# Use Process Integration to Set Material Reuse and Recycling Targets

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## Introduction

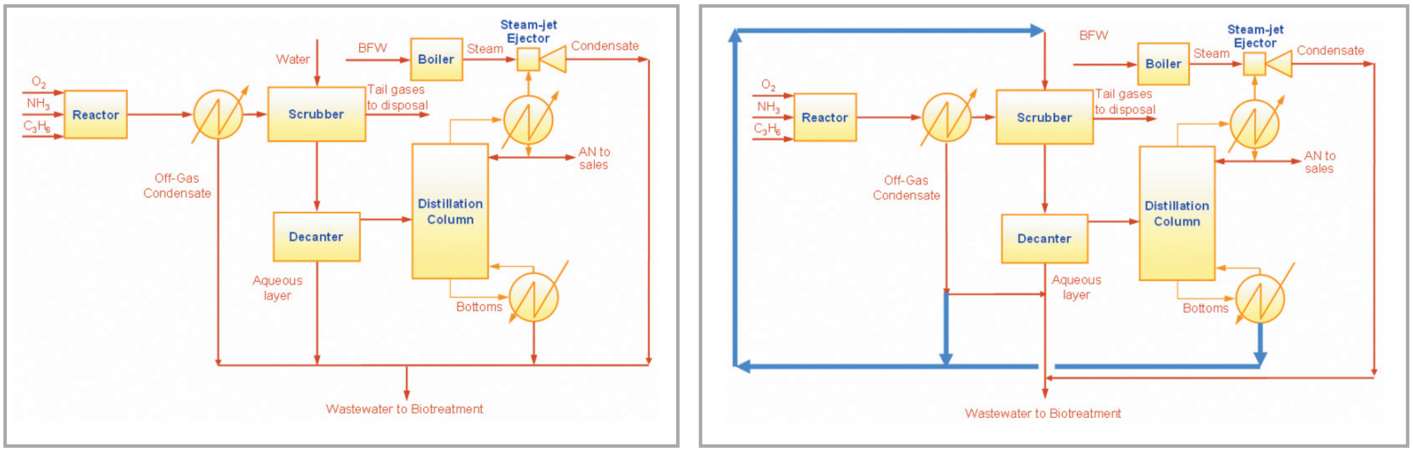
Due to stringent environmental regulations and rising costs of raw materials, the industry is now making an effort to shift from the conventional practice of treating waste after it has been produced (termed as *end-of-pipe* treatment) to a more proactive approach of minimising waste at the root cause (termed as *waste minimisation* or *pollution prevention*). The merit of practising waste minimisation is of two fold. Beside the reduction of waste treatment cost, the company also saves from reduced raw material costs, which may include purchase cost and treatment cost.

Concurrently, the development of systematic design techniques for waste reduction, material reuse and recycling within a process plant has seen extensive progress. In particular, process integration has been one of the most promising techniques for material reuse and recycle over the last decade. Conventionally, *process integration* or more specifically, *pinch analysis* (the graphical approach of process integration) is known to engineers as an energy saving tool. However, with the rise of two new elements, i.e. *mass* and *property integration*, material reuse and recycle can now be handled efficiently with process integration techniques. In the context of process integration, *reuse* means that the effluent from one unit is used in another unit and does not re-enter the unit where it has been previously used. On the other hand, *recycle* allows the effluent to re-enter the unit where it has been previously used. This article discusses the author's recent works on process integration based on pinch analysis techniques for the design of liquid, gas and solid reuse/recycle system.

## Mass integration for water and hydrogen reuse/recycle

Mass integration was introduced based on the analogy of heat integration [1]. Water minimisation was later introduced [2] as a special case of mass integration, aiming for the maximum reuse/recycle of water within the various water *sinks* (units that require feed water) and water *sources* (units that produce water). Much later, another special case of mass integration that has gained much attention is the hydrogen pinch analysis [3]. Both special cases will be illustrated in details in the following section.

A typical pinch analysis study consists of two stages, i.e. setting minimum fresh resource and waste discharge flowrates (often termed as targeting), followed by network design to achieve the targeted flowrates. It is worth mentioning that the focus on pinch analysis is the targeting step. With targeting, the engineer sets a baseline target to determine how well a reuse/recycle system can actually perform based on first principle. Knowing the targets ahead will eliminate the query of "will there be a better design?" during any design exercise. Once the minimum material targets are established, a reuse/recycle network can be designed using any network design tools. The composite curve [4] and cascade analysis technique [5] are by far the most promising techniques in locating the minimum targets in a material



*(a) without water reuse/recycle*

*(b) with water reuse/recycle*

*Figure 1: Process flow diagram of AN production*

reuse/recycle network. The use of these tools will be shown in the following case studies.

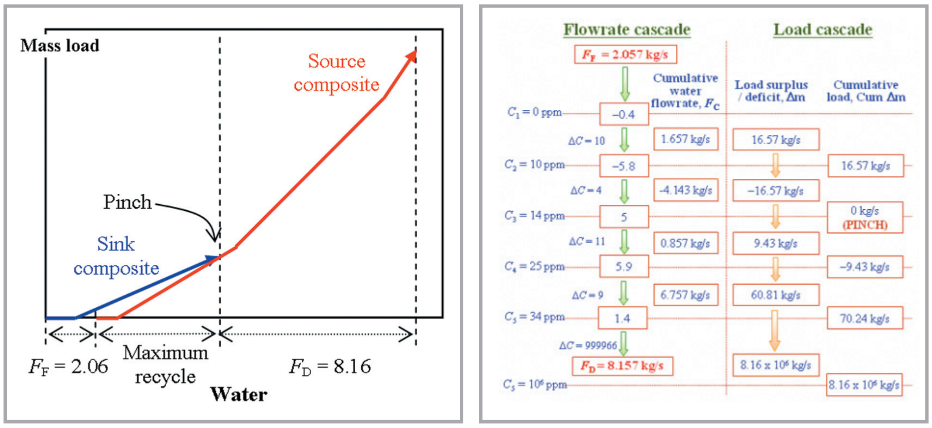
## Water Pinch Analysis

Figure 1(a) shows the process flow diagram of a Acrylonitrile (AN) production [6]. Products from the reactor is cooled and partially condensed. The reactor off-gas is sent to a scrubber that uses fresh water as the scrubbing agent. The bottom product from the scrubber is separated into the aqueous layer and an organic layer in a decanter. The organic layer is later fractionated in a slightly vacuumed distillation column that is induced by a steam-jet ejector. There are two water sinks in this process, i.e. boiler feed water (BFW) and feed stream to the scrubber; and four water sources which include the off-gas condensate, aqueous layer from decanter, distillation column bottoms and steam-jet ejector condensate. Ammonia ($NH_3$) is the main impurity in this process. The *limiting water data* (maximum impurity composition and minimum flowrate) for each process unit is given in Table 1.

*Table 1: Limiting water data for AN production*

| | Water sinks (SK) | Flowrate | $NH_3$ composition |
|---|---|---|---|
| $j$ | Stream | $F_{SK}$ (kg/s) | $y_{SK}$ (ppm) |
| 1 | BFW | 1.2 | 0 |
| 2 | Scrubber | 5.8 | 10 |
| | **Water sources (SR)** | **Flowrate** | **$NH_3$ composition** |
| $i$ | Stream | $F_{SR}$ (kg/s) | $y_{SR}$ (ppm) |
| 1 | Distillation bottoms | 0.8 | 0 |
| 2 | Off-gas condensate | 5 | 14 |
| 3 | Aqueous layer | 5.9 | 25 |
| 4 | Ejector condensate | 1.4 | 34 |

To locate the minimum water flowrates in this process, the engineer can either plot the composite curve (Figure 2a) or carry out the numerical calculation using the algebraic approach of cascade analysis (Figure 2b), which can be automated in a spreadsheet e.g. MS Excel. Figure 2 shows that the fresh water ($F_F$) and wastewater discharge ($F_D$) flowrates of the AN process have been reduced significantly to 2.06 kg/s and 8.16 kg/s.



*(a) with composite curve [4]*

*(b) with cascade analysis technique [5]*

*Figure 2: Targeting the minimum fresh water and wastewater flowrates for AN production*

This corresponds to a reduction of 70% and 38% respectively (original flowrates are obtained from the sum of individual flowrates in Table 1). A pinch composition is found at the composition of 14 ppm, which represents the most constrained area in the reuse/recycle network where maximum recovery may be achieved. Due to space limitation, readers are advised to refer to the original sources for the detailed explanation of these methodologies [4, 5].

In order to achieve the minimum flowrates, the following guidelines can be used to design the network manually or by any linear programming technique [6, 7]:

(a) Flowrate for sinks:

$$\sum_i F_{i,j} = F_{SK,j} \qquad (1)$$

where $F_{i,j}$ is the flowrate between source $i$ and sink $j$.

Material content:

$$\sum_i F_{i,j} y_{SR,i} = F_{SK,j} y_{SK,j} \qquad (2)$$

(b) Flowrate for sources:

$$\sum_j F_{i,j} = F_{SR,i} \qquad (3)$$

Any flowrate from a source that is not fed to a sink will leave as a discharge (waste) stream.

The resulting reuse/recycle scheme is shown in Figure 1(b). Many other process changes such as the use of water purifying units (e.g. filtration, adsorption, etc.) and the elimination of water-consuming units can also be assessed [5, 7].

## Hydrogen Pinch Analysis

Since hydrogen is a valuable resource in the crude oil refinery, its reuse/recycle will lead to big saving in operation cost. Figure 3 shows a simplified refinery process that consists of two hydrogen consumers A and B and a hydrogen plant [8]. Currently, 200 million standard cubic feet per day (MMscfd – omitted in Figure 3) are supplied from the hydrogen plant.

One should note that the hydrogen sinks and sources data needed for hydrogen pinch analysis is not directly taken from the flowsheet. Instead they are calculated by the following equations:

Sink:

$$F_{SK} = F_M + F_R \qquad (4)$$

$$y_{SK} = \frac{F_M y_M + F_R y_R}{F_M + F_R} \qquad (5)$$

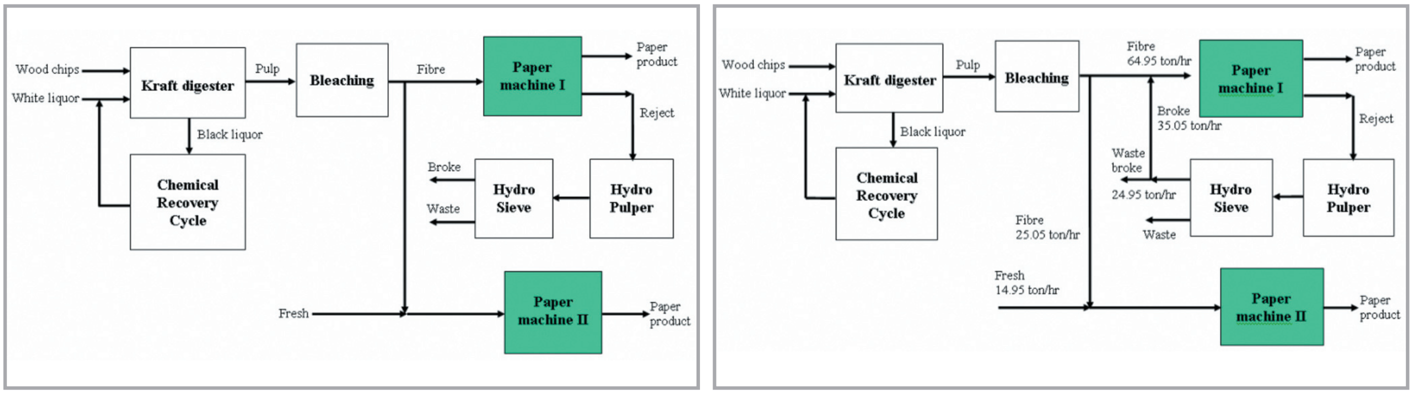
Source:

$$F_{SR} = F_P + F_R \qquad (6)$$

$$y_{SR} = y_P = y_R \qquad (7)$$

where $F_{SK}$, $F_{SR}$, $F_M$, $F_R$ and $F_P$ are the sink, source, make-up, recycle and purge flowrates respectively; while $y_{SK}$, $y_{SR}$, $y_M$, $y_R$ and $y_P$ referring to their hydrogen compositions respectively.

Previously, the analysis of impurity reuse/recycle system has always been carried out by graphical approaches [3, 4, 9]. However, with the latest advancement in the algebraic technique [10], the targeting can now be carried out easily, accurately and promptly using manual calculation or via a spreadsheet programme. Result for the refinery example is shown in the cascade table in Table 2, which is a tabulated representation of cascade



*(a) without fibre recycle*

*(b) with fibre recycle*

*Figure 4: A papermaking process*

analysis of Figure 2(b). Following the design guideline in Equations 1 to 3, one of the possible reuse/recycle networks is shown in Figure 3(b).

Table 2 shows the fresh hydrogen feed ($F_F$) has been reduced from 200 to 183 MMscfd, which represent a significantly saving of 8.5%. Note that, for a complete refinery process which typically has more than two hydrogen-consuming units, greater saving is encountered [8, 9]. Note also that 34% reduction of hydrogen discharge as fuel ($F_D$) has been achieved, i.e. from 50 ro 33 MMscfd.

## Property Integration

Despite the importance of mass integration techniques for material recycle/reuse, these are limited to address problems that are governed by the composition of process streams (e.g. $NH_3$ composition for AN production; mol% impurity for hydrogen reuse/recycle). However, composition is only one of the many material chemical and physical properties. Other commonly encountered properties include pH, density, viscosity, turbidity, solubility, etc. Material reuse/recycle associated with these properties does not fall into the conventional mass integration problems. This is the subject of property integration. In property integration, a general mixing rule to define all possible mixing patterns among the individual properties is given by [11]:

$$\psi(\bar{p}) = \sum_i x_i \psi(p_i) \qquad (8)$$

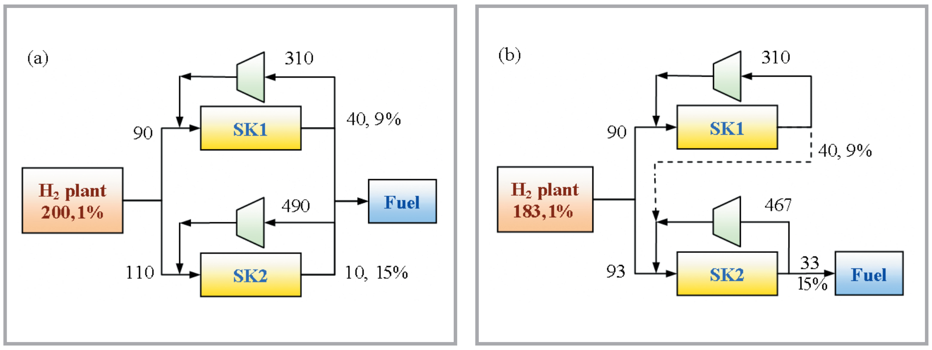
### Fibre reuse/recycling in a paper making process

Figure 4 shows a papermaking process taken from [12, 13]. Wood chips are digested and chemically treated in the Kraft digester before the produced pulp is sent to the bleaching section. The product from this section, i.e. bleached fibre is then sent to two paper machines (Paper Machine I and II), where they are converted into final paper products. Rejected products from Machine I are further treated in Hydro Pulper and Hydro Sieve before the waste and waste fibre streams (broke) are finally discharged. However, due to environmental concerns, the broke is to be recycled to the two paper machines. An external fresh fibre source is currently fed to paper machine II to supplement its fibre need. Thus, by recycling the broke, resource usage is maximised and fresh fibre consumption can be reduced.

To evaluate the quality of the broke to be reused or recycled, we focus on reflectivity R$_\infty$, a dimensionless property that is defined as the reflectance of an infinitely thick

*Table 2: Cascade table for targeting hydrogen reuse/recycling in refinery process*

| $y$ | $\Sigma F_{SK}$ | $\Sigma F_{SR}$ | $\Sigma F_{SR} - \Sigma F_{SK}$ | $F_C$ | $\Delta m$ | Cum. $\Delta m$ |
|---|---|---|---|---|---|---|
| | | | | **$F_F$ = 183** | | |
| 1.00 | | | | | | |
| | | | | 183 | 11.35 | |
| 7.20 | 400 | | -400 | | | 11.35 |
| | | | | -217 | -3.91 | |
| 9.00 | | 350 | 350 | | | 7.44 |
| | | | | 133 | 4.56 | |
| 12.43 | 600 | | -600 | | | 12.00 |
| | | | | -467 | -12.00 | |
| 15.00 | | 500 | 500 | | | **0** |
| | | | | **$F_D$ = 33** | 28.05 | **(PINCH)** |
| 100.00 | | | | | | 28.05 |



*(a) without hydrogen reuse/recycle*

*(b) with hydrogen reuse*

*Figure 3: A refinery process*

material compared to an absolute standard, i.e. magnesium oxide. The mixing rule for reflectivity $R_\infty$ is given as:

$$\overline{R}_\infty = \sum_i x_i R_{\infty,i}^{5.92} \tag{9}$$

In order to carry out a cascade analysis for this problem, one requires the operator value of reflectivity. Comparing Equation 8 and 9, we can express the operator for $R_\infty$, $\psi(R_\infty)$, as follows:

$$\psi\left(R_{\infty,i}\right) = \sum_i x_i R_{\infty,i}^{5.92} \tag{10}$$

Flowrate, reflectivity and its associated operator value of each sink and source is shown in Table 3.

The minimum fresh fibre feed ($F_F$) and discharged ($F_D$) flowrates are easily identified from the cascade table in Table 4 as 14.95 ton/h and 24.95 ton/h respectively [13]. These targets agree with those obtained by property composite curve [12]. The final network design is shown in Figure 4(b).

## Conclusion

This paper summaries some of the author's recent works on material reuse/recycle system design based of process integration, or more specifically pinch analysis techniques. Via mass and property integration, material reuse and recycle can now be carried out for systems involving liquid, gas and solid. By setting the reuse/recycle targets, the engineer identifies the maximum possible saving that can be achieved in a reuse/recycle system prior to detailed network design. ■

*Table 3: Limiting data for papermaking process*

| | Process | Flowrate (ton/h) | Reflectivity, $R_\infty$ (dimensionless) | $\psi$ (dimensionless) |
|---|---|---|---|---|
| (Sinks) | Paper Machine I | 100 | 0.85 | 0.382 |
| | Paper Machine II | 40 | 0.90 | 0.536 |
| (Sources) | Process Fibre | 90 | 0.88 | 0.469 |
| | Broke | 60 | 0.75 | 0.182 |
| | Fresh fibre | Unknown | 0.95 | 0.738 |

*Table 4: Cascade table for targeting fibre reuser/recycle in the papermaking process*

| $\psi_K$ | $\sum F_{SK}$ | $\sum F_{SR}$ | $\sum F_{SR} - \sum F_{SK}$ | $F_C$ | $\Delta m$ | Cum. $\Delta m$ |
|---|---|---|---|---|---|---|
| | | | | $\mathbf{F_F = 14.95}$ | | |
| 0.738 | | | | | | |
| | | | | 14.95 | 3.02 | |
| 0.536 | -40 | | -40 | | | 3.02 |
| | | | | --25.05 | -1.67 | |
| 0.469 | | 90 | 90 | | | 1.35 |
| | | | | 64.95 | 5.66 | |
| 0.382 | -100 | | -100 | | | 7.01 |
| | | | | --35.05 | -7.01 | |
| 0.182 | | 60 | 60 | | | **0** |
| | | | | $\mathbf{F_D = 24.95}$ | 4.54 | **(PINCH)** |
| 0.000 | | | | | | 4.54 |

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