$\Sigma_i \Sigma_j\, [\mathrm{A}F_{i,j} + \mathrm{B}b_{i,j}]D_{i,j} \ \leq CAP \qquad (5)$$

The cost coefficients for the piping, i.e. *A* and *B* are given on an hourly basis. The piping cost consists of a fixed cost component, incurred once a connection is made in the network, as indicated by $b_{i,j}$, and a variable cost, which is roughly proportionate to the flowrate of water delivered through the connection (Gunaratnam *et al.*, 2005). Thus, once a connection is made the fixed cost component is automatically incurred:

$$b_{i,j} \geq \frac{F_{i,j}}{F_i} \qquad \forall i, j \qquad (6)$$

In addition, the effluent volume may also be limited for practical reasons such as the capacity of the sewage treatment facility:

$$\Sigma_i\, [F_i - \Sigma_j F_{i,j}] \ \leq \ EFF \qquad (7)$$

Finally, all the variables in the model are non-negative. These constraints are no longer listed in order to save space. The above LP and MILP models can be easily executed with the aid of commercial optimisation software as they guarantee global optimal solution. In this work, LINGO (Schrage, 1999) and Excel Solver optimisation software are used.

EXAMPLE – PAPER MILLING PROCESS

Figure 1 shows the water network of an existing paper mill (Foo *et al.*, 2006). Old newspapers and magazines as feedstocks for the paper mill are blended with water and chemicals to form pulp slurry or stock. The stock is sent to the forming section of the paper machine to form paper sheet. In the forming and pressing sections, fresh water is fed to remove debris while wastewater is removed from the stock during paper sheet formation. Part of these water streams are then sent to a water storage tank to be reused in other processes.

To remove printing ink from the main stock, the de-inking pulper (DIP) and its associated processes (denoted as "DIP-Others") receive a mixture of fresh water and spent water from the water storage tank. The effluent water from the DIP main process is mixed with freshwater to dilute the stock being pumped to the deculator in the approach flow system (AF) while the effluent from "DIP-Others" is sent to water storage tank. The chemical preparation unit (CP) also consumes fresh water to dilute de-inking chemicals for use during ink removal process in the DIP unit. Part of wastewater from the forming section and the DIP unit are sent for effluent treatment before being finally discharged to the environment.

From Figure 1, the total fresh water consumption is 1,989 ton/h and the total wastewater generation is 1,680 ton/h. At a water supply cost of about $0.15 per ton, the plant spends more than $7,000 per day of operation. At a first glance, this paper mill seems to have already been designed with an extensive water recovery scheme (water from three sources are reused in two sinks). However, as shown by Foo *et al.* (2006), its theoretical minimum fresh water and wastewater flowrates as determined using pinch analysis are as low as 848 ton/h and 539 ton/h respectively. The corresponding water cost for such a network is only about $3,000 per day, or less than half that of the current level. For a new plant, the minimum fresh water and wastewater targets can be achieved by designing the plant with optimal water recovery as a priority. However, this is often not the case for a network that was not designed using process integration techniques. For instance, a big portion of effluent from the forming section is discharged rather than being reused or recycled (Foo *et al.*, 2006). It provides good opportunity for further water recovery.

Due to the existence of a current water network, the minimum water targets based on grassroots design are difficult to achieve without extensive downtime for re-channelling of the plant piping. However, the grassroots water pinch targets identified earlier are still useful as a baseline or benchmark for the retrofit case, as it serves as the upper bound of water saving that may be achieved. The LP and MILP models developed in this work ensure cost-effective solutions to be determined by incorporating other process constraints which are often not considered in grassroots design.

An important constraint that the plant authority has imposed for the network retrofit is that the general topology of the existing water network should be maintained. Hence water streams that are already currently reused in process sinks will no longer be considered during network retrofit. In the retrofitting of the water network, addition reuse or recycle streams may be added, but those that are already in existing will not be removed.

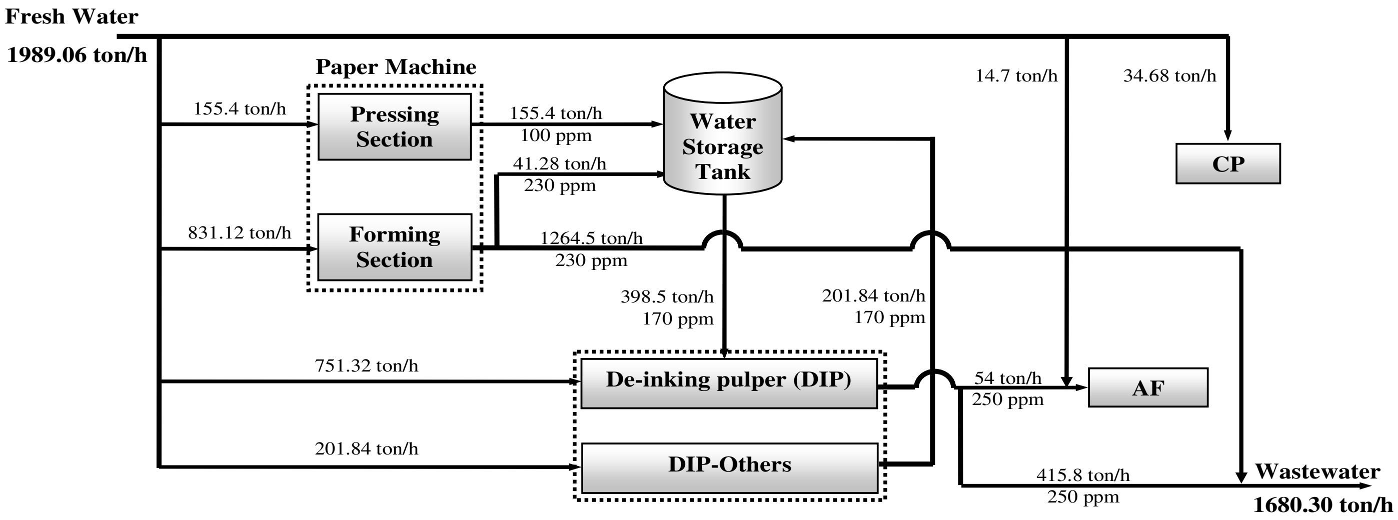

Figure 1. An existing water network for a paper mill (Foo *et al.*, 2006)

Table 1 shows the limiting water data for the paper mill case study, i.e. the maximum permissible inlet (C_j), outlet (C_i) concentrations and limiting flowrates for the water sinks (F_j) and the water sources (F_i) respectively. The most significant water quality factor was determined in consultation with the plant authority to be total suspended solid (TSS). Hence, in this particular case the models are reduced to single-component problems, although this need not be the case for other plants.

Table 1. Limiting water data for the paper mill case study

Water sinks, SK$_j$		**Flowrate**	**Concentration**
j	**Stream**	**F_j (ton/h)**	**C_j (ppm)**
1	Pressing section	155.40	20
2	Forming section	831.12	80
3	DIP-Others	201.84	100
4	DIP	1149.84	200
5	CP	34.68	20
6	AF	68.70	200
Water sources, SR$_i$		**Flowrate**	**Concentration**
i	**Stream**	**F_i (ton/h)**	**C_i (ppm)**
1	Pressing section	155.40	100
2	Forming section	1305.78	230
3	DIP-Others	201.84	170
4	DIP	469.80	250

The water network (Figure 1) may be conveniently represented as a matching matrix (Prakash and Shenoy, 2005b) in Table 2. As shown, water sources *i* (SR$_i$) appears as rows and sink *j* (SK$_j$) as columns, arranged in an increasing order of concentration. The first row of the matching matrix with 0 ppm indicates a fresh water (FW) source while the last column of the matching matrix indicates wastewater (WW).

Table 2. Matching matrix for water network in paper mill

		F_j (ton/h)	155.4	34.68	831.12	201.84	1149.84	68.7	1680.3
		C_j (ppm)	20	20	80	100	200	200	
F_i (ton/h)	**C_i (ppm)**	**SK$_j$** **SK$_i$**	SK1	SK5	SK2	SK3	SK4	SK6	WW
1989.06	0	FW	155.4	34.68	831.12	201.84	751.32	14.7	
155.4	100	SR1					155.4		
201.84	170	SR3					201.84		
1305.78	230	SR2					41.28		1264.5
469.8	250	SR4						54	415.8

However, due to the requirement of maintaining the existing water reuse or recycle streams, an adjusted set of limiting water data need to be derived from Table 1 to be used for the retrofit model (given in Table 3). These changes are as follows:

- The flowrate requirements and maximum permissible inlet concentration of water sinks SK4 and SK6 have been adjusted by deducting both the water flowrate and contaminant mass loads contributed by the existing reuse/recycle streams from their total requirement.
- The discharge flowrates from SR2 and SR4 are taken as the available surplus flowrates from these sources after removing the portions already allocated for reuse in the current network.

Table 3. Adjusted limiting water data for the paper mill case study

Water sinks, SK*j*		**Flowrate**	**Concentration**
j	**Stream**	**F_j (ton/h)**	**C_j (ppm)**
1	Pressing section	155.40	20
2	Forming section	831.12	80
3	DIP-Others	201.84	100
4	DIP	751.32	227.09
5	CP	34.68	20
6	AF	14.7	16.33
Water sources, SR*i*		**Flowrate**	**Concentration**
i	**Stream**	**F_i (ton/h)**	**C_i (ppm)**
2	Forming section	1264.5	230
4	DIP	415.8	250

To account for detailed piping cost, the Manhattan distance between each available source i to each potential sink j, $D_{i,j}$ is needed. The distances are given in Table 4. Note that only two sources are shown, since other sources that are already being reused/recycled to the water sinks are not included.

Table 4. Manhattan distance for source *i* to sink *j* (in meters).

Sink **Source**	Pressing section	Forming section	DIP-Others	DIP	CP	AF
Forming section	5	5	72	103	58	8
DIP	103	98	40	5	85	98

Five retrofit scenarios described previously are presented. Each scenario represents potential decision-making aspects encountered in real process integration projects. Cost coefficients used in Equation 5 are given as USD 3606.3 $\text{s.m}^{-1}\text{ton}^{-1}$ (A) and USD 124.6 m^{-1} (B) respectively.

Scenario 1 - Maximum water recovery

The objective for Scenario 1 is to maximise wastewater recovery while maintaining existing water network structure. Efforts for water saving is performed by re-routing the water sources that are currently sent for discharge to be reused/recycled to the water sinks.

Due to the limitation imposed by the existing network structure, there are only two water source candidates that may be considered in this scenario, i. e. Forming Section (SR2) and DIP (SR4). When the water source(s) is sent to a sink, the fresh water flowrate that is originally supplied to the sink is reduced to match the flowrate demand of the sink. The extent of recovery of water source(s) to a sink is subjected to the maximum permissible concentration limit of the sink.

Solution generated by the LP model, using only Equations 1 – 4 in the model, is shown in Table 5. Note that only water sources that are involved in network retrofit are shown (with its available flowrate shown in column 1). Based on the LP program, the minimum fresh water requirement is targeted as 853 ton/h showed in column 1 and row 4 of Table 5. As shown, a total of 1,136 ton/h (1,265 ton/h – 128 ton/h) of water have been recovered from the Forming Section to all sinks; while no water is recovered from DIP. As a result, the fresh water consumption is reduced from 1,989 ton/h (Figure 1) to 853 ton/h, which represent a reduction of 57.1 %. Based on the fresh water cost of $0.15/ton, fresh water saving is determined to be $4,090/day. The total investment on the piping is determined as $115,781 using Equation 5, and results in a payback time of 28 days.

Table 5. Water network for Scenario 1.

		F_j (ton/h)	14.70	155.40	34.68	831.12	201.84	751.32	544.07
		C_j (ppm)	16.33	20.00	20.00	80.00	100.00	227.09	
F_i (ton/h)	**C_i (ppm)**	**SK_j / SR_i**	SK6	SK1	SK5	SK2	SK3	SK4	WW
852.83	0.00	FW	13.66	141.89	31.66	542.03	114.08	9.51	
1264.50	230.00	SR1	1.04	13.51	3.02	289.09	87.76	741.81	128.27
415.80	250.00	SR2							415.80

Scenario 2 – Capital investment limits

In Scenario 1, when maximum recovery or minimum fresh water consumption is set as the objective function, the resulted network requires a high capital investment of $115,781. There may be cases where the process plant management does not wish to invest such capital to carry out a retrofit project. Instead, a maximum capital investment limit may be defined based on financial considerations, and an optimal solution subject to this capital constraint is desired. This effect is achieved by incorporating Equations 5 and 6 into the model. For example, a new retrofit option is developed subject to a new constraint of maximum capital investment of $50,000.

As shown in Table 6, the resulting network requires 126 ton/h (= 979 ton/h – 853 ton/h) higher fresh water flowrate as compared to Scenario 1. Fresh water saving is determined as $3,636, which leads to a payback time of 14 days. Significantly, the fresh water savings achieved for Scenario 2 (50.8%) approaches that of Scenario 1 (57.1%), but is achieved at less than half the capital cost. As higher water saving is generally expected when higher capital investment is spent, sensitivity analysis can be used to determine capital cost and water conservation tradeoffs. For instance, solving the model with a capital investment of $60,000 leads to fresh water reduction of 53.4% (927 ton/h), while $70,000 leads to 55.4 % fresh water reduction (888 ton/h). These sub-scenarios provide additional information for plant management to decide the amount of investment for the retrofit project.

Table 6. Water network for Scenario 2.

		F_j (ton/h)	14.7	155.40	34.68	831.12	201.84	751.32	670.35
		C_j (ppm)	16.33	20	20	80	100	227.09	
F_i (ton/h)	**C_i (ppm)**	**SK_j** **SR_i**	SK6	SK1	SK5	SK2	SK3	SK4	WW
979.10	0	FW	13.66	141.89	34.68	542.03	201.84	45.00	
1264.50	230	SR2	1.04	13.51		289.09		298.09	662.77
415.80	250	SR4						408.22	7.58

Scenario 3 – Wastewater reduction percentage

Scenario 3 presents a different situation where a given amount of wastewater flowrate reduction is needed in the plant. This situation may arise due to the bottleneck of the wastewater treatment system, and is incorporated into the model using Equation 7. At the same time, the original objective function is replaced by the capital cost for retrofit:

$$\text{Minimise } \Sigma_i \Sigma_j [\mathrm{A}F_{i,j} + \mathrm{B}b_{i,j}]D_{i,j} \tag{8}$$

Table 7 shows the results for a target of 50% wastewater reduction. As a result, 840 ton/h of wastewater is produced from the plant. This corresponds to fresh water consumption of 1,149 ton/h. The total investment on the piping cost is $30,851, and a payback period of 10 days is achieved.

Table 7. Water network for Scenario 3.

		F_j (ton/h)	14.70	155.40	34.68	831.12	201.84	751.32	840.15
		C_j (ppm)	16.33	20	20	80	100	227.09	
F_i (ton/h)	C_i (ppm)	SK$_j$ SR$_i$	SK6	SK1	SK5	SK2	SK3	SK4	WW
1148.91	0	FW	14.70	141.89	34.68	542.03	201.84	213.77	
1264.50	230	SR2		13.51		289.09		121.75	840.15
415.80	250	SR4						415.80	

Scenario 4 – Forbidden matches for self-recycling

Scenario 4 presents another water recovery option where self-recycle is prohibited. The main consideration of not having self-recycling is to prevent certain contaminants from building up in the system; in addition, Tan *et al.* (2007) have shown that water networks with self-recycle are more vulnerable to being disrupted by variations in water stream quality. In this Scenario, water from Forming section (SR2) is prohibited from being recycled back to its inlet (SK2), while water from DIP (SR4) is likewise prohibited from being sent to itself as well as its associated processes (SK3 and SK4). These restrictions can be integrated into the model by setting the binary variables for these links to zero. The resulting network is shown in Table 8, where the prohibited matches are marked with a cross. The minimum fresh water flowrate in this scenario is determined as 876 ton/h, with a capital cost investment of $152,012 and payback time of 38 days. Note that this scenario can be easily incorporated into earlier scenarios if necessary.

Table 8. Water network for Scenario 4.

		F_j (ton/h)	14.70	155.40	34.68	831.12	201.84	751.32	567.20
		C_j (ppm)	16.33	20.00	20.00	80.00	100.00	227.09	
F_i (ton/h)	C_i (ppm)	SK$_j$ SR$_i$	SK6	SK1	SK5	SK2	SK3	SK4	WW
875.96	0.00	FW	13.66	141.89	31.66	565.16	114.08	9.51	
1264.50	230.00	SR2	1.04	13.51	3.02	x	87.76	741.81	417.36
415.80	250.00	SR4				265.96	x	x	149.84

Scenario 5 – Fuzzy Model for Reconciling Conflicting Objectives

The previous scenarios clearly illustrate that different optimal networks exist for different priorities. In particular, it is evident that maximising water recovery increases capital costs, and, conversely, minimising capital cost limits water recovery. Hence, the problem involves inherent conflicts that can be resolved by selecting a priority objective to be optimised, and setting acceptable limits for the others by formulating them as constraints. Note that this approach requires an implicit prioritization of one objective over the others.

An alternative approach is to optimise the different objectives simultaneously. One specific procedure is symmetric fuzzy optimization, which was first proposed by Zimmermann (1978). This method was recently used to design robust water networks with data uncertainties (Tan and Cruz, 2004), and is adapted in this work to simultaneously maximise water recovery and minimise capital cost.

The steps involved are as follows. The decision maker must first specify target values for water recovery and capital cost. For each objective, two “anchor points” must be identified (Zimmermann, 1978; Dyson, 1980). The first anchor point corresponds to the worst performance level that is deemed to be barely acceptable (with a numerical degree of satisfaction of 0); the second anchor point corresponds to a performance level that is judged to be fully satisfactory (corresponding to a degree of satisfaction of 1). The anchor points for the case study are given in Table 9. These anchor points define the fuzzy level of satisfaction of each objective, which for simplicity is assumed to vary linearly between the extremes listed in Table 9; for example, a capital cost value of $30,000 will have a degree of satisfaction of 0.5.

Table 9. Anchor points for the fuzzy model

Objective	Worst acceptable value	Fully satisfactory value
Fresh water demand (ton/h)	1200	850
Capital cost ($)	50,000	10,000

A new variable, λ, is introduced in the model. This variable assumes values in the interval [0, 1]. It is a numerical measure of total “satisfaction.” The degree of satisfaction of each fuzzy objective must be at least equal to λ. Hence, λ assumes the value of the least satisfied objective in the model. Fuzzy optimization then involves maximising λ, while still satisfying the non-fuzzy constraints in the model. The overall objective is to maximise the fuzzy degree of satisfaction:

$$\text{Maximise } \lambda \tag{9}$$

λ is related to the water usage objective, as follows:

$$\Sigma_j F_{\mathrm{FW},j} \leq 1200 - \lambda(1200 - 850) \tag{10}$$

This constraint replaces Equation 1 of the original model. Note that the right hand side of Equation 10 reduces to 1200 if $\lambda = 0$, and to 850 if $\lambda = 1$.

Thus, the objective value is more acceptable if the value is lower. A similar fuzzy objective is specified for capital cost:

$$\Sigma_i \Sigma_j \, [\mathrm{A}F_{i,j} + \mathrm{B}b_{i,j}]D_{i,j} \le 50{,}000 - \lambda(50{,}000 - 10{,}000) \tag{11}$$

Again, the right hand side of Equation 11 reduces to the anchor points found in Table 9 whenever λ becomes 1 or 0. All the other constraints pertaining to material balances are retained as before without modification. It can be seen that λ behaves as a variable that modulates or equalises the degree of satisfaction of the conflicting fuzzy objectives in Equations 10 and 11. While the model becomes slightly more complicated by the addition of one new variable, the formulation remains linear.

Solution of the fuzzy model gives the network found in Table 10. This network requires 1092 ton/h of fresh water and requires a capital investment of \$37,636, which results in a payback period of 12 days. The optimal value of λ is 0.31. The given solution represents the best compromise between the two objectives. At the same time, Zimmermann (1978) has shown this solution to be Pareto optimal. It is not possible to improve water recovery without incurring added capital cost; nor is it possible to design a cheaper network without sacrificing water recovery.

Table 10. Water network for Scenario 5.

		F_j (ton/h)	14.70	155.40	34.68	831.12	201.84	751.32	567.20
		C_j (ppm)	16.33	20.00	20.00	80.00	100.00	227.09	
F_i (ton/h)	**C_i (ppm)**	**SK_j** **SR_i**	SK6	SK1	SK5	SK2	SK3	SK4	WW
875.96	0.00	FW	13.66	141.89	34.68	542.03	201.84	157.71	
1264.50	230.00	SR2	1.04	13.51	0.00	289.09		177.81	783.05
415.80	250.00	SR4						415.80	

A summary of the different scenarios as well as the base case and grassroots networks (Foo *et al.*, 2006) is presented in Table 11. All scenarios feature short payback time, even though high capital cost are needed to carry out the retrofit work (particularly for Scenarios 1 and 4). This is mainly due to the large volume of water savings that can be achieved in each case. This also means that the existing water network in Figure 1 has not been designed to achieve maximise water recovery.

Table 11. Summary of proposed scenarios for network retrofit

Scenarios	Fresh water flowrate (ton/h)	Wastewater flowrate (ton/h)	Fresh water reduction (%)	Capital cost investment ($)	Payback time (days)
Base case	1989.06	1680.3	NIL	NIL	NIL
Grassroots	848.12	539.36	57.4	NIL	NIL
Scenario 1	852.83	544.07	57.12	115, 780	28
Scenario 2	979.10	670.35	50.78	50, 000	14
Scenario 3	1148.91	840.15	42.24	30, 851	10
Scenario 4	875.96	567.20	55.96	152, 011	38
Scenario 5	1091.81	897.25	45.11	37,636	12

CONCLUSION

Water network synthesis for grassroots design is very much established. In contrast, network synthesis for retrofit design has received far less attention from the process integration research community, despite the large number of opportunities for implementing water conservation in existing plants. In this work, simple mathematical models based on linear programming and mixed-integer linear programming has been developed to systematically address the network retrofit problem. The focus is on modifying plants that already have existing, but suboptimal, water reuse or recycle systems. A procedure to derive adjusted limiting process data so as to eliminate the need to remove or redirect any existing water reuse/recycle streams has also been developed. Different scenarios are presented to address different possible cases that may be encountered in a retrofit project. A fuzzy variant of the optimization model is also developed to reconcile the conflict inherent in minimising both water and capital cost. The approach is demonstrated on a case based on an operational paper mill. All scenarios show good economic performance, with payback times ranging from 10 – 38 days. The model formulation allows for sufficient flexibility in incorporating various retrofit constraints specific to the plant site during the optimisation, as dictated by the conditions of a given application.

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