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Correct identification of limiting water data for water network synthesis

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Abstract Data extraction is one of the most critical steps in carrying out a process integration study for managing water usage and discharge. Correct identification of limiting water data during process integration for water minimisation has a significant impact on the water savings achievable for a given process. This paper presents the procedure and heuristics to extract the correct limiting water data from a process plant. In addition to limiting data on pollutant concentration, the paper discusses the optimal data extraction rules pertaining to flowrate of water demand and segregation of mixed streams. The paper also quantifies the consequences of inappropriate data extraction. Two case studies are used to illustrate the insights and consequences of data extraction in water minimisation problems.

Introduction

The current drive towards environmental sustainability and the rising costs of fresh water and effluent treatment have encouraged the process industry to find new ways to reduce fresh water consumption and wastewater generation. Concurrently, the development of systematic

techniques for water reduction, reuse and recycle within a process plant has seen extensive progress. The advent of water pinch analysis as a tool for the synthesis of water network has been one of the most significant advances in the area of water conservation over the last decade. Water pinch analysis is a systematic technique for implementing strategies to maximise water reuse and recycling through integration of water-using activities or processes. Maximising water reuse and recycling can minimise freshwater consumption and wastewater generation. Typical solution of water pinch analysis is comprised of two steps, i.e. setting minimum fresh water and wastewater flowrates, followed by network design to achieve the flowrate targets.

Wang and Smith (1994) initiated a two-stage water pinch approach based on the more generalised mass exchange network synthesis problems (El-Halwagi and Manousiouthakis 1989). They termed the maximum inlet and outlet concentrations of a water-using process the *limiting water data*. In the first stage of network synthesis, limiting water profile is derived from the limiting water data to locate the minimum fresh water and wastewater flowrates prior to detailed network design (second stage of network synthesis). These authors also consider for flowrate constraints in their later work (Wang and Smith 1995). The basic concept underlying these works is that, all water-using processes are modelled as mass transfer operations. However, representing all water-using processes with mass transfer-based model may not be always adequate. Some industrial operations such as boiler blowdown, cooling tower make-up and reactor effluent are typical examples where water quantity are more important than the water quality. In these cases, the mass transfer-based approach fails to model these operations.

Dhole et al. (1996) later introduced a new water source and demand composite curves to overcome the limitations of mass transfer-based model. Mixing and bypassing techniques were proposed to further reduce the fresh water consumption. However, Polley and Polley (2000) later pointed out that, unless the correct

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stream mixing system was identified, the apparent targets generated by Dhole et al. (1996) could be substantially higher than the true minimum utility targets.

A numerical tool called the Evolutionary Table that is equivalent to Dhole's composite curves was later developed by Sorin and Bédard (1999), to determine the fresh water and wastewater targets. They pointed out that the targeting technique introduced by Dhole et al. (1996) could result in a number of "local" pinch points, which might not necessarily be the actual or the "global" pinch points. However, Hallale (2002) later pointed out that the Evolutionary Table by Sorin and Bédard (1999) may not also give the right solution, as they greatly depend on the mixing patterns of the process streams (which is suppose a part of the network design). Moreover, when more than one global pinch points occurred in water-using processes, the Evolutionary Table failed to locate them correctly.

More recently, two widely accepted graphical approaches in locating the global minimum water flowrates were individually developed by Hallale (2002), El-Halwagi et al. (2003) and Prakash and Shenoy (2005). Hallale (2002) presented an iterative graphical procedure called the water surplus diagram which is identical to the grand composite curves in heat exchanger network synthesis (Linnhoff et al. 1982). To avoid the iterative nature of the water surplus diagram, El-Halwagi et al. (2003) developed a non-iterative graphical technique referred to as the "material-recovery pinch analysis." The procedure is based on a composite representation of process sources and sinks on a load-versus-flow diagram. The result of the analysis is the identification of rigorous targets for minimum usage of water, maximum recycle, and minimum discharge of wastewater. Prakash and Shenoy (2005) developed a similar non-iterative graphical approach for water targeting along with network synthesis tools.

On the other hand, numerical equivalent tools for targeting minimum water flowrates have also been developed. Water cascade analysis (WCA) technique presented by Manan et al. (2004) is equivalent to the water surplus diagram (Hallale 2002), with the elimination its iterative calculation steps. Almutlaq and El-Halwagi (2005) presented another cascade analysis tool that is based on the composite curves of El-Halwagi et al. (2003). These four latest graphical and numerical tools are by far the most promising techniques in locating the minimum water targets in a water network. While graphical targeting tools provide the conceptual insights for network synthesis, numerical tools are preferred when rapid and accurate answers, or when repeated calculation is needed.

Apart from the targeting stage, numerous techniques have also been proposed to design a water network. This includes the use of water grid diagram (Wang and Smith 1994; Mann and Liu 1999), load table (Olesen and Polley 1997), water main method (Kuo and Smith 1998; Castro et al. 1999; Feng and Seider 2001) for mass transfer-based process; as well as source sink mapping

diagram (Dunn and Bush 2001; Dunn and Wenzel 2001; Parthasarathy and Krishnagopalan 2001; Wenzel et al. 2002; El-Halwagi 1997), source sink approach (El-Halwagi 1997; Hallale 2002; Vaidyanathan et al. 1998; Prakash and Shenoy 2005) as well as the load problem table (Aly et al. 2005) for non-mass transfer-based processes.

Correct identification of the limiting water data is the key step in a pinch analysis approach for setting the minimum utility targets and synthesising an optimal water network. Once the utility targets are established, the maximum water recovery network will be designed to achieve the minimum water targets using the above-mentioned network design tools. Inaccurate identification of limiting water data will lead to higher water targets, and subsequently a sub-optimal water network. The procedure for extracting the appropriate limiting water data will be discussed in the following section on theoretical analysis and demonstrated next using two literature case studies.

Theoretical analysis

Data extraction is one of the most time consuming steps in an industrial water recycling project. There are several ways of evaluating limiting water data. These include manufacturer's design data, physical limitations (e.g. flooding flowrate, weeping flowrate, channelling flowrate, saturation composition), or technical constraints (e.g. to avoid scaling, corrosion, explosion, contaminant build-up, etc.). These data may be documented in equipment specification sheets. In the absence of equipment specification sheets, one can also refer to the historical data of the process operation to obtain the equipment operating condition. An example of such a graph is shown in Fig. 1, where the operating flowrate and composition of the feed stream into a water-using operation is observed to lie between upper and lower bounds. Most processes operate between the upper and

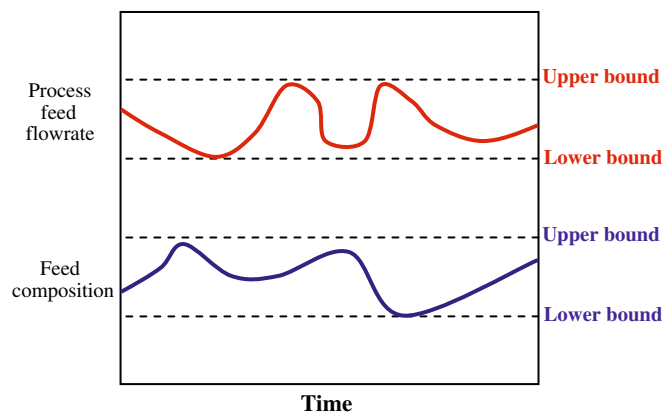


Fig. 1 Historical data of process operation

lower bounds of each process parameter to ensure product quality while avoiding the equipment from overloading. A good example is the operating flowrate in an absorption column. The minimum operating flowrate is needed to avoid channelling (in packed columns) or weeping (in tray columns). On the other hand, the maximum operating flowrate is the upper operating limit before the column floods.

Much of the discussion on extracting limiting data has focused in composition issues. Following the concept of Wang and Smith (1994), the maximum permissible inlet concentration for all operations (given as the upper bound of feed composition in Fig. 1) are assigned as the *limiting concentration* for all water demands. It is important to note that when the concept of limiting water data firstly described by Wang and Smith (1994), the focus was on water-using units that resemble mass exchangers. In these units, the main objective of mass transfer processes is to remove mass loads from rich process streams. As such, the focus is primarily on concentration constraints. In addition to extracting concentration data, there are two other factors that strongly impact data extraction: flowrate and stream mixing. In spite of their importance in data extraction and target setting, very little has been published on their impact and insights. In the following, we discuss appropriate data extraction for flowrates and mixing as well as pitfalls and consequences of inappropriately extracting these data.

Extracting flowrate data

As mentioned earlier, it is important to consider flowrate constraints in deriving the limiting water data particularly for non-mass transfer-based water-using processes (see discussion in Polley and Polley 2000; Hallale 2002 and Manan et al. 2004). To cater for non-mass transfer-based operations, we need to identify the *limiting flowrate* for both water demands and sources of the water-using processes. As shown by Fig. 1, there is a feasible range for admissible flowrate to the unit. While any flowrate within that range is acceptable, the limiting flowrate for water demand should be assigned to the minimum acceptable flowrate required by the water-using operation. One can obtain this value by taking the minimum value of the feed flowrate in Fig. 1. This is due to the fact that assigning the minimum operating flowrate as the limiting flowrate will ensure that the generated flowrate targets of the network being the minimum possible. This can be explained by examining the composite curves of the material-recovery pinch diagram (El-Halwagi et al. 2003) in Fig. 2a, where composite curves are constructed using the limiting flowrate based on the minimum operating flowrates. Hence, maximum reuse/recycle is achieved within the water network with the targeted minimum fresh water and wastewater flowrates.

On the other hand, if one were to assign the maximum operating flowrate to be the limiting flowrate of the water demands, this will lead to higher fresh water targets of the network and, consequently, higher wastewater discharge. Indeed, the increase in fresh water and wastewater flowrates corresponds to the difference between the extracted flowrate data and the minimum flowrate targets. This situation is shown in Fig. 2b.

Another important consideration is the need for incorporating “safety factors” in extracting limiting data for sinks. For highly sensitive processes, some safety factors should be incorporated during data extraction to insure an operable process when water reuse/recycle schemes are carried out. One way of incorporating these safety factors is to define the bounds on operable regions as a fraction (subset) of the original feasibility region. For instance, the historical data shown in Fig. 1 define operability bounds. These bounds may be shrunk by a certain percentage to serve as safety factors. The broader issues of process uncertainty and fluctuations have been recently addressed for mass transfer-based processes (Koppol and Bagajewicz 2003; Tan et al. 2004).

Stream mixing

Another pitfall that may be encountered in extracting data for streams that result through mixing involves the consideration of segregation. An example is a terminal wastewater stream that is generated by combining multiple wastewater streams. If one were to extract the operating flowrate of the terminal wastewater streams as the source limiting flowrate, a sub-optimum solution will be obtained. Stream mixing degrades the quality of stream for reuse or recycle purpose, as streams get diluted unnecessarily. Figure 3 shows the situation for this case. When water sources of different concentrations are mixed, a new source composite curve is formed (dashed line in Fig. 3a). This results in an infeasible network as the source composite curve lies on the left side of the sink composite. To restore a feasible network, the source composite is shifted to the right of the demand composite curve until a new pinch point is formed (El-Halwagi et al. 2003). As a result, much higher fresh water and wastewater flowrates are encountered for this network (Fig. 3b).

The graphical concepts illustrated by Figs. 2 and 3 can be handled numerically through analogous algebraic techniques. In the rest of this paper, the WCA technique proposed by Manan et al. (2004) will be used to illustrate the effects of data extraction and to calculate the water targets. The WCA is a numerical technique that is based on the concept of water surplus diagram (Hallale 2002). WCA eliminates the tedious iterative step associated with the graphical technique to

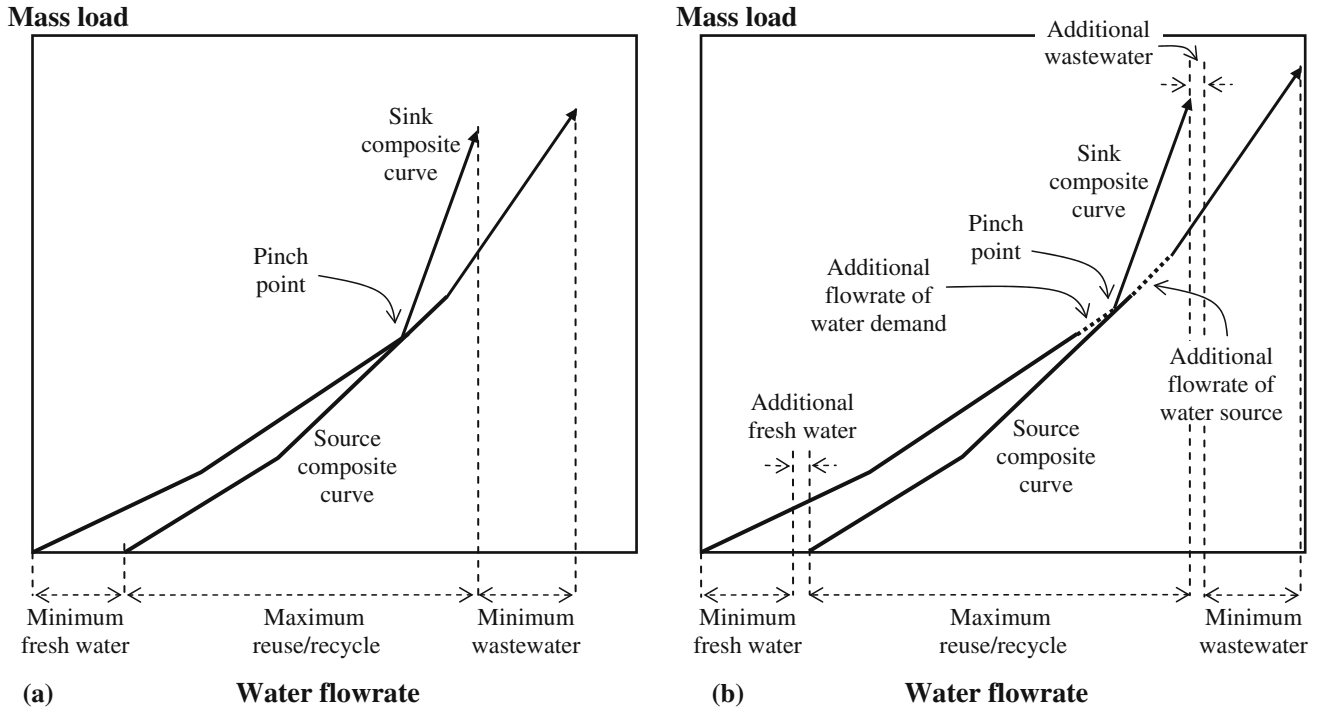


Fig. 2 a Composite curves with minimum operating flowrate as limiting flowrate; b additional fresh water and wastewater are encountered when maximum operating flowrate is used as limiting flowrate

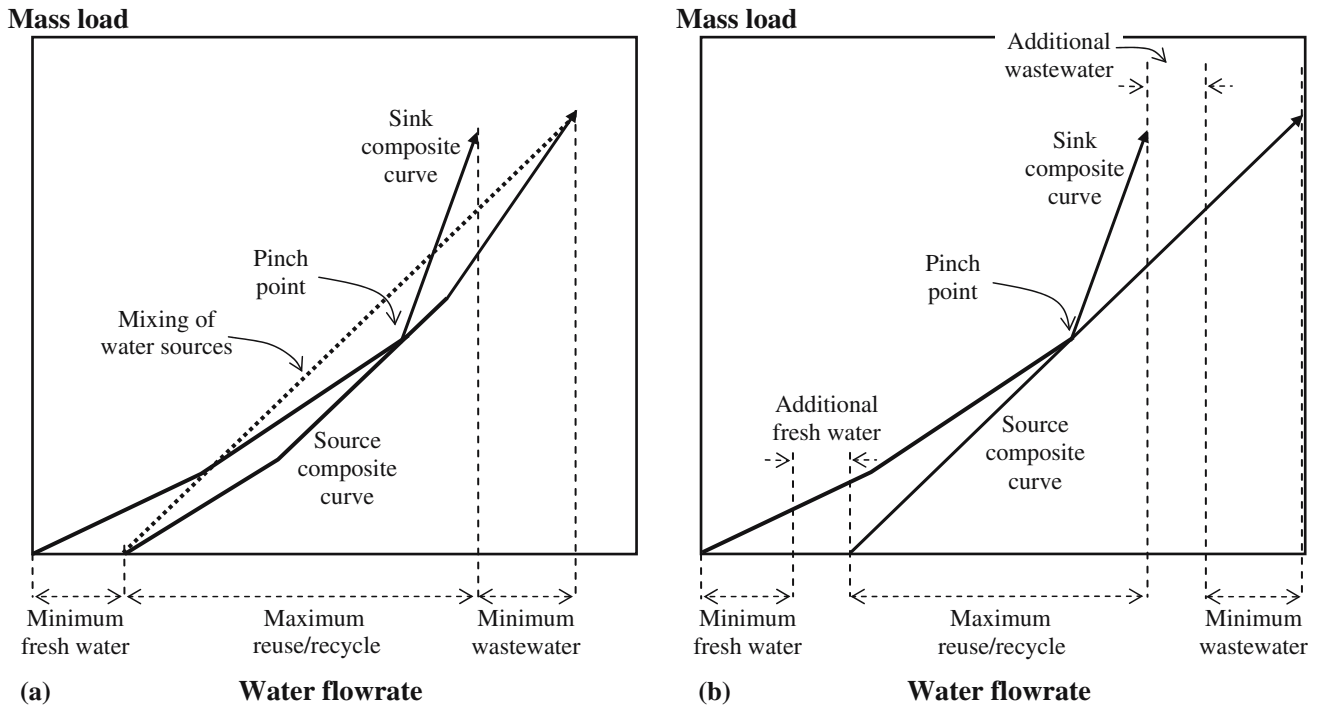


Fig. 3 a Inappropriate mixing of water sources; b source composite curves shift that leads to larger fresh water and wastewater flowrate targets

quickly yield the minimum water and wastewater targets, the pinch location(s) as well as the water allocation targets of a water network. Detailed procedure for

carrying out this analysis is presented in Manan et al. (2004). Two literature case studies will now be used to illustrate these concepts.

Example 1: tricresyl phosphate process

The tricresyl phosphate process (El-Halwagi 1997) consists of five water-using processes, i.e. Washer 1, Washer 2, Scrubber 1, Scrubber 2 and flare seal pot. Contaminant in concern for water minimisation study in this process is cresol. For each of the water demand and source, specific constraints are imposed on the water inlet flowrate (F_j) as well as the cresol inlet concentration (C_j), as given below:

1. Washer 1

- $F_j = 2.45$ kg/s
- $0 \leq C_j$ in washing water (ppm) ≤ 5

2. Washer 2

- $F_j = 2.45$ kg/s
- C_j in washing water (ppm) = 0 (fresh water must be used)

3. Scrubber 1

- $0.7 \leq F_j$ (kg/s) ≤ 0.84
- $0 \leq C_j$ in feed water (ppm) ≤ 30

4. Scrubber 2

- $0.5 \leq F_j$ (kg/s) ≤ 0.6
- $0 \leq C_j$ in feed water (ppm) ≤ 30

5. Flare seal pot

- $0.2 \leq F_j$ (kg/s) ≤ 0.25
- $0 \leq C_j$ in feed water (ppm) ≤ 100 .

As has been discussed in the previous section, it is common to find industrial processes that operate within a range of minimum and maximum operating condition. Scrubber 1, Scrubber 2 and the flare seal pot are typical examples in the case of tricresyl phosphate process. For instant, the minimum operating flowrate for the flare seal pot is needed to form a buffer zone between fire and the source of flare gas so as to prevent back-propagation of fire. On the other hand, the maximum operating flowrate represents the limit before the pot overflows (El-Halwagi 1997). Note also that some water-using processes including Washer 1 and Washer 2 may require a uniform flowrate for operation.

Following the earlier discussion, the minimum operating flowrate (fixed flowrate for Washer 1 and Washer 2) and the maximum permissible concentration are taken as the limiting water data for the water demands. The flowrates of the inlet and outlet streams for all mass transfer-based water-using processes in this case study

were assumed constant. The limiting outlet concentrations for all processes were calculated by doing mass balance on the contaminant mass load transferred from the process rich streams (El-Halwagi 1997). The limiting water data for all processes are given in Table 1.

The minimum flowrate targets were determined upon completion of water data extraction. This is done by using the WCA technique proposed by Manan et al. (2004). The results from WCA is shown in the water cascade table (WCT) in Table 2. The fresh water (F_{FW}) and wastewater (F_{WW}) flowrates were calculated at 3.02 kg/s for this process (recalling that all processes are mass transfer-based with equal inlet and outlet flowrates). This represents a 52% reduction for both fresh water and wastewater flowrates from the original water network (summation of the individual process flowrates in Table 1). Table 2 shows the pinch concentration for the water network at 76.36 ppm where zero cumulative mass load (Cum. Δm) is observed. The pinch concentration is the most constraint part for the water network, where maximum water recovery can be achieved. From the WCT (Table 2), Washer 1 (S_1) was identified as the pinch-causing source for this case study. In order to achieve the minimum water targets, 0.63 kg/s of water source (found in the interval between 30 and 76.36 ppm) should be allocated to the region above the pinch while 1.82 kg/s (found between 76.36 and 100 ppm), should be allocated below the pinch (Manan et al. 2004).

We now demonstrate the effect of using the maximum operating flowrate as the limiting flowrate to calculate water targets for a network. Koppol et al. (2003) assumed the maximum operating flowrate for each water demand as the limiting water data for the tricresyl phosphate case study. As illustrated in Fig. 2, this naturally results in higher fresh water and wastewater flowrates at 11.385 ton/h (3.16 kg/s), as shown in the WCT in Table 3. This may seem to be mild savings as compared to the true minimum water flowrates of 3.02 kg/s identified in Table 2. However, assuming the maximum operating flowrate may lead to huge potential

Table 1 Limiting water data for tricresyl phosphate process

| Water demands, D_j | | F_j (kg/s) | C_j (ppm) |
|----------------------|----------------|--------------|-------------|
| j | Stream | | |
| 1 | Washer 1 | 2.45 | 5 |
| 2 | Washer 2 | 2.45 | 0 |
| 3 | Scrubber 1 | 0.70 | 30 |
| 4 | Scrubber 2 | 0.50 | 30 |
| 5 | Flare seal pot | 0.20 | 100 |
| Water sources, S_i | | F_i (kg/s) | C_i (ppm) |
| i | Stream | | |
| 1 | Washer 1 | 2.45 | 76.36 |
| 2 | Washer 2 | 2.45 | 0.07 |
| 3 | Scrubber 1 | 0.70 | 410.57 |
| 4 | Scrubber 2 | 0.50 | 144 |
| 5 | Flare seal pot | 0.20 | 281.5 |

Table 2 WCT for tricresyl phosphate process (with correct identification of limiting water data)

| C_k (ppm) | $\Sigma_j F_j$ (kg/s) | $\Sigma_i F_i$ (kg/s) | $\Sigma_i F_i - \Sigma_j F_j$ (kg/s) | F_C (kg/s) | Δm (mg/s) | Cum. Δm (mg/s) |
|-------------|-----------------------|-----------------------|--------------------------------------|-----------------|-------------------|------------------------|
| | | | | $F_{FW} = 3.02$ | | |
| 0.00 | 2.45 | | -2.45 | | 0.57 | 0.04 |
| 0.07 | | 2.45 | 2.45 | | 3.02 | 14.89 |
| 5.00 | 2.45 | | -2.45 | | 0.57 | 14.26 |
| 30.00 | 1.20 | | -1.20 | | -0.63 | -29.19 |
| 76.36 | | 2.45 | 2.45 | | 1.82 | 43.03 (PINCH) |
| 100.00 | 0.20 | | -0.20 | | 1.62 | 71.30 |
| 144.00 | | 0.50 | 0.50 | | 2.12 | 291.55 |
| 281.50 | | 0.20 | 0.20 | | 2.32 | 299.49 |
| 410.57 | | 0.70 | 0.70 | | | 705.37 |
| 1,000,000 | | | | $F_{WW} = 3.02$ | 3,019,130 | 3,019,835 |

losses for water-intensive processes with larger range of operations. This effect will be demonstrated in the Kraft pulping process case study presented next.

Example 2: kraft pulping process

The Kraft pulping process (El-Halwagi 1997) consists of mainly non-mass transfer-based water-intensive processes. Contaminant in concern for water minimisation study in this process is methanol. The operating constraints for the water demands and sources are given as follow:

Water demands

1. Pulp washing

- $F_j = 467$ ton/h
- C_j in washing water ≤ 20 ppm

2. Chemical recovery

- $165 \leq F_j$ (ton/h) ≤ 180
- C_j in feed water ≤ 20 ppm

3. Direct contact condenser

- $F_j = 8.2$ ton/h
- C_j in feed water ≤ 10 ppm.

Water sources

1. Combined wastewater stream W6 ($F_i = 22.68$ ton/h, $C_i = 7189$ ppm), which consists of the underflow from primary condenser W3 ($F_i = 12.98$ ton/h, $C_i = 419$ ppm) and underflow from turpentine condenser W5 ($F_i = 9.7$ ton/h, $C_i = 16,248$ ppm).

2. Combined wastewater stream W7 ($F_i = 10.78$ ton/h, $C_i = 9,900$ ppm), resulting from fresh water ($F_i = 8.20$ ton/h, $C_i = 0$ ppm) that is added to condense a vapour stream (2.58 ton/h, 41,360 ppm).
3. Combined condensate W12 ($F_i = 268.7$ ton/h, $C_i = 114$ ppm), which consists of combined condensate from second, third, and fourth evaporators (W8, $F_i = 116.5$ ton/h, $C_i = 20$ ppm), condensate from fifth evaporator (W9, $F_i = 48.0$ ton/h, $C_i = 233$ ppm), condensate from sixth evaporator (W10, $F_i = 52.0$ ton/h, $C_i = 311$ ppm), and condensate from surface condenser (W11, $F_i = 52.2$ ton/h, $C_i = 20$ ppm).
4. Wastewater from concentration and filtration units W13 ($F_i = 300$ ton/h, $C_i = 30$ ppm).
5. Condensed wastewater in paper-making process W14 ($F_i = 140$ ton/h, $C_i = 15$ ppm).

For water intensive system such as the Kraft pulping process, appropriate data extraction is critical to ensure maximum water savings. We will demonstrate three different scenarios to highlight the importance of correct identification of limiting water data.

Scenario 1: Maximum water savings with maximum permissible concentration and minimum operating flowrate

Based on the specified constraints for the various water demands, both pulp washing and direct contact condenser require a fixed amount of feed water whereas chemical recovery operates with a range feed flowrates. In order to minimise water targets, the demand flowrates for pulp washing and direct contact condenser was fixed and the minimum operating flowrate for chemical recovery was assumed as the limiting water data. In addition, the maximum permissible concentration was assumed for all water demands.

Table 3 WCT with higher water flowrate targets for tricresyl phosphate process (maximum operating flowrate as limiting flowrate)

| C_k (ppm) | $\Sigma_j F_j$ (kg/s) | $\Sigma_i F_i$ (kg/s) | $\Sigma_i F_i - \Sigma_j F_j$ (kg/s) | F_C (kg/s) | Δm (mg/s) | Cum. Δm (mg/s) |
|-------------|-----------------------|-----------------------|--------------------------------------|-----------------|-------------------|------------------------|
| | | | | $F_{FW} = 3.17$ | | |
| 0.00 | -2.45 | | -2.45 | | 0.72 | 0.05 |
| 0.07 | | 2.45 | 2.45 | 3.17 | 15.61 | 0.05 |
| 5.00 | -2.45 | | -2.45 | 0.72 | 17.90 | 15.66 |
| 30.00 | -1.44 | | -1.44 | -0.72 | -33.56 | 33.56 |
| 76.36 | | 2.45 | 2.45 | 1.73 | 40.80 | 0.00 (PINCH) |
| 100.00 | -0.25 | | -0.25 | 1.48 | 36.90 | 40.80 |
| 125.00 | | 0.6 | 0.6 | 2.08 | 249.54 | 77.71 |
| 245.20 | | 0.25 | 0.25 | 2.33 | 237.12 | 327.25 |
| 347.14 | | 0.84 | 0.84 | | | 564.37 |
| 1,000,000 | | | | $F_{WW} = 3.17$ | 3,164,981 | 3,165,545 |

One should exercise extra care when extracting data which involves stream mixing. Following the earlier discussion, mixing unnecessarily dilute streams and degrades their quality for reuse or recycle purposes. Note in this case that W6 and W12 are both the mixing products of various water sources at different concentration levels. To avoid prematurely degrading the streams' quality, the limiting data for these water sources should be extracted as the individual streams that form the water sources. Hence, for combined wastewater stream W6, the limiting water data is the constituent streams W3 and W5. Applying the same strategy for wastewater stream W12 yields streams W8, W9, W10 and W11 as the limiting data. Table 4 summarises the extracted limiting water data for the case study.

The WCT in Table 5 shows the minimum fresh water (F_{FW}) and wastewater (F_{WW}) flowrates for the process at 89.90 and 191.86 ton/h, respectively. This represents a reduction of 86% fresh water and 74% wastewater. The pinch concentration is located at 30 ppm. This is the best achievable target using the mixing and segregation strategies outlined by El-Halwagi (1997).

Scenario 2: Maximum operating flowrate as limiting water data

As shown in the tricresyl phosphate process in Example 1 as well as Fig. 2, assigning the maximum operating flowrate for a water demand will lead to a network with higher water targets. This effect is more pronounced for water-intensive processes such as the Kraft pulping process.

Table 6 shows the WCT for the case when the maximum operating flowrate is taken as the limiting water data of the chemical recovery. Note that, flow-

rates of sources W3, W13 and W14 have been adjusted to balance the mass. As shown, both fresh water and wastewater flowrates increase by 3.67 ton/h, a slight increase of 4% as compared to Scenario 1. However, taking a basis of 8000 hours of annual operation, this is equivalent to an additional flowrate of 29,360 ton/year. With fresh water costs of \$1.50/ton and wastewater treatment and discharge cost of \$10/ton, this translates into an extra annual operating cost of \$337,000!

Scenario 3: Inappropriate mixing of water sources

Following the illustration of Fig. 3, this scenario demonstrates how a potentially bigger water savings opportunity may be missed if the limiting data

Table 4 Limiting water data for Kraft pulping process

| Water demands, D_j | | F_j | C_j |
|----------------------|-------------------|---------------|-------------|
| j | Stream | (ton/h) | (ppm) |
| 1 | Pulp washing | 467 | 20 |
| 2 | Chemical recovery | 165 | 20 |
| 3 | Condenser | 8.2 | 10 |
| Water sources, S_i | | F_i (ton/h) | C_i (ppm) |
| i | Stream | | |
| 1 | W3 | 12.98 | 419 |
| 2 | W5 | 9.7 | 16,248 |
| 3 | W7 | 10.78 | 9,900 |
| 4 | W8 | 116.5 | 20 |
| 5 | W9 | 48 | 233 |
| 6 | W10 | 52 | 311 |
| 7 | W11 | 52.2 | 20 |
| 8 | W13 | 300 | 30 |
| 9 | W14 | 140 | 15 |

Table 5 WCT for Kraft pulping process

| C_k (ppm) | $\Sigma_j F_j$ (ton/h) | $\Sigma_i F_i$ (ton/h) | $\Sigma_i F_i - \Sigma_j F_j$ (ton/h) | F_C (ton/h) | Δm (kg/h) | Cum. Δm (kg/h) |
|-------------|------------------------|------------------------|---------------------------------------|-------------------|-------------------|------------------------|
| | | | | $F_{FW} = 89.90$ | | |
| 0 | | | 0 | 89.90 | 0.90 | |
| 10 | 8.2 | | -8.2 | 81.70 | 0.41 | 0.90 |
| 15 | | 140 | 140 | 221.70 | 1.11 | 1.31 |
| 20 | 632 | 168.7 | -463.3 | -241.60 | -2.42 | 2.42 |
| 30 | | 300 | 300 | 58.40 | 11.86 | 0.00 (PINCH) |
| 233 | | 48 | 48 | 106.40 | 8.30 | 11.86 |
| 311 | | 52 | 52 | 158.40 | 17.11 | 20.15 |
| 419 | | 12.98 | 12.98 | 171.38 | 1,624.85 | 37.26 |
| 9,900 | | 10.78 | 10.78 | 182.16 | 1,156.35 | 1,662.12 |
| 16,248 | | 9.7 | 9.7 | $F_{WW} = 191.86$ | 188,742.66 | 2,818.47 |
| 1,000,000 | | | | | | |

involving the combined wastewater streams is wrongly extracted. With water demand for chemical recovery maintained at 165 ton/h as in Scenario 1, the five combined wastewater streams were extracted as limiting data as listed in the WCT (Table 7). The data yield fresh water and wastewater targets at 185.97 and 287.93 ton/h, an increase of over 100% as compared to Scenario 1. This also means an extra annual operating cost of \$8.8 million to be spent by the process.

Conclusion

Data extraction is the most crucial step to ensure maximum benefits and savings in a water minimisation project. In this work, it has been shown that correct identification of limiting water data will have significant influence on water targets. In particular, guidelines, insights, and pitfalls were presented on data extraction pertaining to demand flowrate and source mixing. To

Table 6 WCT with higher water targets (maximum operating flowrate as limiting flowrate)

| C_k (ppm) | $\Sigma_j F_j$ (ton/h) | $\Sigma_i F_i$ (ton/h) | $\Sigma_i F_i - \Sigma_j F_j$ (ton/h) | F_C (ton/h) | Δm (kg/h) | Cum. Δm (kg/h) |
|-------------|------------------------|------------------------|---------------------------------------|-------------------|-------------------|------------------------|
| | | | | $F_{FW} = 93.57$ | | |
| 0 | | | 0 | 93.57 | 0.94 | |
| 10 | 8.2 | | -8.2 | 85.37 | 0.43 | 0.94 |
| 15 | | 142.67 | 142.67 | 228.04 | 1.14 | 1.36 |
| 20 | 647 | 168.7 | -478.3 | -250.27 | -2.50 | 2.50 |
| 30 | | 305.73 | 305.73 | 55.47 | 11.26 | 0.00 (PINCH) |
| 233 | | 48 | 48 | 103.47 | 8.07 | 11.26 |
| 311 | | 52 | 52 | 155.47 | 16.79 | 19.33 |
| 419 | | 19.58 | 19.58 | 175.05 | 1,659.60 | 36.12 |
| 9,900 | | 10.78 | 10.78 | 185.83 | 1,179.62 | 1,695.72 |
| 16,248 | | 9.7 | 9.7 | $F_{WW} = 195.53$ | 192,348.11 | 2,875.34 |
| 1,000,000 | | | | | | |

Table 7 WCT with higher water targets (mixing of water sources)

| C_k (ppm) | $\Sigma_j F_j$ (ton/h) | $\Sigma_i F_i$ (ton/h) | $\Sigma_i F_i - \Sigma_j F_j$ (ton/h) | F_C (ton/h) | Δm (kg/h) | Cum. Δm (kg/h) |
|-------------|------------------------|------------------------|---------------------------------------|-------------------|-------------------|------------------------|
| 0 | | | 0 | $F_{FW} = 185.97$ | | |
| 10 | 8.2 | | -8.2 | 185.97 | 1.86 | 1.86 |
| 15 | | 140 | 140 | 177.77 | 0.89 | 2.75 |
| 20 | 632 | | -632 | 317.77 | 1.59 | 4.34 |
| 30 | | 300 | 300 | -314.23 | -3.14 | 1.20 |
| 114 | | 268.7 | 268.7 | -14.23 | -1.20 | 0.00 |
| 7,198 | | 22.68 | 22.68 | 254.47 | 1,800.39 | (PINCH) 1,800.39 |
| 9,900 | | 10.78 | 10.78 | 277.15 | 751.36 | 2,551.75 |
| 1,000,000 | | | | $F_{FW} = 287.93$ | 285,081.40 | 287,633.15 |

ensure maximum savings, the minimum operating flowrate and the maximum permissible concentration should be taken as limiting data for a water demand. Stream segregation should be considered and mixing should be avoided for water sources, and segregated streams that form the combined wastewater stream should be considered as limiting data. Two case studies were solved to illustrate the consequences on data extraction on the targets of fresh water and wastewater flowrates.

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