CHAPTER THREE
GRAPHICAL TECHNIQUES FOR DIRECT RECYCLE STRATEGIES

Processing facilities are characterized by the use of tremendous amounts of material resources. If not managed properly, such enormous usage can lead to the depletion of natural resources poses many economic, social, and ecological challenges. Therefore, the process industries have embarked on major material-conservation initiatives to enhance market competitiveness and sustainability. Several strategies can lead to material conservation including segregation, mixing, recycle/reuse, material substitution, reaction alteration, and process modification. In this Chapter, we focus stream rerouting including segregation, mixing, and recycle/reuse. *Segregation* refers to avoiding the mixing of streams. Segregation of streams with different compositions avoids unnecessary loss of driving force of streams. Such management of driving forces enhance the performance of process units (e.g., separators) and can also provide composition levels that allow the streams to be recycled directly to process units. *Recycle* refers to the utilization of a process stream (e.g., a waste or a low-value stream) in a process unit (a sink). While reuse is distinguished from recycle by emphasis that reuse corresponds to the reapplication of the stream for the original intent, we will use the term recycle in a general sense that includes reuse. In particular, we will start with *direct recycle* where the streams are rerouted without the installation of new devices. Direct recycle is typically classified as a now/low cost strategies since it basically involves pumping and piping and in some cases may even by achieved without the need for additional pumping or piping.

First, a targeting technique will be described to identify bounds on minimum usage of fresh resources and minimum discharge of wastes through recycle/reuse. Next, a systematic procedure is presented to implement the specific stream rerouting that attains the identified target.

PROBLEM STATEMENT

Consider a process with a number of process sources (e.g., process streams, wastes) that can be considered for possible recycle and replacement of the fresh material and/or reduction of waste discharge. Each source, i, has a given flow rate, W_i, and a given composition of a targeted species, y_i. Available for service is a fresh (external) resource that can be purchased to supplement the use of process sources in sinks. The sinks are process units such as reactors, separators, etc. Each sink, j, requires a feed whose flow rate, G_j^{in}, and an inlet composition of a targeted species, z_j^{in}, must satisfy certain bounds on their values.

The objective is to develop a graphical procedure that determines the target for minimum usage of the fresh resource, maximum material reuse, and minimum discharge to waste. Therefore, the design questions to be answered include:

- Should a stream (source) be segregated and split? To how many fractions? What should be the flowrate of each split?
- Should streams or splits of streams be mixed? To what extent?
- What should be the optimum feed entering each sink? What should be its composition?
- What is the minimum amount of fresh resource to be used?
- What is the minimum discharge of unused process sources?

SOURCE-SINK MAPPING DIAGRAM AND LEVER-ARM RULES

The source-sink mapping diagram (El-Halwagi and Spriggs, 1996, El-Halwagi, 1997) is a visualization tool that can be used to derive useful recycle rules. As mentioned in the problem statement, there are bounds on flowrate and composition entering each sink. These bounds are described by the following constraints:

$$G_j^{\min} \le \mathrm{G}_{\mathrm{j}}^{\mathrm{in}} \le G_j^{\max} \qquad \text{where } j = 1,2, \ldots, N_{\mathrm{sinks}} \tag{3.1}$$

where $G_j^{\min}$ *and* $G_j^{\max}$ are given lower and upper bounds on admissible flowrate to unit j.

$$z_j^{\min} \le \mathrm{z}_{\mathrm{j}}^{\mathrm{in}} \le z_j^{\max} \qquad \text{where } j = 1,2, \ldots, N_{\mathrm{sinks}} \tag{3.2}$$

where $z_j^{\min}$ *and* $z_j^{\max}$ are given lower and upper bounds on admissible compositions to unit j.

The flowrate and composition bounds for each sink can be determined based on several consideration such as:

- Technical considerations (e.g., manufacturer's specifications operable composition ranges to avoid scaling, corrosion buildup, etc., operable flowrate ranges such as weeping/flooding flowrates).
- Safety (e.g., to stay away from explosion regions).
- Physical (e.g., saturation limits).
- Monitoring: These bounds can also be determined from historical data of operating the unit which are typically available through the process information monitoring system. Figure 3.1. illustrates the bounding of feed flowrate and composition for sink j based on monitored data for which the sink performed acceptably.

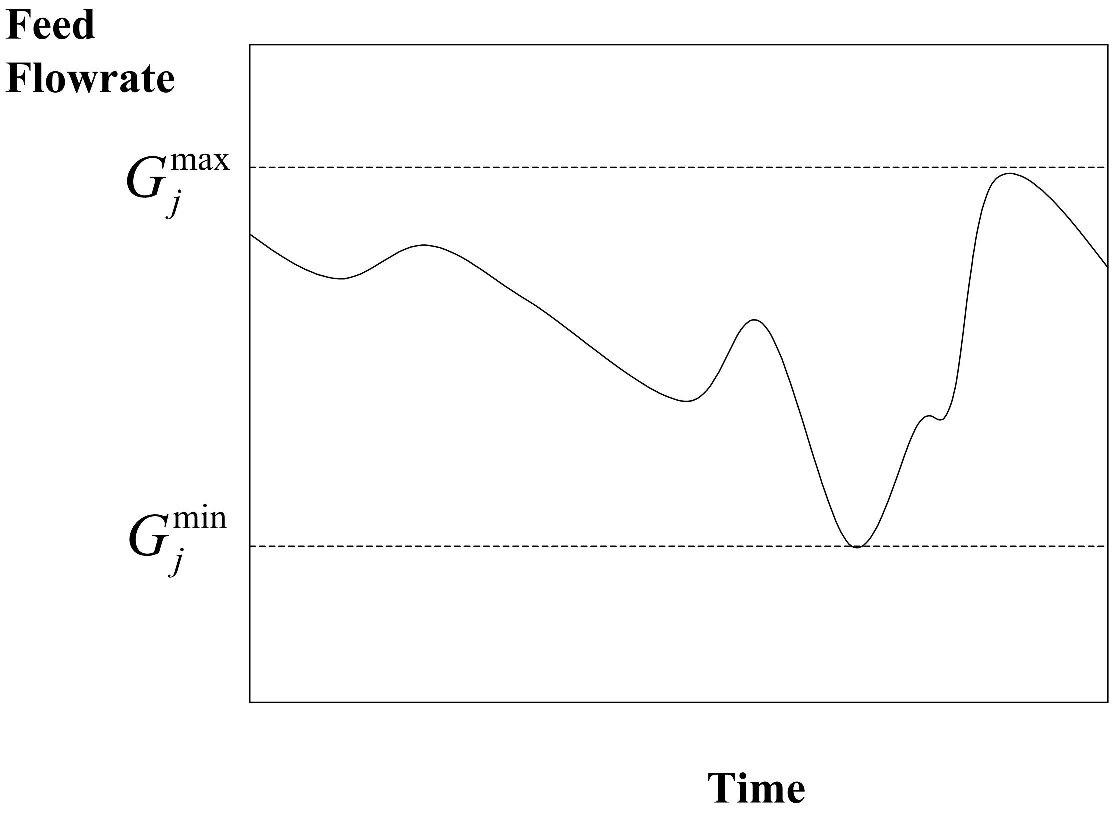

Fig. 3.1a. Bounding Feed Flowrate Based on Monitored Data

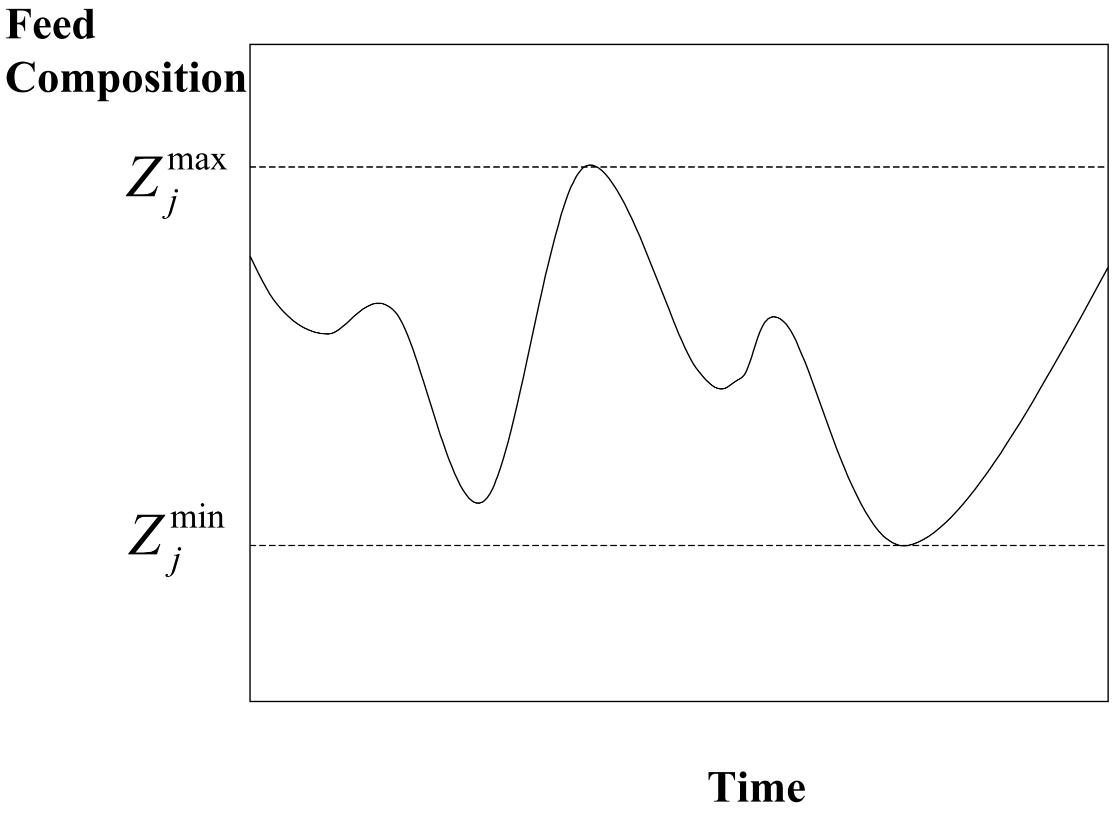

Fig. 3.1b. Bounding Feed Composition Based on Monitored Data

- Constraint propagation: In some cases (Fig. 3.2), the constraints on a sink (j) are based on critical constraints for another unit (j+1). Using a process model to relate the inlets of units j and j+1, we can derive the constraints for unit j based on those for unit j+1. For instance, suppose that the constraints for unit j+1 are given by:

$$0.06 \le z_{j+1}^{in} \le 0.08 \tag{3.3a}$$

and the process model relating the inlet compositions to units j and j+1 can be expressed as:

$$z_{j+1}^{in} = 2\, z_j^{in} \tag{3.3b}$$

Therefore, the bounds for unit j are calculated to be:

$$0.03 \le z_j^{in} \le 0.04 \tag{3.3c}$$

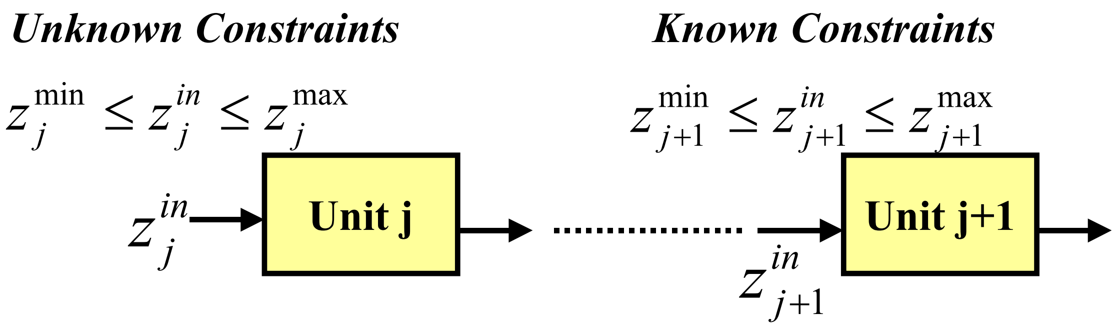

Fig. 3.2. Constraint Propagation to Determine Composition Bounds

For each targeted species, a diagram called the source-sink mapping diagram (Fig. 3.3) is constructed by plotting the flowrate versus composition. On the source-sink mapping diagram, sources are represented by shaded circles and sinks are represented by hollow circles. The constraints on flowrate and composition are respectively represented by horizontal and vertical bands. The intersection of these two bands provides a zone of acceptable load and composition for recycle. If a source (e.g., source a) lies within this zone, it can be directly recycled to the sink (e.g., sink S). Moreover, sources b and c can be mixed using the lever-arm principle to create a mixed stream that can be recycled to sink S.

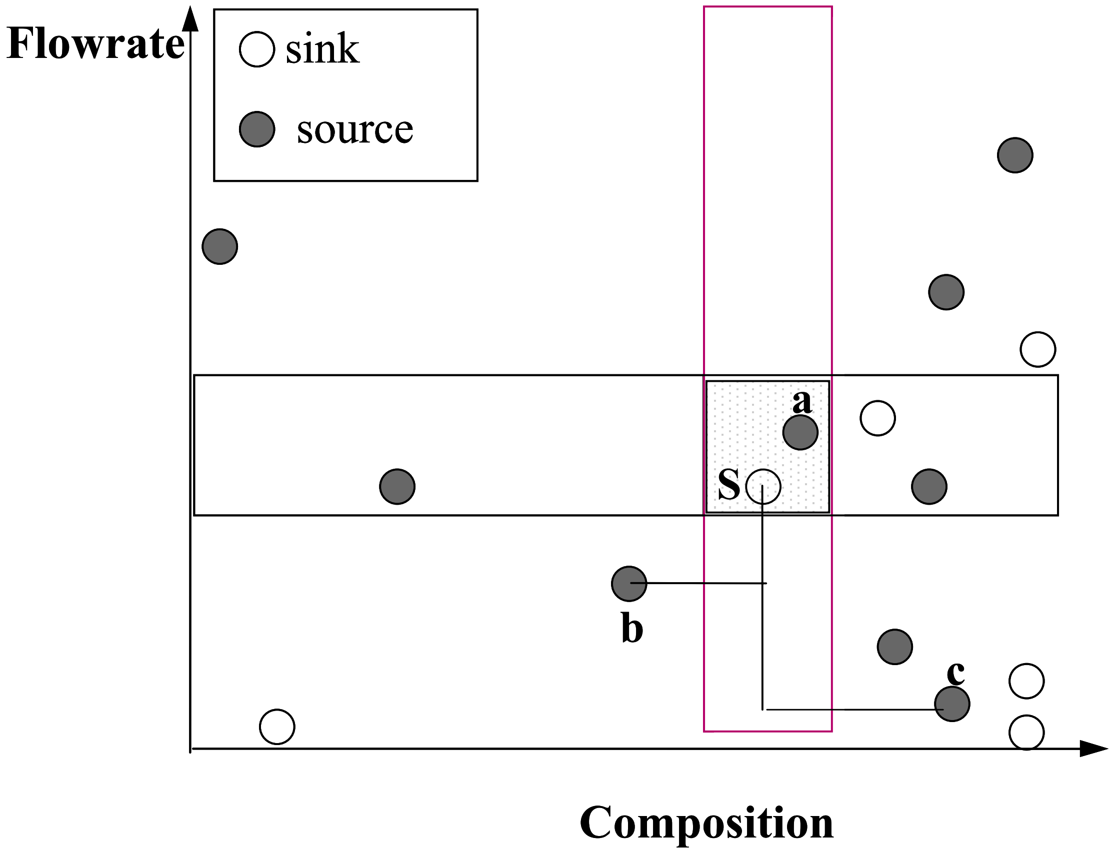

Fig. 3.3 Source-Sink Mapping Diagram

The lever arms can be determined based on material balance. Consider the mixing of two sources, a and b shown in Fig. 3.4. The flowrates of the two sources are W_a and W_b and their compositions are y_a and y_b. The mixture resulting from the two sources has a flowrate $W_a + W_b$ and a composition, y_s. The resulting flowrate and composition of the mixture satisfy the flowrate and composition constraints for sink S.

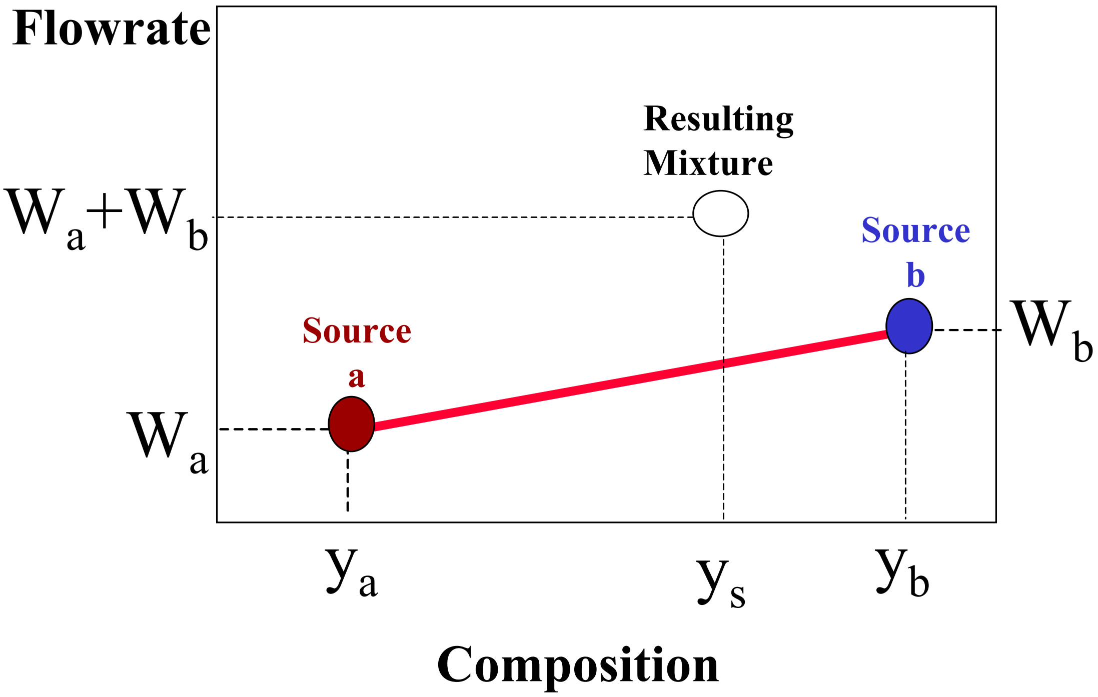

Fig. 3.4. Mixing of Sources a and b

A material balance for the targeted species around the mixing operation can be expressed as:

$$y_s(W_a + W_b) = y_a W_a + y_b W_b \tag{3.4a}$$

Rearranging terms, we get

$$\frac{W_a}{W_b} = \frac{y_b - y_s}{y_s - y_a} \tag{3.4b}$$

or

$$\frac{W_a}{W_b} = \frac{Arm\ for\ a}{Arm\ for\ b} \tag{3.4c}$$

where

Arm for a = $y_b – y_s$ (3.4d)

and

Arm for b = y_s - y_a (3.4e)

Similarly,

$$\frac{W_a}{W_a + W_b} = \frac{Arm\ for\ a}{Total\ arm} \tag{3.5a}$$

where the total arm is the sum of arm for a and arm for b. Hence

$$\text{Total arm} = y_b - y_a \tag{3.5b}$$

The lever arms for the individual sources as well as the resulting mixture are shown in Fig. 3.5. It is worth noting that these are the horizontal lever arms. Those arms can also be shown on the tilted line connecting sources a and b. In such cases, the ratio of the arms will be exactly the same as the ratio of the horizontal arms because of angle similitude.

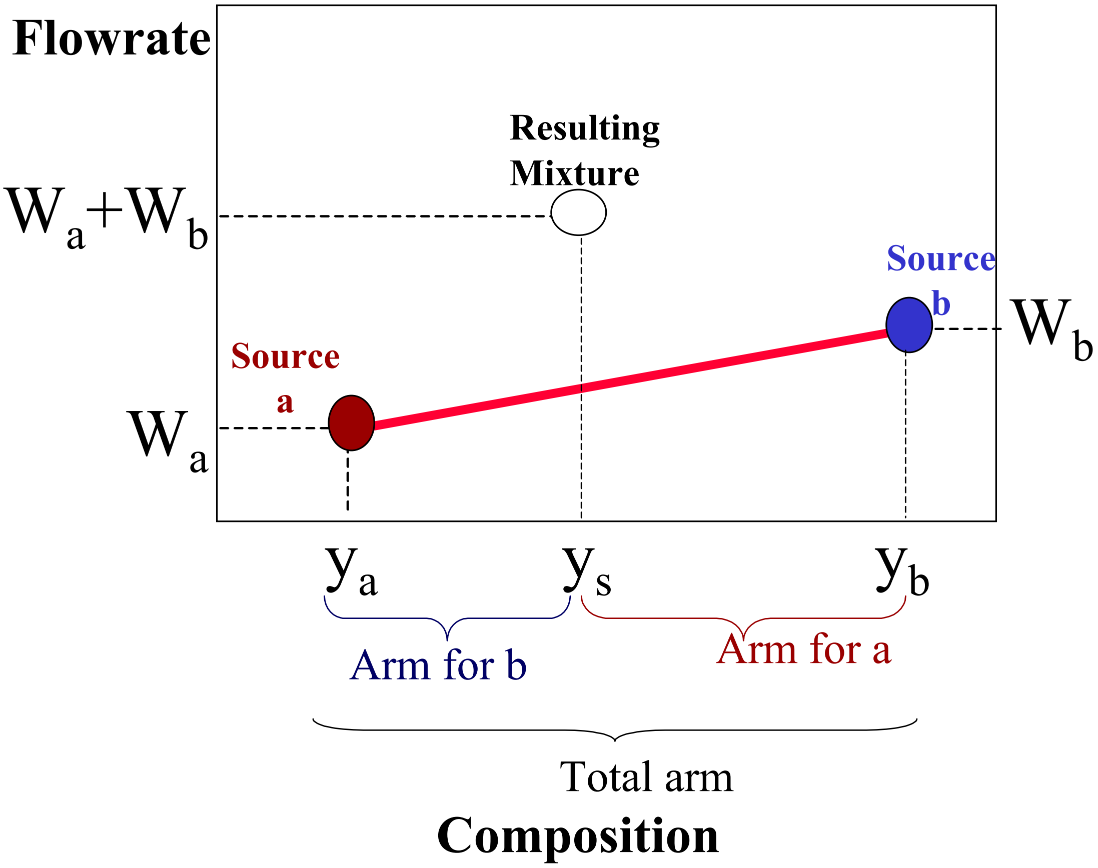

Fig. 3.5 Lever Arm Rule for Mixing

We are now in a position to derive key recycle rules based on lever arms. In particular, it is possible to identify useful rules for composition of feed entering a sink and prioritization of sources to be recycled. Consider the sink j shown in Fig. 3.6. The composition bounds are given by constraint (3.2). Currently, a fresh resource is used to satisfy the sink requirements. A process source a (e.g., waste stream) may be rerouted to sink j where a portion of its flowrate can be mixed with the fresh resource to reduce the consumption of the fresh resource in the sink. In order to minimize the usage of the fresh flowrate while satisfy the composition constraints for the sink, what should be the composition of the feed entering the sink? Should it be $z_j^{\min}$, $z_j^{\max}$ or some intermediate value, z_j^{avg} ? According to the lever-arm rule described by Eq. 3.5a, we get:

$$\frac{\text{Fresh flowrate used in sink}}{\text{Total flowrate fed to sink}} = \frac{\text{Fresh arm}}{\text{Total arm}} \tag{3.6a}$$

i.e.,

$$\frac{\text{Fresh flowrate used in sink}}{\text{Total flowrate fed to sink}} = \frac{y_a - z_{\text{Feed to sink}}}{y_a - y_F} \tag{3.6b}$$

The right hand side of Eq. (3.6a) or (3.6b) is referred to as the relative fresh arm. For a given requirement of the total flowrate fed to the sink, the flowrate of the fresh is minimized when $z_{\text{Feed to sink}}$ is maximized. Hence, the composition of the feed entering the sink should be set to $z_j^{\max}$. This analysis leads to the following rule:

<u>Sink Composition Rule:</u> When a fresh resource is mixed with process source(s), the composition of the mixture entering the sink should be set to a value that minimizes the fresh arm. For instance, when the fresh resource is a pure substance that can be mixed with pollutant-laden process sources, the composition of the mixture should be set to the maximum admissible value.

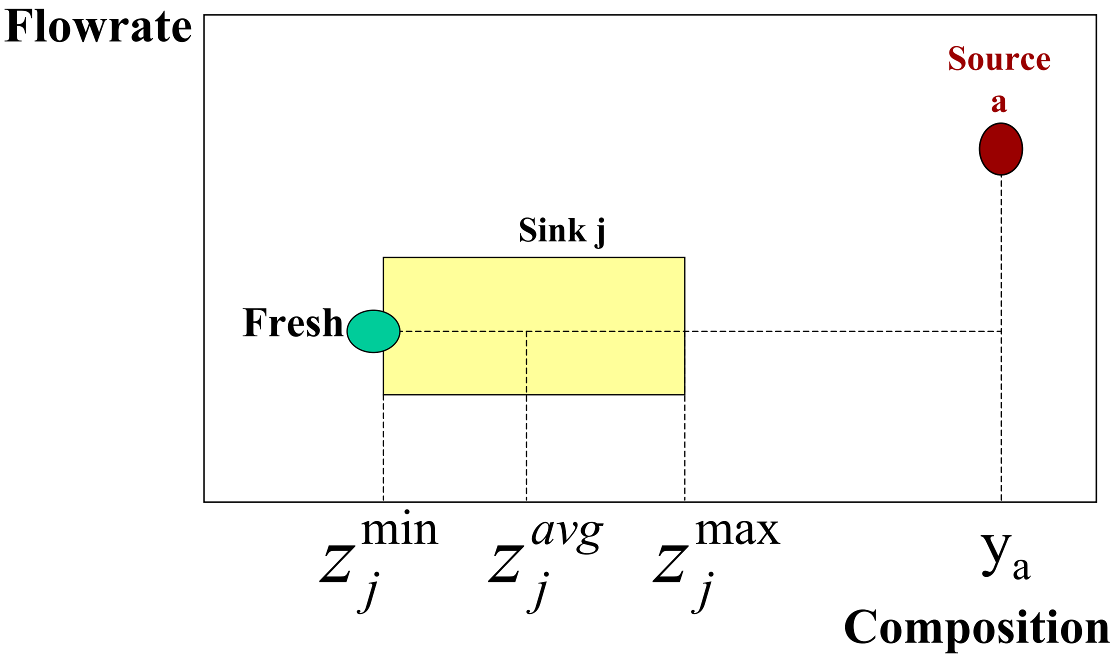

Fig. 3.6 Selection of Feed Composition to Sink

Another important aspect is the prioritization of sources. Consider the system shown in Fig. 3.7. A process sink currently uses a fresh resource. In order to reduce the fresh usage, two process sources are considered for recycle. Both sources have sufficient flowrate to satisfy the sink but their compositions exceed the maximum admissible composition to the sink. Nonetheless, upon mixing with the fresh resource in proper proportions, both process sources can be fed to the sink. The question is which source should be used: a or b?

According to Fig. 3.7 and Eq. 3.5b:

Fresh arm when source a is used = $y_a - z_j^{max}$ (3.7)

where z_j^{max} is set as the composition of the mixture as described in the sink composition rule. Similarly,

Fresh arm when source b is used = $y_b - z_j^{max}$ (3.8)

The arms given by Eqs. (3.7) and (3.8) are referred to as the absolute fresh arms when sources a and b are used. Clearly, the absolute fresh arm for a is shorter than the fresh arm for b. However, Eq. 3.6 indicates that in order to minimize the usage of the fresh resource, the relative fresh arm (which is the ratio of the absolute fresh arm to the total arm of the mixture) should be minimized. It can be shown that minimizing the absolute fresh arm for a source corresponds to minimizing the relative fresh arm for the source. To prove this observation, we compare the relative fresh arms for sources a and b:

$$\text{Relative fresh arm for a} = \frac{y_a - z_j^{\max}}{y_a - y_F} \tag{3.8}$$

and

$$\text{Relative fresh arm for b} = \frac{y_b - z_j^{\max}}{y_b - y_F} \tag{3.9}$$

Let us now evaluate the ratio of the two relative fresh arms:

$$\frac{\text{Relative fresh arm for a}}{\text{Relative fresh arm for b}} = \frac{y_a - z_j^{\max}}{y_a - y_F} \Bigg/ \frac{y_b - z_j^{\max}}{y_b - y_F} = \frac{y_a - z_j^{\max}}{y_a - y_F} \Bigg/ \frac{(y_b - y_a) + (y_a - z_j^{\max})}{(y_b - y_a) - (y_a - y_F)} = \frac{\dfrac{(y_b - y_a)}{(y_a - y_F)} + 1}{\dfrac{(y_b - y_a)}{(y_a - z_j^{\max})} + 1}$$

(3.10)

But, as can be seen from Fig. 3.7

$$y_a - y_F > y_a - z_j^{\max} \tag{3.11a}$$

Hence,

$$\frac{y_b - y_a}{y_a - y_F} < \frac{y_b - y_a}{y_a - z_j^{\max}} \tag{3.11b}$$

Combining inequalities (3.10) and (3.11b), we get

Relative fresh arm for a < Relative fresh arm for b (3.12)

Inequality 3.12 allows us to look at the absolute fresh arms instead of calculating the relative fresh arms. We can now state the following important observation:

Source Prioritization Rule: In order to minimize the usage of the fresh resource, recycle of the process sources should be prioritized in order of their fresh arms starting with the source having the shortest fresh arm. For instance, in Fig. 3.7. source a should be recycled before source b is considered. In other words, the recyclable source with the shorted relative fresh arm should be used first until it is completely recycled[1] then the source with next-to-shortest fresh arm is recycled, and so on.

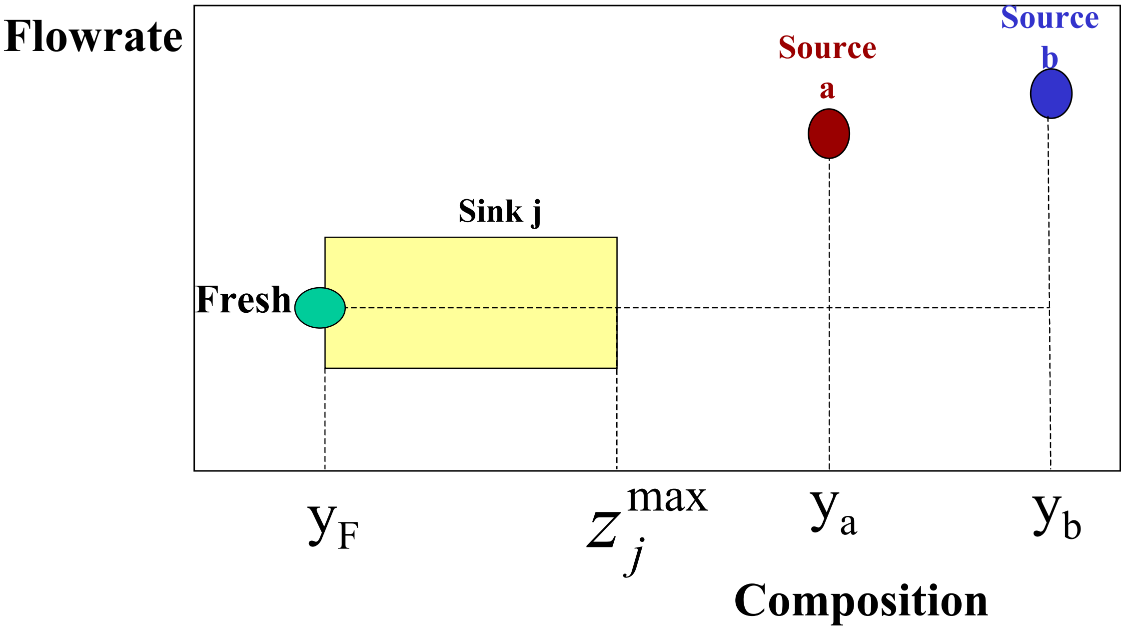

Fig. 3.7 Source Prioritization Rule

SELECTION OF SOURCES, SINKS, AND RECYCLE ROUTES

In principle, it is possible to replace any fresh source of the targeted species with an equivalent amount of recycle from a terminal or an in-process stream. If the flowrate and

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[1] "Completely recycled" can be to more than one unit. Hence, it is possible to recycle a portion of this source and mix it with another source, then use the rest of the source in another sink. For instance, if using the shortest-arm source in a sink will not satisfy the sink composition rule (e.g., the use of the shortest-arm source will not maximize the inlet composition). In such cases, a portion of the shortest-arm source is mixed with the next source to maximize the inlet composition of the sink and the rest of this source is used in another sink. Therefore,

composition of the recycled stream meet constraints (3.1) and (3.2) for units employing fresh sources, then we can undertake direct recycle from those terminal streams to those units employing fresh sources. On the other hand, if flowrate and/or composition constraints are not met, then the terminal streams must be intercepted to render them in a condition that allows replacement of fresh sources. Here, we focus on direct recycle opportunities particularly for cases when the net generation of the targeted species is independent of the recycle strategy. In such cases, it is important to note that these *recycle activities should be directed to rerouting process streams to units that employ fresh resources so as to replace fresh resources with recycled process streams.* In order to illustrate this observation, let us consider the process shown in Fig. 3.8. In this process, three fresh streams (j=1-3) carry the targeted species. The required input load of the kth targeted species in these streams is denoted by $Fresh\_Load_{k,j}$. The targeted species leave the process in four terminal streams; two of which (i=1,2) are recyclable (with or without interception) and the other two (i=3,4) are forbidden from being recycled. The total load from the four terminal streams is given by $Terminal\_Load_{k,1} + Terminal\_Load_{k,2} + Terminal\_Load_{k,3} + Terminal\_Load_{k,4}$.

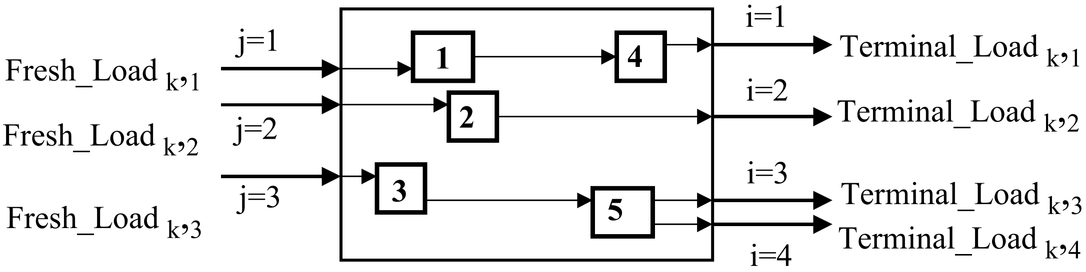

Fig. 3.8a. A Generic Process before Recycle (Noureldin and El-Halwagi, 2000)

Let us first consider recycle from terminal streams to units that do not employ fresh resources. For instance, as shown by Fig. 3.8b, let us recycle a load of $R_{k,1}$ from i=1 to the inlet of unit #5 and a load of $R_{k,2}$ from i=2 to the inlet of unit #4. Since we are dealing with the case where recycle activities have no effect on $Net\_process_k$, the loads in the individual terminal streams are simply redistributed with the total terminal load remaining the same ($Terminal\_Load_{k,1} + Terminal\_Load_{k,2} + Terminal\_Load_{k,3} + Terminal\_Load_{k,4}$). Therefore, in

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the shortest-arm source will still be completely used or committed (in more than one unit) before the next source this case, sinks that do not employ fresh sources of the targeted species are poor destinations for recycle.

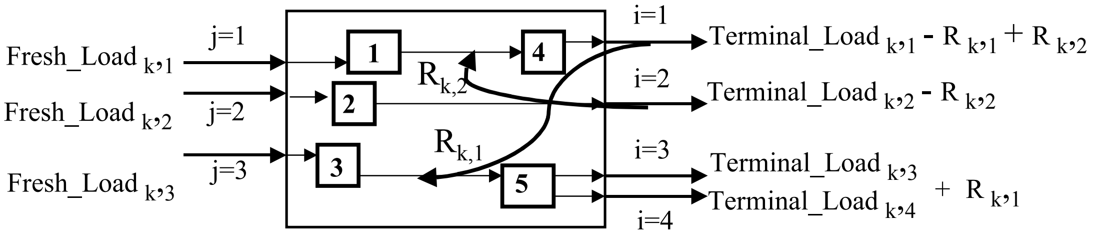

Fig. 3.8b. The Process after Recycle to Poor Sinks (Noureldin and El-Halwagi, 2000) (Total Terminal Load of Targeted Species Remains Unchanged)

Next, we consider recycles that reduce fresh loads. For instance, let us examine the effect of recycling a load of $R_{k,1}$ from i=1 to the inlet of unit #2 and a load of $R_{k,2}$ from i=2 to the inlet of unit #1. This is shown by Fig. 3.8c. The result of the fresh-source replacement is a net reduction of $R_{k,1} + R_{k,2}$ from $FRESH\_LOAD_k$ and consequently the total terminal loads are reduced by $R_{k,1} + R_{k,2}$. It is worth noting that these appropriate recycles are not limited to terminal streams. Instead, what is needed is the replacement of fresh loads with recycled loads from an in-plant or a terminal source. For example, the same effect shown in Fig. 3.8c can be accomplished by recycling (with or without interception) from in-plant sources (e.g. i=5) as shown in Fig. 3.8d.

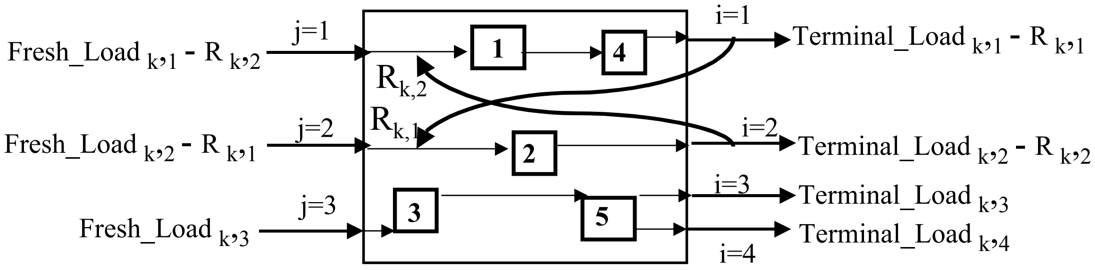

Fig. 3.8c. The Process after Recycle to Proper Sinks to Replace Fresh Loads of Targeted Species (Noureldin and El-Halwagi, 2000)

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is used.

(Total Terminal Load of Targeted Species is Reduced)

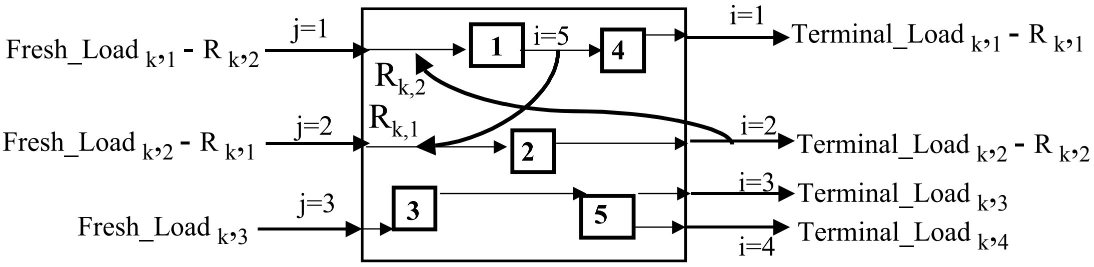

Fig. 3.8d. Recycle to Replace Fresh Sources Using In-Plant and Terminal Streams (Noureldin and El-Halwagi, 2000)

The foregoing discussion illustrates that in the case where the net generation/depletion of the targeted species is independent of stream rerouting activities, recycle should be allocated to sinks that consume fresh resource. The recyclable sources may be terminal streams or in-plant streams on the path to terminal streams. The result of such selection of sources and sinks leads to a reduction in both fresh consumption and waste discharge.

EXAMPLE 3.1. MINIMIZATION OF FRESH REACTANT IN A CHEMICAL PLANT

Consider the chemical process shown in Fig. 3.9. The reactor consumes 100 kg/s of fresh feed. In order to reduce the consumption of the fresh reactant, two process sources are considered for recycle to the reactor: the top and bottom products of a separation system. The flowrates of the top product is 60 kg/s and it has 10% (mass basis) of impurities. The bottom product has a flowrate of 216 kg/s and its content of impurities is 75% (mass basis). Determine the recycle strategies that minimize the usage of the fresh reactant.

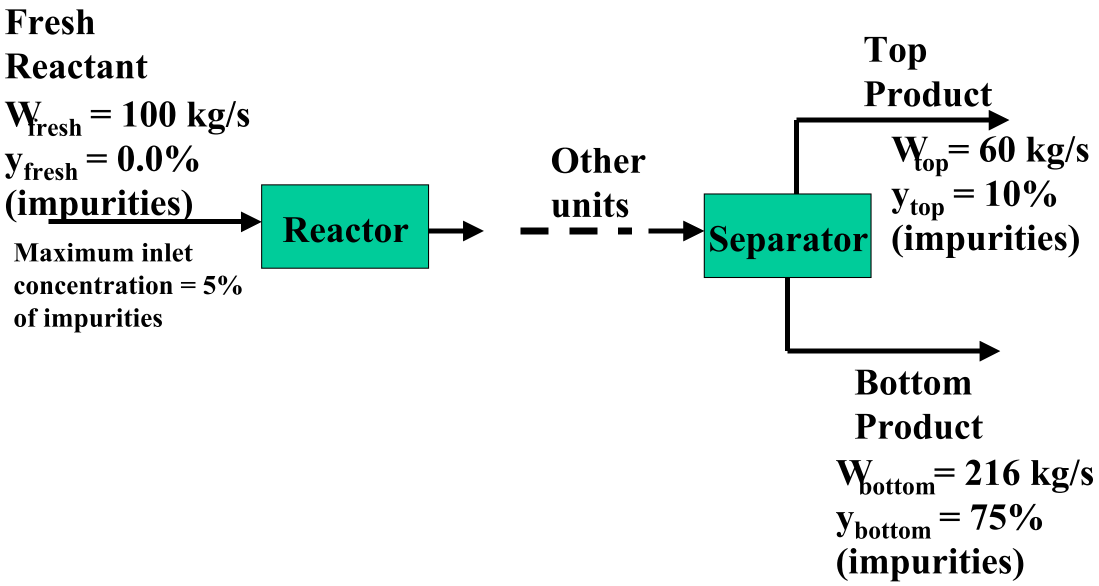

Fig. 3.9. Simplified Process Sheet of Relevant Units in Chemical Plant of Example 3.1.

Solution: The problem entails two candidate recycle alternatives as shown in Fig. 3.10. The flowrates to be recycled from the top and bottom products are designated by W^R_{Top} and W^R_{Bottom}. In order to determine the recycle strategies, we represent the sources and the sink on the source-sink mapping diagram (Fig. 3.11).

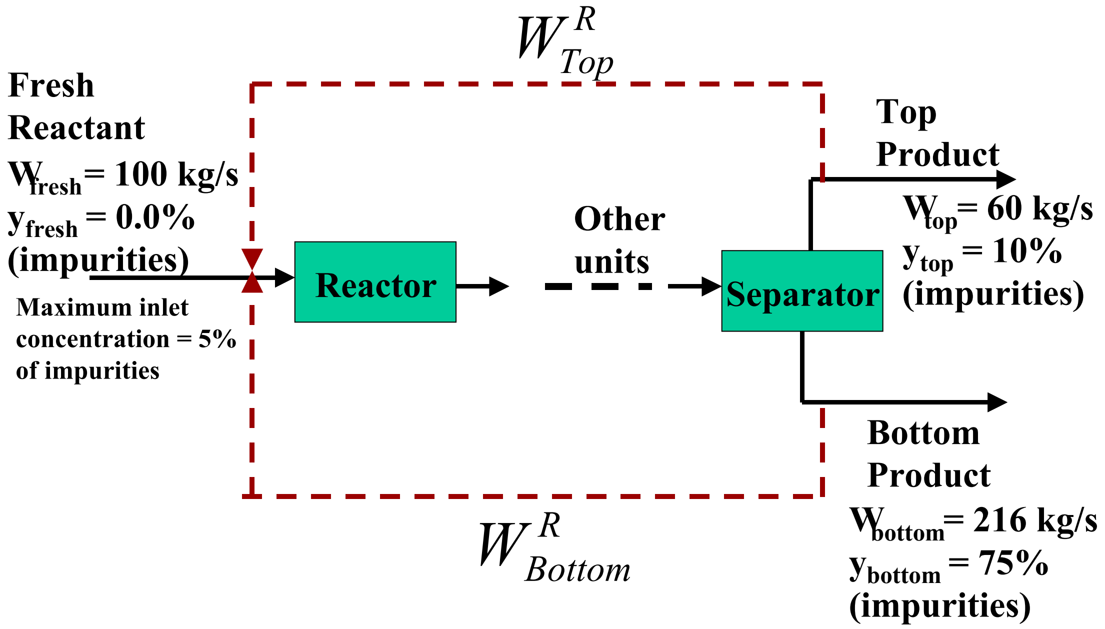

Fig. 3.10. Recycle Alternatives for Example 3.1.

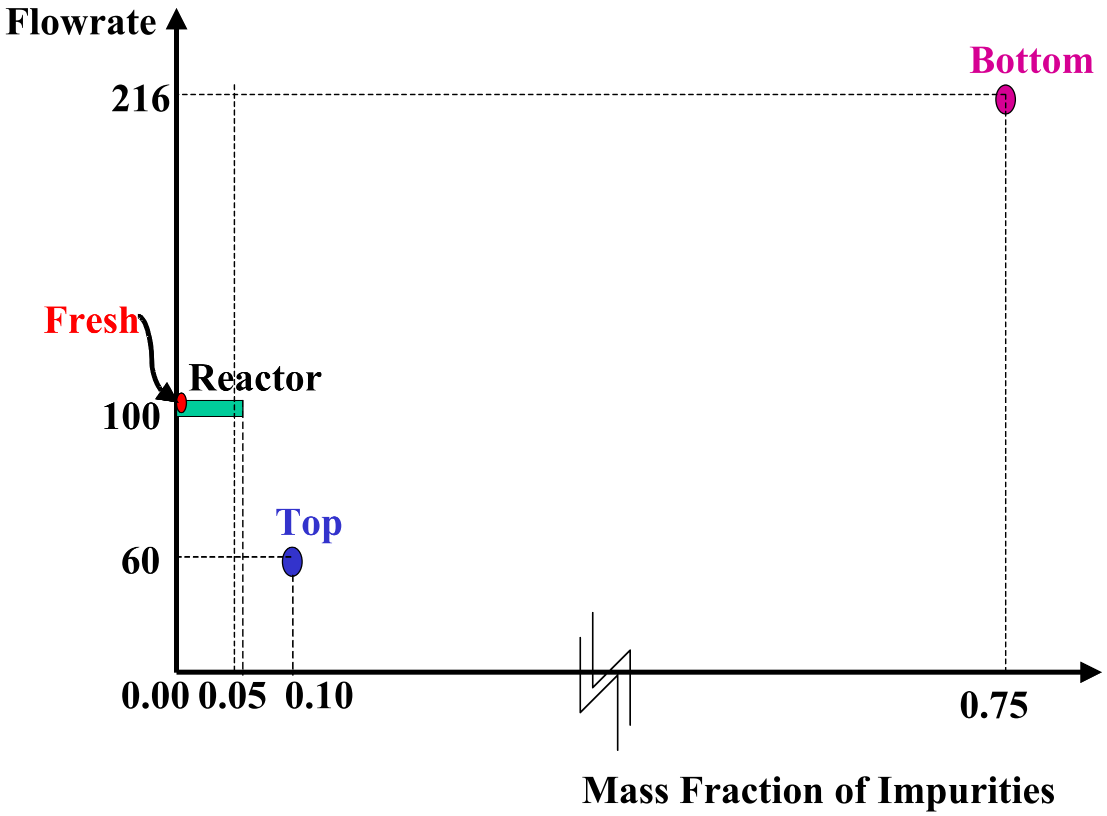

Fig. 3.11. Source-Sink Mapping Diagram fro Example 3.1.

Since the top product has the shortest fresh arm, we start with recycle from top product. According to lever-arm Eq. (3.6b),

$$\frac{Fresh}{100} = \frac{0.10 - 0.05}{0.10 - 0.00} \tag{3.13a}$$

or

$$Fresh = 50.0 \text{ kg/s} \tag{3.13b}$$

The flowrate of the top product recycled to the reactor can be calculated by material balance:

$$\text{Fresh} + W_{Top}^{R} = 100.0 \tag{3.14a}$$

i.e.,

W_{Top}^{R} = 50.0 kg/s (3.14b)

It is worth noting that since not all the top product has been recycled, there is no need to consider the bottom product for recycle (i.e., W_{Bottom}^{R} = 0.0 kg/s). This is attributed to the source prioritization rules which indicates that the source with the shortest fresh arm should be completely used before the next-to-shortest fresh-armed source be considered.

Alternatively, the same result can be obtained from a component material balance including recycle from the top stream (shortest fresh arm) and the fresh reactant:

Fresh * 0.00 + W_{Top}^{R} * 0.10 = 100.0*0.05 (3.15)

Along with Eq. (3.14a), we get W_{Top}^{R}= 50 kg/s and Fresh = 50.0 kg/s. Therefore, a 50% reduction in fresh consumption is accomplished through direct recycle.

It is instructive to examine the case if the shortest-arm rule was not followed and recycle from the bottom product was considered. In this case, the overall and component materials balances can be expressed as:

Fresh + W_{Bottom}^{R} = 100.0 (3.16)

Fresh * 0.0 + W_{Bottom}^{R} * 0.75 = 100*0.05 (3.17)

Therefore,

W_{Bottom}^{R} = 6.7 kg/s (3.18)

and

Fresh = 100.0 - 6.7 = 92.3 kg/s (3.19)

which corresponds to 6.7% reduction in fresh consumption.

The previous analysis illustrates the merit of the source prioritization rule by ordering the sequence of recycles accoring to the length of the fresh arms.

EXAMPLE 3.2. NITROGEN RECYCLE IN A MAGNETIC TAPE PLANT

Consider the magnetic-tape manufacturing process shown in Fig. 3.12. In this process (Dunn et al., 1995, El-Halwagi, 1997), coating ingredients are dissolved in 0.09 kg/s of organic solvent and mixed to form a slurry. The slurry is suspended with resin binders and special additives. Next, the coating slurry is deposited on a base film. Nitrogen gas is used to induce evaporation rate of solvent that is proper for deposition. In the coating chamber, 0.011 kg/s of solvent are decomposed into other organic species. The decomposed organics are separated from the exhaust gas in a membrane unit. The retentate stream leaving the membrane unit has a flowrate of 3.0 kg/s and is primarily composed of nitrogen that is laden with 1.9 wt/wt% of the organic solvent. The coated film is passed to a dryer where nitrogen gas is employed to evaporate the remaining solvent. The exhaust gas leaving the dryer has a flowrate of 5.5 kg/s and contains 0.4 wt/wt% solvent. The two exhaust gases are mixed and disposed off.

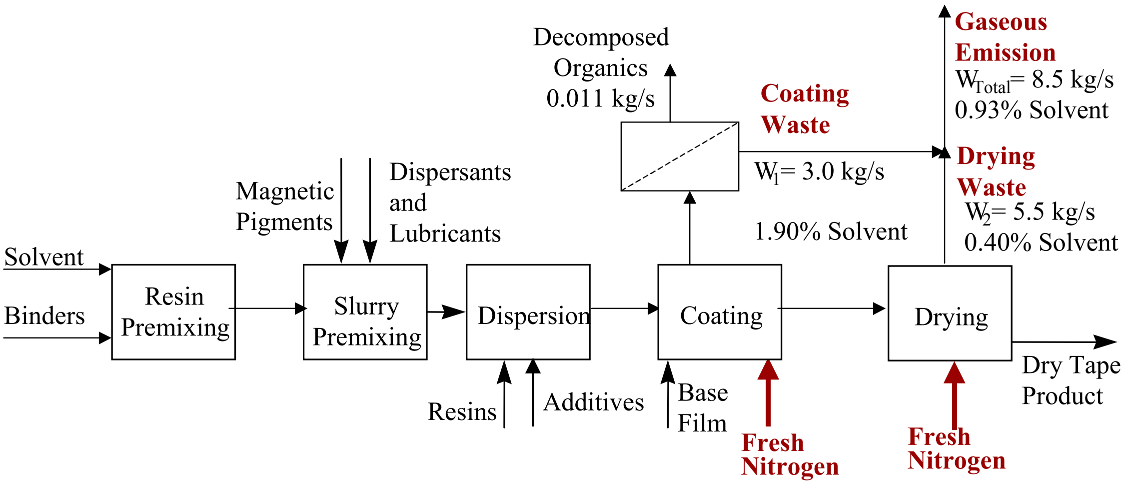

Fig. 3.12. Schematic representation of a magnetic tape manufacturing process (El-Halwagi, 1997)

It is desired to undertake a direct-recycle initiative to use solvent-laden nitrogen (gaseous wastes) in lieu of fresh nitrogen gas in the coating and drying chambers. The following constraints on the gaseous feed to these two units should be observed:

Coating

- $3.0 \leq \text{flowrate of gaseous feed (kg/s)} \leq 3.2$ (3.20)
- $0.0 \leq \text{w}t\%\,of\ solvent \leq 0.2$ (3.21)

Dryer

- $5.5 \leq \text{flowrate of gaseous feed (kg/s)} \leq 6.0$ (3.22)
- $0.0 \leq \text{w}t\%\,of\ solvent \leq 0.1$ (3.23)

It may be assumed that outlet gas composition from the coating and the dryer chambers are independent of the entering gas compositions.

Using segregation, mixing and direct recycle, what is minimum consumption of nitrogen gas that should be used in the process? What are the strategies leading to the target?

Solution:

The first step in solving the problem is to determine the sources and sinks to be included in the analysis. The exhaust gas emission is segregated to its two sources: coating waste and drying waste. We will consider the recycle of the segregated sources and not the mixed source. Since mixing of sources is one of the solution strategies, there is no loss of generality and if the mixed source is to be recycled in its mixed form, it will appear in the analysis by showing the mixing of the segregated sources. Regarding the selection of the sinks, we select the coating and the drying chambers since they employ fresh nitrogen (as described in Figures 3.8a – d).

The source-sink mapping diagram for the problem is shown in Fig. 3.13. The admissible recycle regions for the two sinks are shown as the boxes resulting from the intersection of the flowrate constraints with the composition constraints (inequalities 3.20 – 3.23).

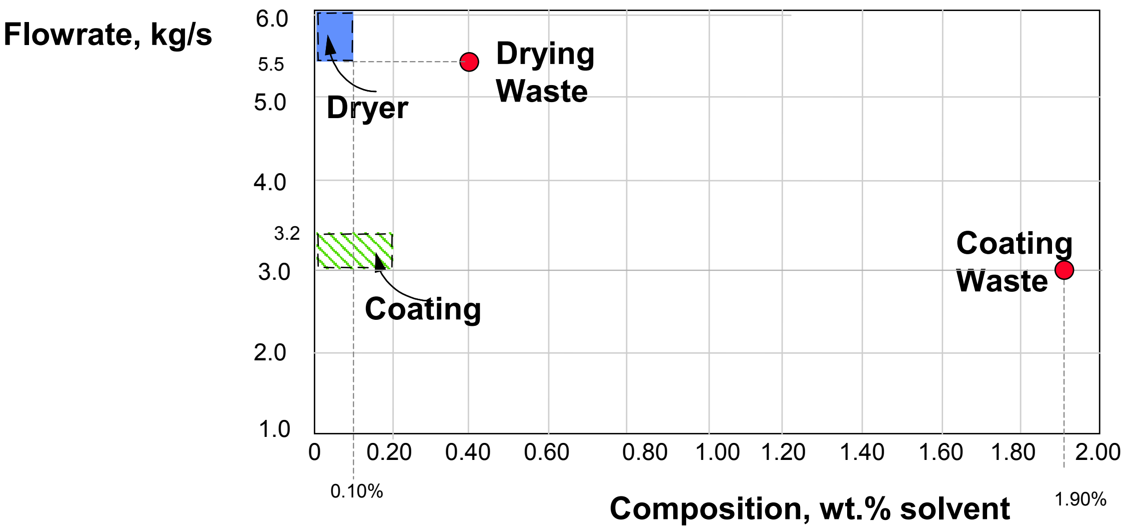

Fig. 3.13. Source-Sink Mapping Diagram for Magnetic Tape Plant

For the coating unit, the shortest fresh arm of process sources is that of drying waste. As can be seen from Fig. 3.13, the flowrate and composition of the drying waste exceed the maximum allowable for coating. The excess flowrate is an easily resolvable problem since a portion of the drying waste flowrate is to be recycled and the rest is to be bypassed. However, the unacceptably high composition of the solvent in the drying waste must be reduced. One way of reducing the solvent content is to use an interception device (e.g., separator). This will be covered in later chapters. However, since our focus here is on direct recycle where no new equipment is to be added, we must consider mixing a portion of the drying waste with fresh nitrogen, thereby adjusting the composition of the mixture to lie inside the coating box. According to the sink composition rule, in order to minimize consumption of fresh nitrogen, the composition of the mixture entering the coating should be selected so as to minimize the fresh arm of the drying waste. Hence, the composition of the mixture is set to its maximum admissible value which is 0.002 (mass fraction of solvent). As for the flowrate of the feed to the coating unit, since the range is 3.0 to 3.2 kg/s, we choose 3.0 kg/s to reduce fresh nitrogen requirements. Let us designated the flowrate of the drying waste that is to be recycled to the coating as $W_{DryingWaste \rightarrow Coating}$. This recycled flowrate is to be calculated along with the fresh requirement of the coating unit according to the scheme shown in Fig. 3.14.

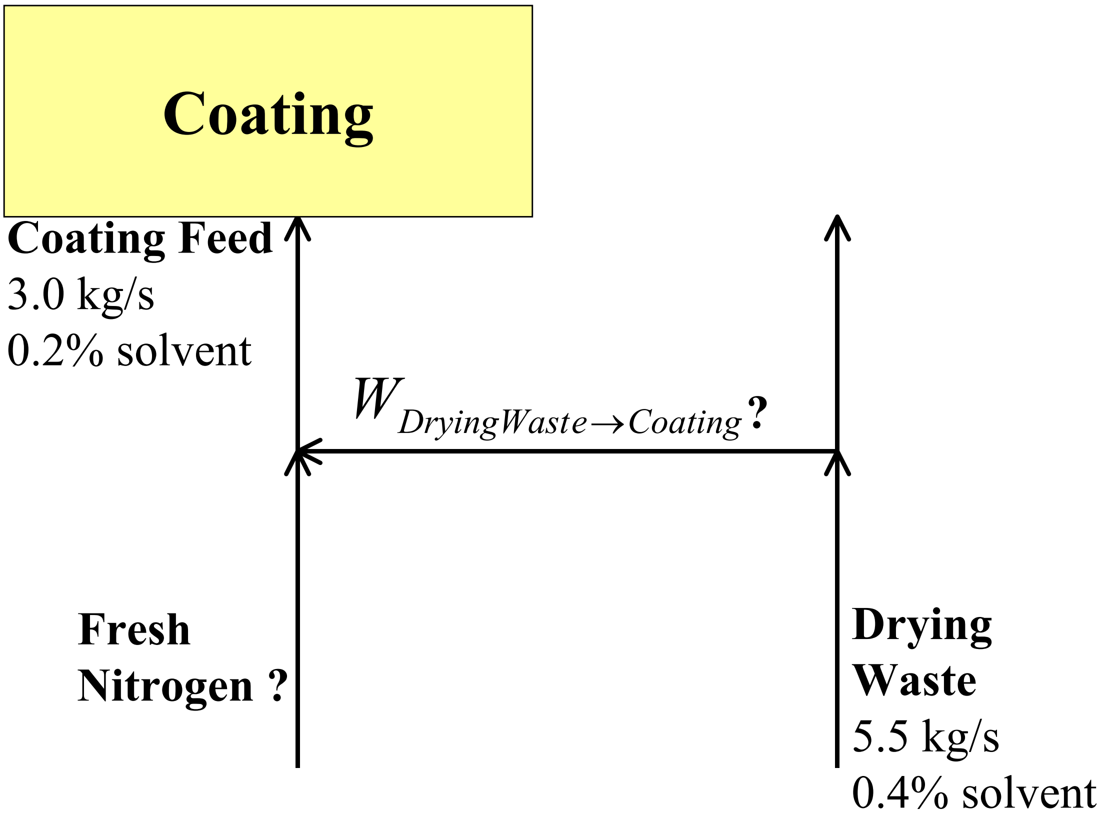

Fig. 3.14. Mixing of Drying Waste with Fresh Nitrogen to Provide Feed to Coating

According to lever-arm Eq. (3.6b),

$$\frac{\text{Fresh nitrogen in coating}}{3.0} = \frac{0.004 - 0.002}{0.004 - 0.00} \tag{3.24a}$$

or

Fresh nitrogen used in coating = 3.0 - 1.5 = 1.5 kg/s (3.24b)

and

$$W_{DryingWaste \to Coating} = 3.0 - 1.5 \text{ kg/s} \tag{3.25}$$

Alternatively, component material balance for the feed of the coating yields

$$(W_{DryingWaste \to Coating} * 0.004 + \text{Fresh nitrogen to Coating} * 0.000) = 3.0 * 0.002 \tag{3.26}$$

i.e.,

$$W_{DryingWaste \to Coating} = 1.5 \text{ kg/s}$$

Since the drying waste has not been fully utilized, its remaining flowrate should be considered for recycle to the drying unit as it provides a shorter fresh arm than the drying waste. For the drying unit, Eq. (3.6b) can be written as:

$$\frac{\text{Fresh nitrogen used in drying}}{5.5} = \frac{0.004 - 0.001}{0.004 - 0.00} \tag{3.27a}$$

or

Fresh nitrogen used in drying unit = 4.125 kg/s (3.27b)

Hence,

$$W_{DryingWaste \rightarrow Drying} = 5.500 - 4.125 = 1.375 \text{ kg/s} \tag{3.28}$$

Alternatively, component material balance for the feed of the dryer yields

$(W_{DryingWaste \rightarrow Coating} *0.004 + \text{Fresh nitrogen to Coating}*0.000) = 5.50*0.001$

$$W_{DryingWaste \rightarrow Drying} = 1.375 \text{ kg/s} \tag{3.26b}$$

Based on Eqs. (3.24b) and (3.27b), we have

Minimum fresh nitrogen consumption in coating and drying after direct recycle = 1.500 + 4.125 = 5.625 kg/s (3.29)

Compared to the original fresh nitrogen consumption of 8.500 kg/s, direct recycle saves 34% of fresh nitrogen purchase.

EXAMPLE 3.3. MULTIPLICITY OF RECYCLE IMPLEMENTATIONS: VINYLA ACETATE CASE STUDY

An important question is whether or not it is possible to develop more than one direct-recycle strategy that can achieve the same target (e.g., of fresh consumption or waste discharge)? It is indeed possible in some cases to have multiple (sometimes infinite) direct-recycle strategies that can be implemented to attain the same target. This is the case of degnerate solutions. *Degeneracy* in recycle strategies referes to the ability of different recycle structures to achieve the same target. To illustrate this concept, let us consider the vinyl acetate monomer (VAM) plant (Fig. 3.15) presented in Example 2.1. with more data and process details to enable the consideration of recycle strategies.

Vinyl acetate monomer “VAM” is manufactured by reacting acetic acid with oxygen and ethylene according to the following chemical reaction:

C_2H_4	+	0.5 O_2	+	$C_2H_4O_2$	=	$C_4H_6O_2$	+	H_20
Ethylene		Oxygen		Acetic Acid		VAM		Water

Consider the process shown in the next figure. 10,000 kg/hr of acetic acid “AA” along with 200 kg/hr of water are evaporated in an acid tower. The vapor is fed with oxygen and ethylene to the reactor where 7,000 kg/hr of acetic acid are reacted and 10,000 kg/hr of VAM are formed. The reactor off gas is cooled and fed to first absorber where AA (5,100 kg/hr) is used as a solvent. Almost all the gases leave from the top of the first absorption column together with 1,200 kg/hr of AA. This stream is fed to the second absorption column where water (200 kg/hr) is used to scrub acetic acid. The bottom product of the first absorption column is fed to the primary distillation tower where VAM is recovered as a top product (10,000 kg/hr) along with small amount of AA which are not worth recovering (100 kg/hr) and water (200 kg/hr). This stream is sent to final finishing. The bottom product of the primary tower (6,800 kg/hr of AA and 2,300 kg/hr of water) is mixed with the bottom product of the second absorption column (1,200 kg/hr of AA and 200 kg/hr of water). The mixed waste is fed to a neutralization system followed by biotreatment.

The following technical constraints should be observed in any proposed solution:

Neutralization:

- $0 \le \text{Flowrate of Feed to Neutrazation (kg / hr)} \le 11{,}000$ (3.30)
- $0 \le \text{AA in Feed to Neutralization (wt.\%)} \le 85\%$ (3.31)

Acid Tower:

- $10{,}200 \le \text{Flowrate of Feed to Acid Tower (kg / hr)} \le 11{,}200$ (3.32)
- $0.0 \le \text{Water in Feed to Acid Tower (wt.\%)} \le 10.0$ (3.33)

First Absorber:

- $5{,}100 \le \text{Flowrate of Feed to Absorber I (kg/hr)} \le 6{,}000$ (3.34)
- $0.0 \le \text{Water in Feed to Absorber I (wt.\%)} \le 5.0$ (3.35)

It can be assumed that the process performance will not significantly change as a result of direct recycle activities.

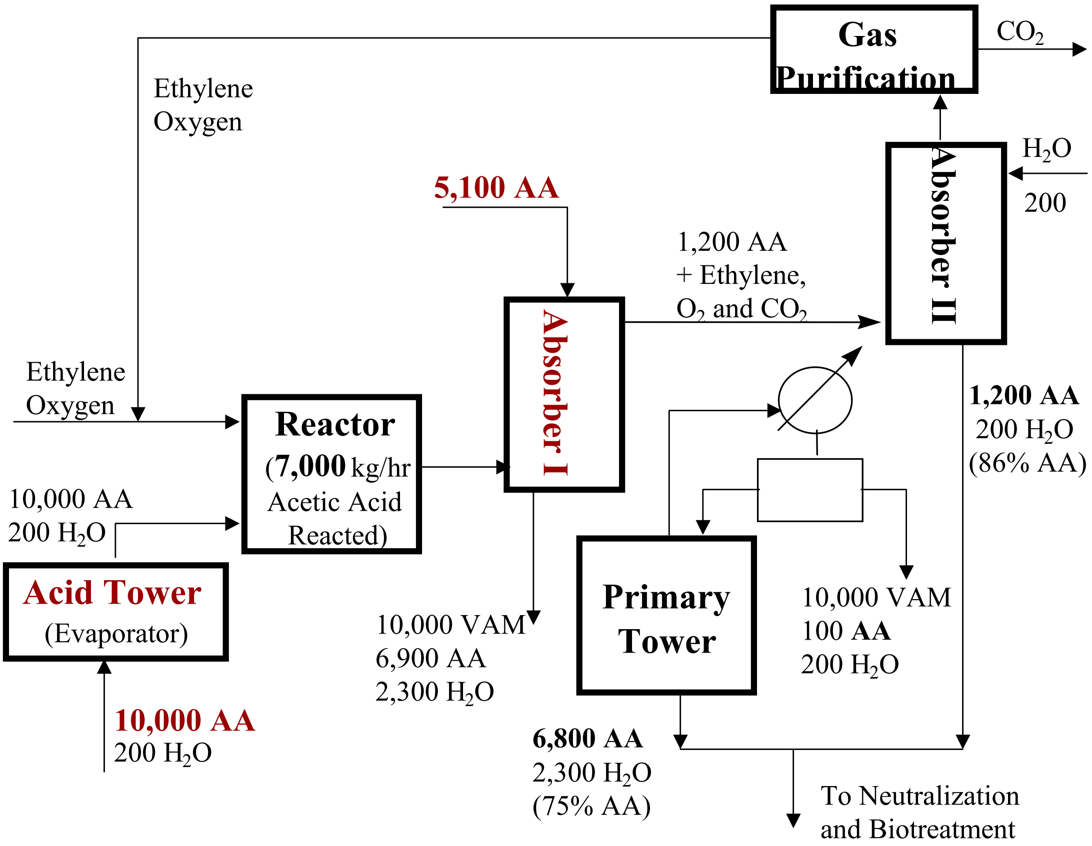

Fig. 3.15. Schematic Flowsheet of VAM Process (all numbers are in kg/hr)

What is the target for minimum usage (kg/hr) of fresh acetic acid in the process if segregation, mixing, direct recycle are used? Can you find more than one strategy to reach the target?

Solution:

We start by selecting the sources and sinks to be included in the analysis. The wastewater fed to neutralization and biotreatment is segregated to its two sources: bottoms of absorber II (referred to as R_1) and bottoms of primary tower (designated by R_2). As for the choice of the sinks, we select the acid tower and absorber I (referred to as S_1 and S_2, respectively) since they employ fresh acetic acid (as described in Figures 3.8a – d). The source-sink mapping diagram for the problem is shown in Fig. 3.13.

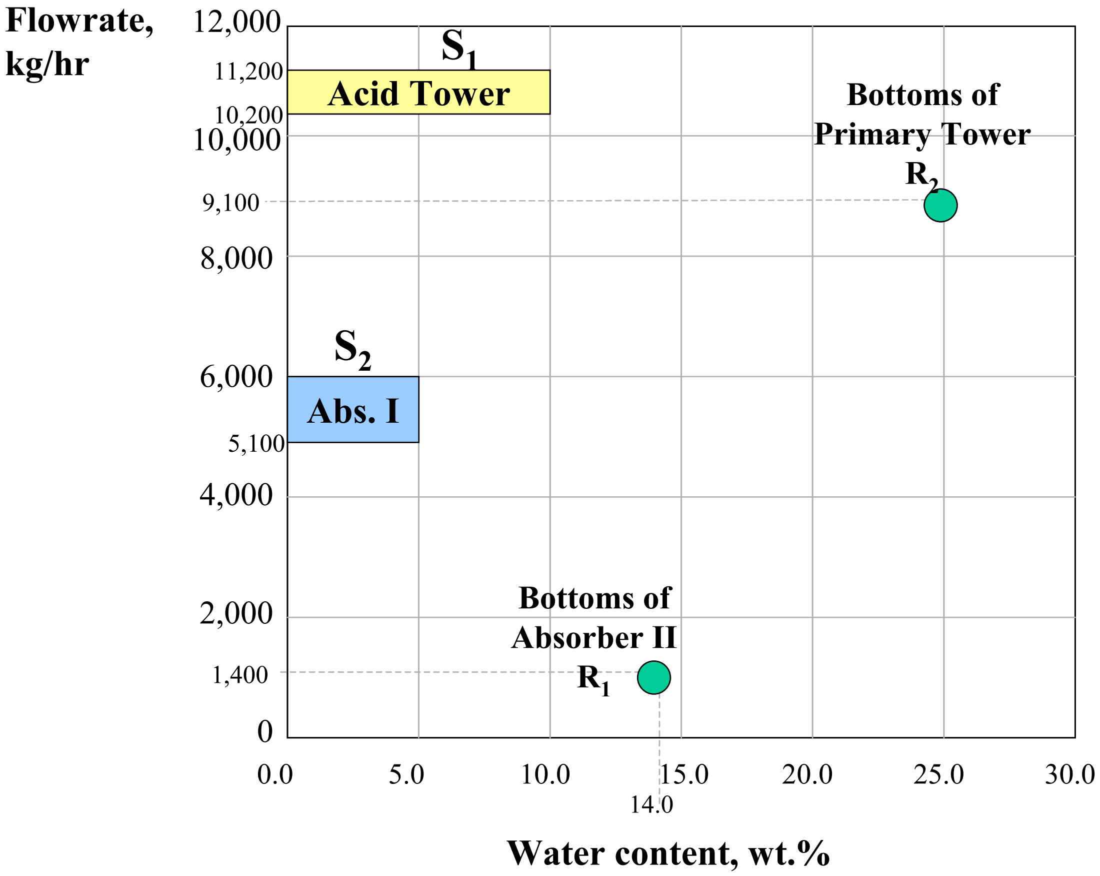

Fig. 3.16. Source-Sink Mapping Diagram for the VAM Case Study

For the acid tower (sink S_1), R_1 shows the shortest fresh (acetic acid) arm among process sources. Let us determine what flowrate of R_1 should be recycled to S_1. Assuming that only R_1 and fresh AA are mixed and fed to S_1, Eq. (3.6b), we get:

$$\frac{\text{Fresh AA used in } S_1}{10{,}200} = \frac{0.14 - 0.10}{0.14 - 0.00} \qquad (3.36a)$$

or

Fresh AA in S_1 = 2,914 kg/hr (3.37b)

Hence, the flowrate to be recycled from R_1 to S_1 would be

$W_{R_1 \to S_1}$ = 10,200 – 2,914 = 7,286 kg/s (3.38)

However, the maximum recyclable flowrate of S_1 is 1,400 kg/hr. Therefore, all of R_1 will be recycled to S_1. Now that all of R_1 is completely recycled, we move to the next-to-shortest arm which corresponds to R_2. The question is what flowrate of R_2 is recyclable to S_1 (referred to as $W_{R_2 \to S_1}$) to minimize the usage of fresh AA? A water balance for S_1 is expressed as:

$1{,}400 * 0.14 + W_{R_2 \to S_1} * 0.25 + \text{Fresh AA in } S_1 * 0.0 = 10{,}200 * 0.10$ (3.39a)

Therefore,

$W_{R_2 \to S_1}$ = 3,296 kg/hr (3.39b)

and

Fresh AA in S_1 = 10,200 – 1,400 – 3,296 = 5,504 kg/hr (3.40)

Next, we recycle from R_2 to S_2 and mix with fresh AA. Hence,

$$\frac{\text{Fresh AA used in } S_2}{5{,}100} = \frac{0.25 - 0.05}{0.25 - 0.00} \qquad (3.41a)$$

or

Fresh AA in S_2 = 4,080 kg/hr (3.41b)

Hence, the flowrate to be recycled from R_2 to S_2 would be

$W_{R_2 \to S_2}$ = 5,100 – 1,020 = 1,020 kg/hr (3.42)

Based on Eqs. (3.40) and (3.42), we get

Target for minimum fresh usage when direct recycle is implemented

$$= 5{,}504 + 4{,}080 = 9{,}584 \text{ kg/hr} \qquad (3.43)$$

A schematic representation of this solution is shown in Fig. 3.17a.

Next, it is required to determine if there are other direct recycle strategies leading to the same AA target. One alternative is to start the recycle to sink S_2. The shortest fresh arm is provided by R_1. It can be shown that all of R_1 is recyclable to S_2 with the rest of the feed to S_2 coming from R_2 and fresh AA. A water balance for S_2 is expressed as:

$$1{,}400*0.14 + W_{R_2 \to S_2}*0.25 + \text{Fresh AA in } S_1*0.0 = 5{,}100*0.05 \qquad (3.44a)$$

Therefore,

$$W_{R_2 \to S_2} = 236 \text{ kg/hr} \qquad (3.44b)$$

and

$$\text{Fresh AA in } S_1 = 5{,}100 - 1{,}400 - 236 = 3{,}464 \text{ kg/hr} \qquad (3.45)$$

Next, we recycle from R_2 to S_1 and mix with fresh AA. Hence,

$$\frac{\text{Fresh AA used in } S_1}{10{,}200} = \frac{0.25 - 0.10}{0.25 - 0.00} \qquad (3.46a)$$

or

$$\text{Fresh AA in } S_2 = 6{,}120 \text{ kg/hr} \qquad (3.46b)$$

Hence, the flowrate to be recycled from R_2 to S_1 would be

$$W_{R_2 \to S_1} = 10{,}200 - 6{,}120 = 4{,}080 \text{ kg/hr} \qquad (3.47)$$

Based on Eqs. (3.45) and (3.46b), we get

Target for minimum fresh usage when direct recycle is implemented

$$= 3{,}464 + 6{,}120 = 9{,}584 \text{ kg/hr} \qquad (3.49)$$

which is the same target found through an alternative recycle strategy. A schematic representation of this solution is shown in Fig. 3.17b.

Another alternative can be found by splitting R_1 between S_1 and S_2 in any proportion. For instance, let us split R_1 equally between S_1 and S_2. In this case, a water balance for S_1 is expressed as:

$$700*0.14 + W_{R_2 \to S_1}*0.25 + \text{Fresh AA in } S_1 * 0.0 = 10{,}200*0.10 \tag{3.50a}$$

Therefore,

$$W_{R_2 \to S_1} = 3{,}688 \text{ kg/hr} \tag{3.50b}$$

and

$$\text{Fresh AA in } S_1 = 10{,}200 - 700 - 3{,}688 = 5{,}812 \text{ kg/hr} \tag{3.51}$$

Similarly, a water balance for S_2 is expressed as:

$$700*0.14 + W_{R_2 \to S_2}*0.25 + \text{Fresh AA in } S_1 * 0.0 = 5{,}100*0.05 \tag{3.52a}$$

Therefore,

$$W_{R_2 \to S_2} = 628 \text{ kg/hr} \tag{3.52b}$$

and

$$\text{Fresh AA in } S_1 = 5{,}100 - 700 - 628 = 3{,}772 \text{ kg/hr} \tag{3.53}$$

Based on Eqs. (3.51) and (3.53), we get

Target for minimum fresh usage when direct recycle is implemented

$$= 5{,}812 + 3{,}772 = 9{,}584 \text{ kg/hr} \tag{3.54}$$

which is the same target found through an alternative recycle strategy. A schematic representation of this solution is shown in Fig. 3.17c.

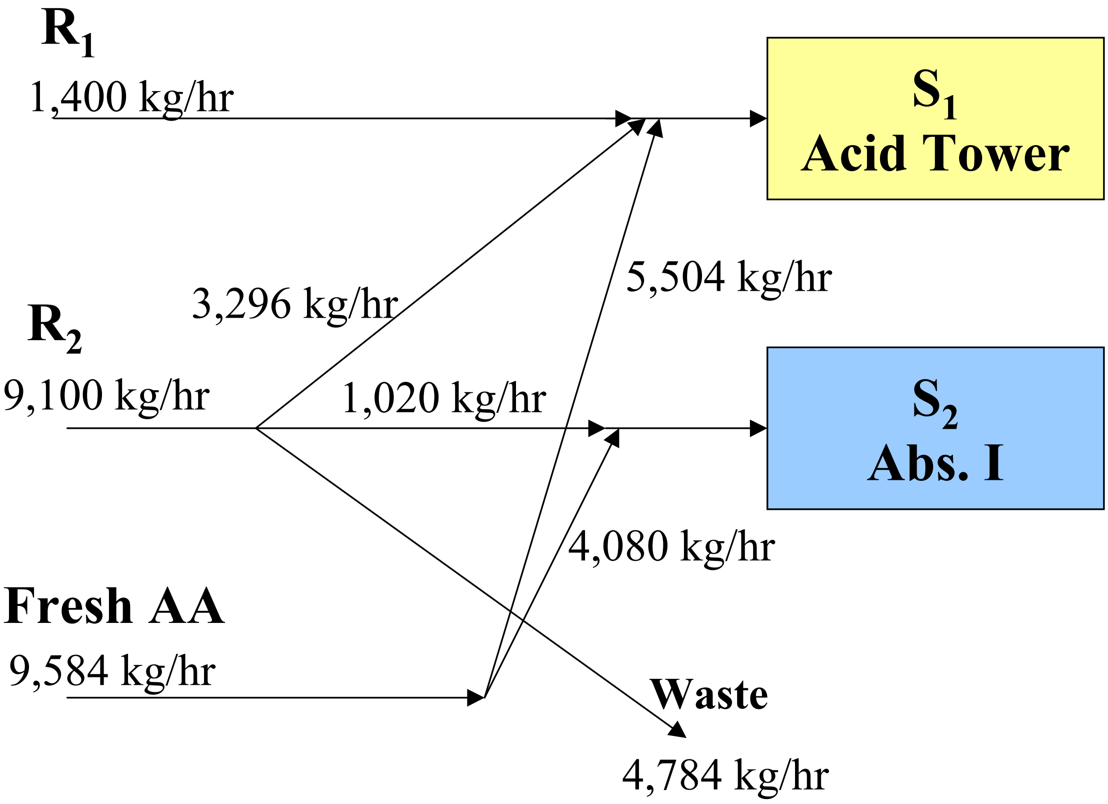

Fig. 3.17a Direct-Recycle Configuration when All of R_1 is Fed to S_1

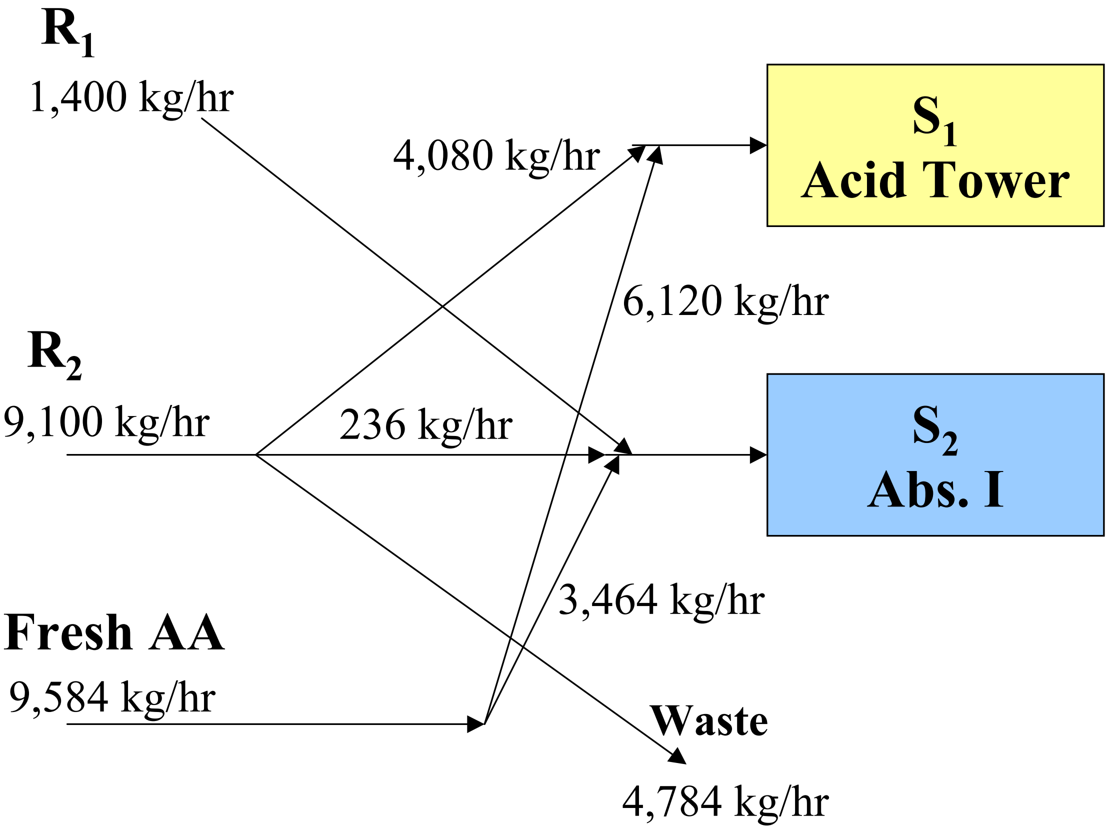

Fig. 3.17b Direct-Recycle Configuration when All of R_1 is Fed to S_2

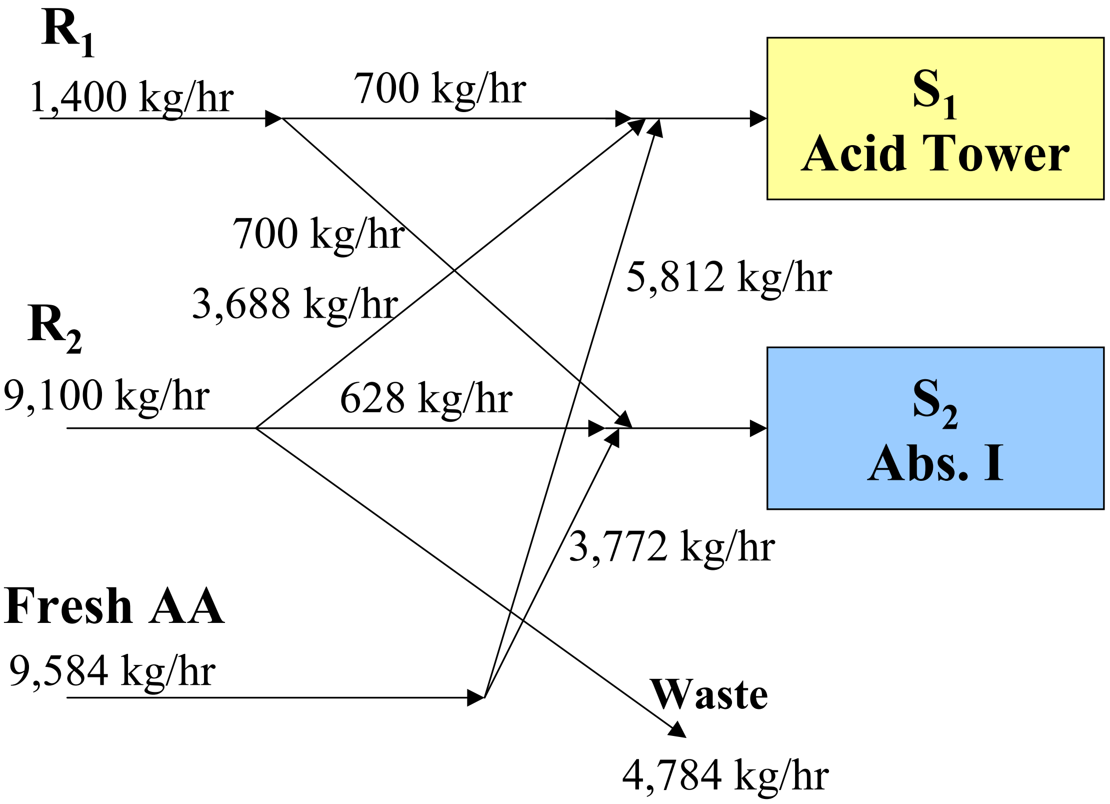

Fig. 3.17c Direct-Recycle Configuration when R_1 is Split Equally between S_1 and S_2

Along the same lines, R_1 can be split between S_1 and S_2 in any proportion (while completely recycling all its flowrate), and the target for minimum usage of fresh AA will be the same. Hence, there are infinite number of recycle strategies that attain the same target for fresh AA consumption. Consequently, it is critical to have the ability to identify the target without detailing the recycle strategy. This is the objective of the next section.

DIRECT-RECYCLE TARGETS THROUGH MATERIAL-RECYCLE PINCH DIAGRAM

In many cases, it is useful to identify performance targets as a result of direct recycle strategies without detailing those strategies. Targeting is an important activity since it spares the designer from the detailed computations particularly when there are numerous solutions or when there are many sources and sinks. Additionally, targeting for the whole system emphasizes the integrated nature without getting entangled in the detailed analysis. It also sheds useful insights on the key characteristics of the system. In the following, a rigorous targeting method will be presented to benchmark performance of the process when direct-recycle strategies are considered.

To illustrate the targeting procedure, let us first consider the case of a *pure fresh* resource that is to be replaced by process sources. Later, this restriction will be relaxed. Therefore, constraint (3.2) can be rewritten as:

$$0 \le z_j^{in} \le z_j^{max} \quad \text{where } j = 1,2, \ldots, N_{sinks} \tag{3.55}$$

Additionally, we consider the case when the flowrate to be fed to each sink, G_j, is given. The load of impurities entering the jth sink is given by:

$$M_j^{Sink} = G_j z_j^{in} \tag{3.56}$$

Therefore, the composition constraint of the sink (3.55) may be replaced by the following constraint on load:

$$0 \le M_j^{Sink} \le M_j^{max} \qquad \text{where } j = 1,2, \ldots, N_{sinks} \tag{3.57}$$

where

$$M_j^{max} = G_j \, z_j^{max} \tag{3.58}$$

Therefore, we can restate the sink-composition rule as the following *sink-load rule*:

If the sink requires the use of fresh source, its inlet impurities load should be maximized, i.e.,

$$M_j^{in,optimum} = M_j^{max} \qquad \text{where } j = 1,2, \ldots, N_{sinks} \tag{3.59}$$

unless no fresh resource is to be used in this sink (in which case, the inlet load of the sink is that of the recycled/reused sources).

The sink-load rule coupled with the source-prioritization rule constitute the basis for the following graphical procedure referred to as the ***material recycle pinch diagram*** (El-Halwagi et al., 2003):

1. Rank the sinks in ascending order of maximum admissible composition of impurities, $z_1^{\max} \leq z_2^{\max} \leq \ldots z_j^{\max} \ldots \leq z_{N_{Sinks}}^{\max}$
2. Rank sources in ascending order of impurities composition, i.e.

$y_1 < y_2 < \ldots y_i \ldots\ldots < y_{N_{Sources}}$

3. Plot the maximum admissible load of impurities in each sink ($M_j^{Sink,\max} = G_j z_j^{\max}$) versus its flowrate. Therefore, each sink is represented by an arrow whose vertical distance is $M_j^{Sink,\max} = G_j z_j^{\max}$, horizontal distance is flowrate, and slope is $z_j^{\max}$. Start with the first sink (which has the lowest $z_j^{\max}$). From the arrowhead of this sink, plot the second sink. Proceed to plot the rest of the sinks using superposition of the sinks arrows in ascending order. The resulting curve is referred to as the ***<u>sink composite curve</u>*** (Fig. 3.18). The sink composite is a cumulative representation of all the sinks and corresponds to the upper bound on their feasibility region.
4. Represent each source as an arrow by plotting the load of each source versus its flowrate. The load of the ith source is calculated through:

   $$M_i^{Source} = W_i y_i \tag{3.60}$$

   Start with the source having the least composition of impurities and place its arrow tail anywhere on the horizontal axis. As will be shown later, it is irrelevant where this arrow tail is placed. Continue with the other sources and use superposition as shown in Fig. 3.19 to create a ***source composite curve***. The source composite curve is a cumulative representation of all process streams considered for recycle. Now, we have the two composite curves on the same diagram (Fig. 3.20).
5. Move the source composite stream horizontally till it touches the sink composite stream with the source composite below the sink composite in the overlapped region. The point where they touch is the material recycle pinch point (Fig. 3.21). The flowrate of sinks below which there are no sources is the target for minimum fresh usage. The flowrate in the overlapped region of process sinks and sources represents the directly-recycled flowrate. Finally, the flowrate of the sources above which there are no sinks is the target for minimum waste discharge. Those targets are shown on Fig. 3.22.

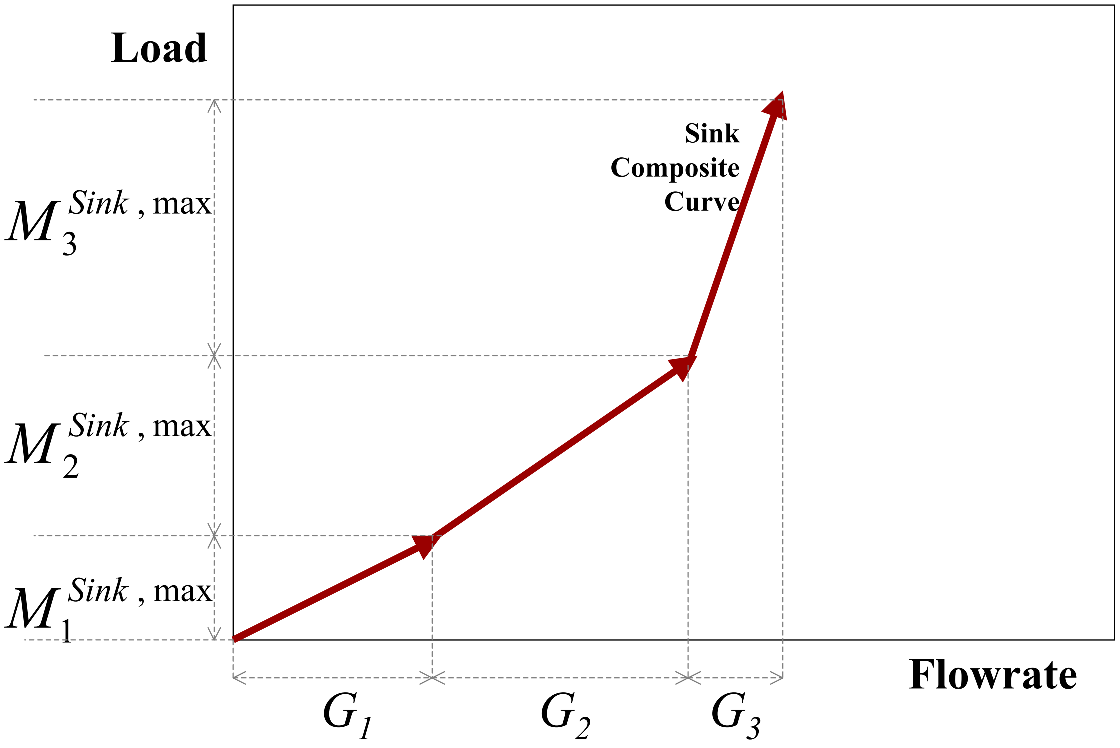

Figure 3.18: Developing Sink Composite Diagram

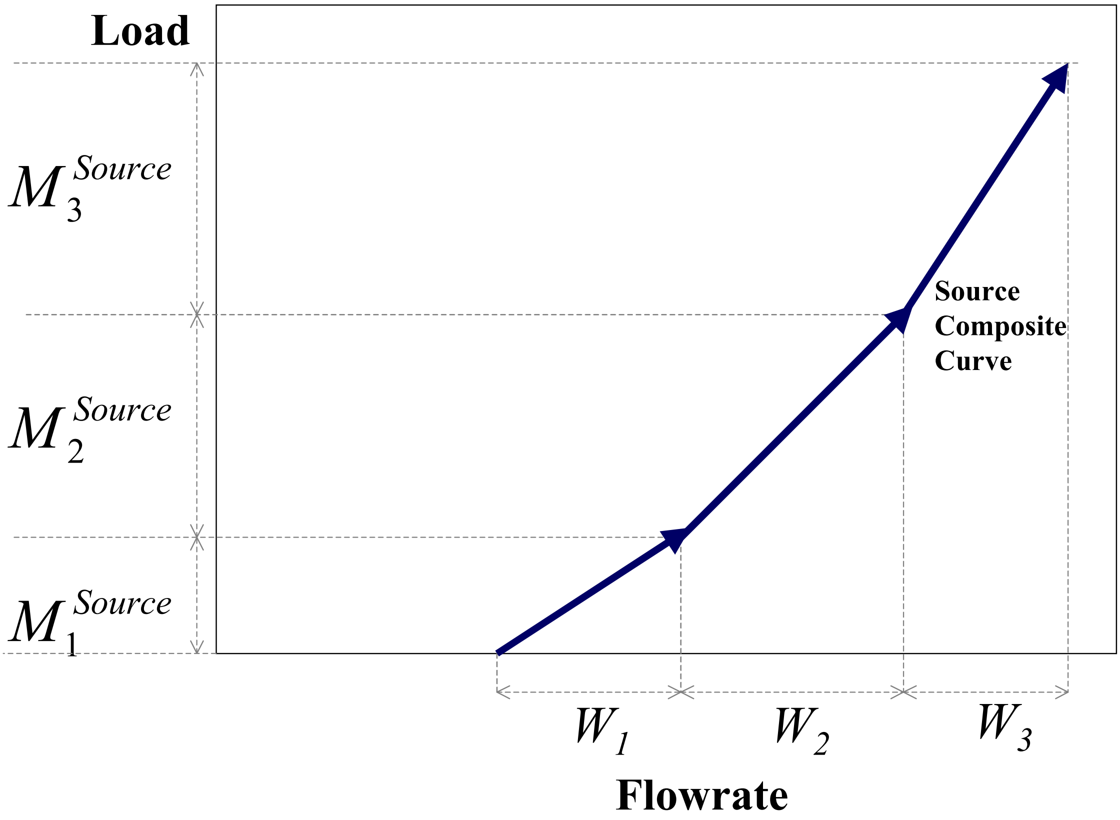

Figure 3.19: Developing Source Composite Diagram

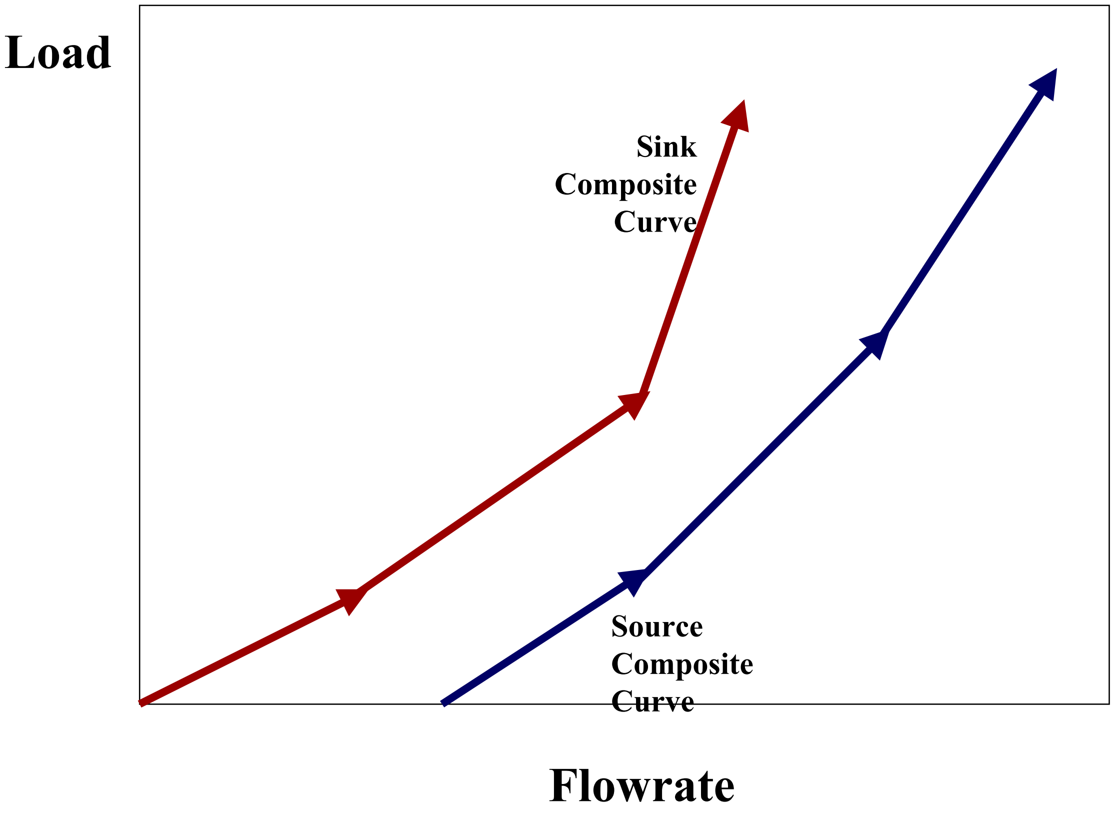

Figure 3.20: Sink and Source Composite Diagrams

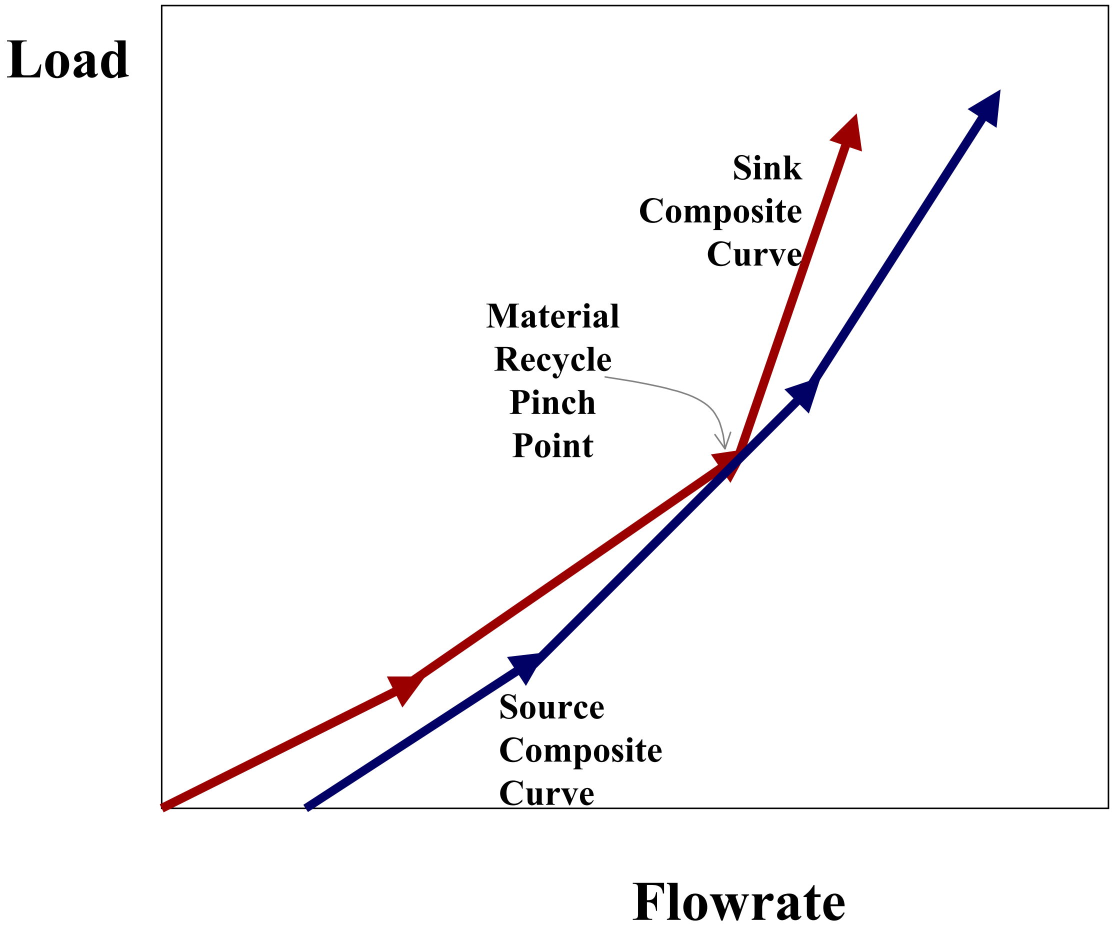

Figure 3.21: Material Recycle Pinch Diagram (El-Halwagi et al., 2003)

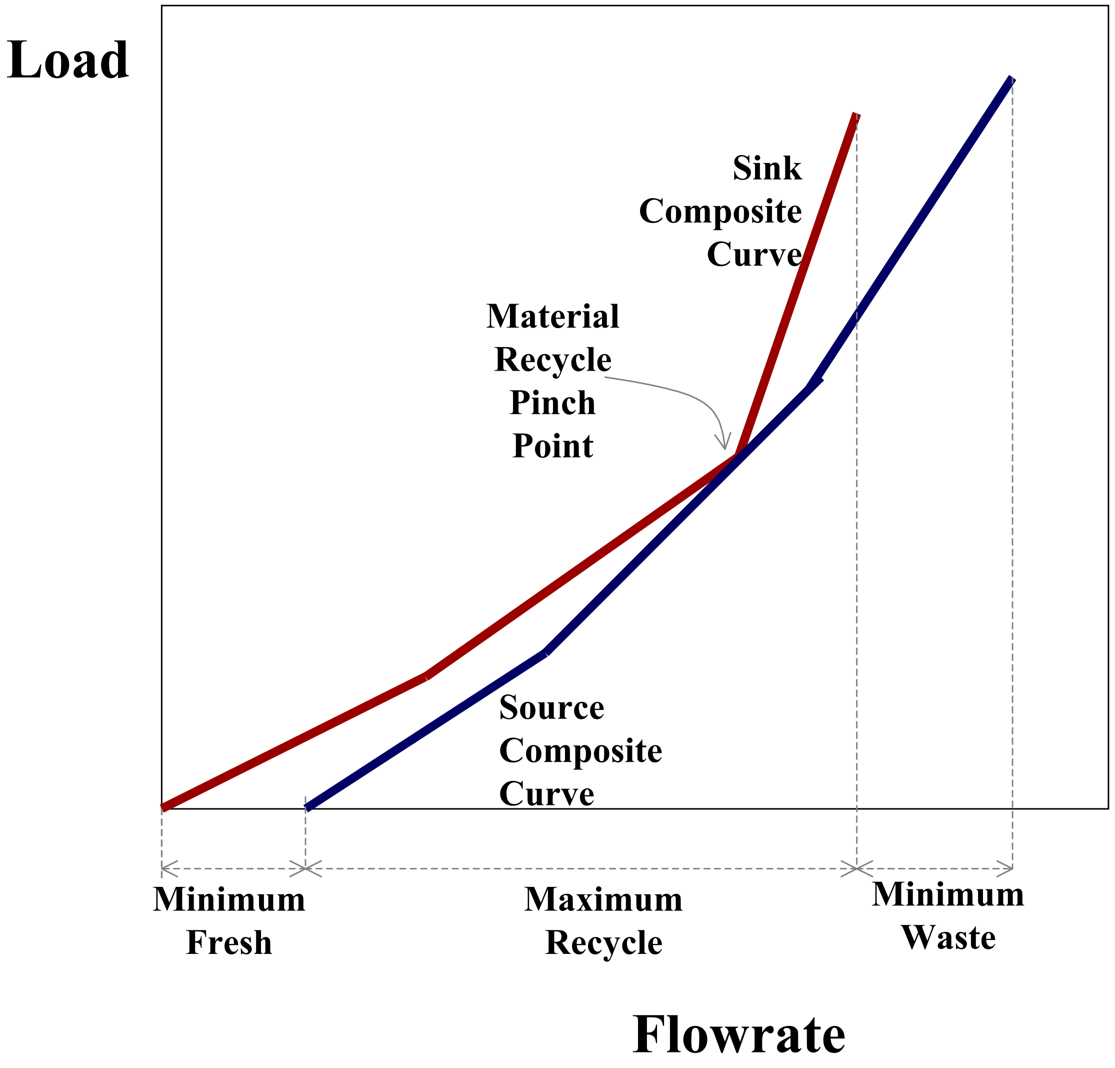

Figure 3.22: Identifying Targets for Minimum Fresh Usage, Maximum Direct Recycle, and Minimum Waste Discharge (El-Halwagi et al., 2003)

DESIGN RULES FROM THE MATERIAL-RECYCLE PINCH DIAGRAM

A key insight can be observed from the material-recycle pinch diagram. The pinch point distinguishes two zones. Below that point, fresh resource is used in the sinks while above that point unused process sources are discharged. The primary characteristic for the pinch point is based on the following observation: the pinch point is the point where the load of recycled/reused sources match that of the sink. Hence, it corresponds to the most constrained point in the recycle system. If the two composite curves are not touched at the pinch (e.g., by moving the source composite to the left, thereby passing a flowrate of α through the pinch), the fresh usage and waste discharge are both increased by the same magnitude of the flowrate passed through the pinch (α). Additionally, the extent of recycled flowrate is also reduced by the same magnitude (α) as shown by Fig. 3.23. On the other hand, if we move the source composite to the left of the pinch, a portion of the source composite will lie above the sink composite thereby leading to the violation of constraint (3.57). This situation is shown in Fig. (3.24).

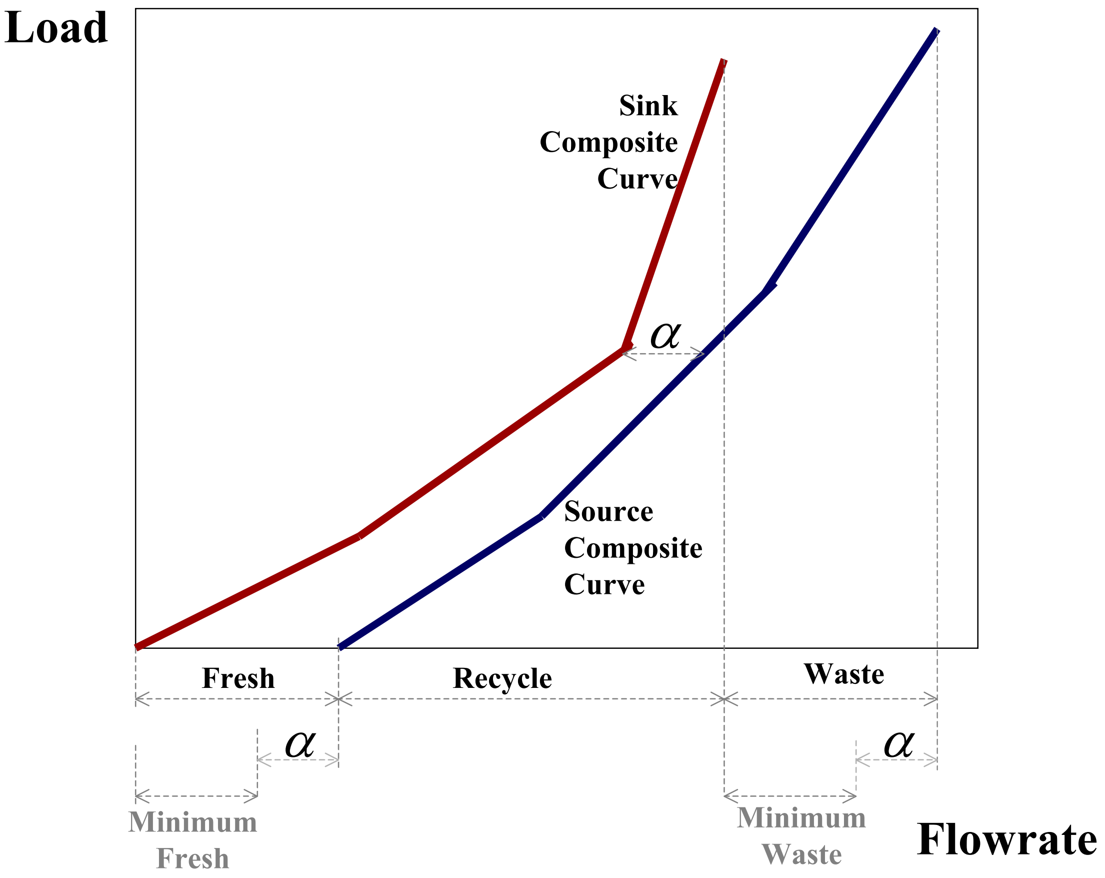

Figure 3.23: Passing Flowrate (α) through the Pinch Point Leads to Less Integration

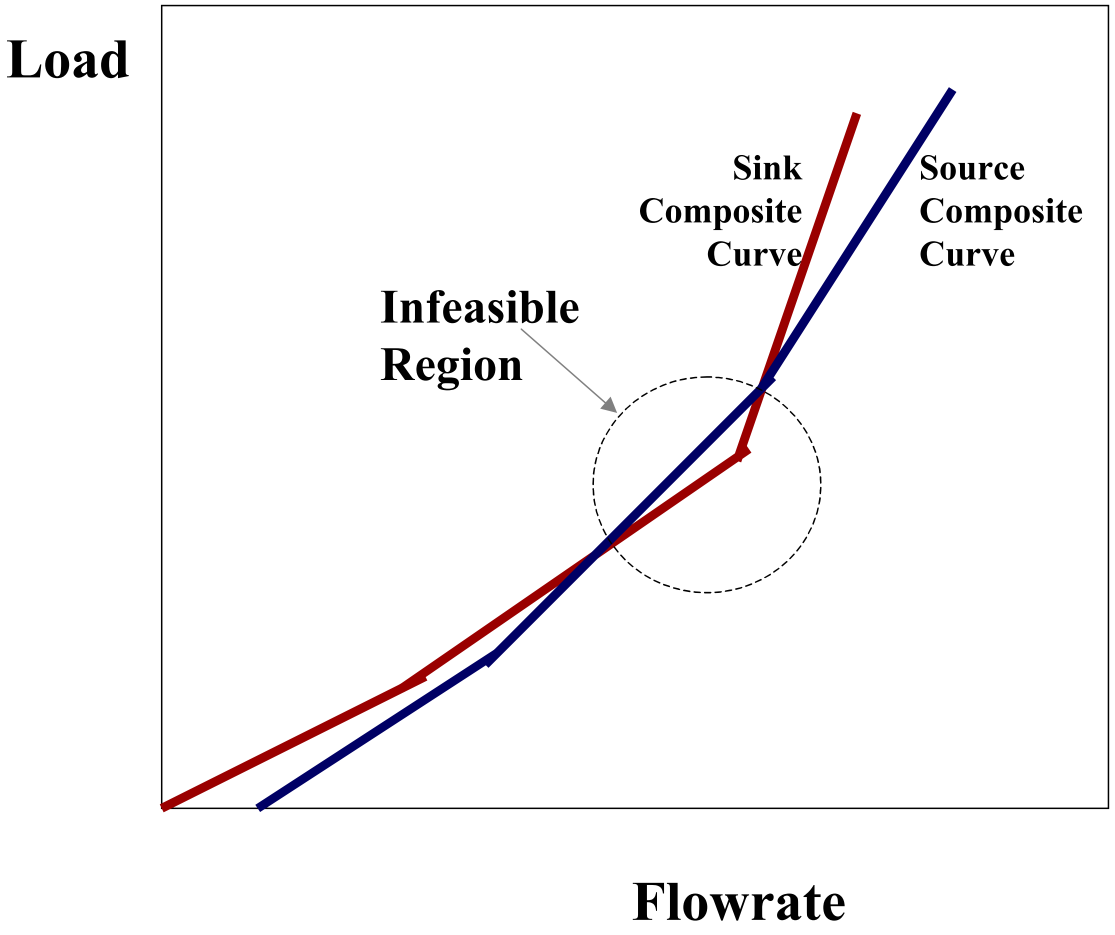

Figure 3.24: Violating Pinch Point Leads to Infeasibility

The above discussion indicates that in order to achieve the minimum usage of fresh resources, maximum reuse of the process sources, and minimum discharge of waste, the following ***three design rules*** are needed:

- *No flowrate should be passed through the pinch (i.e. the two composites must touch)*
- *No waste should be discharged from sources below the pinch*
- *No fresh should be used in any sink above the pinch*

The targeting procedure identifies the targets for fresh, waste and material reuse without commitment to the detailed design of the network matching the sources and sinks. In detailing the solution, there can be more than one solution satisfying the identified targets. Those solutions can be identified using the source-sink mapping diagram. To compare the multiple solutions having the same target of fresh usage and waste discharge, other objectives should be used (e.g. capital investment, safety, flexibility, operability, etc.).

EXTENSION TO CASE OF IMPURE FRESH

The same targeting procedure can be extended for cases when the fresh resource is impure. In the case of pure fresh, the source composite curve was slid on the horizontal axis. The reasin for this is that with no impurities in the fresh, it does not contribute the load of impurities regardless of how much flowrate of fresh is used. Consequently, the horizontal axis serves as a locus for the fresh resource. When the fresh is impure but cleaner than the rest of the sources, its locus becomes a straight line emanating from the origin and having a slope of y_{Fresh} (composition of impurities in the fresh). Hence, the source composite curve is slid on the fresh locus until it touches the sink composite while lying below it in the overlapped region. This case is shown by Fig. 3.25. If the fresh resource was not the source with the least composition of impurities, the same procedure can be adopted by ranking the sources in ascending order of composition and placing the locus of the fresh at its proper rank.

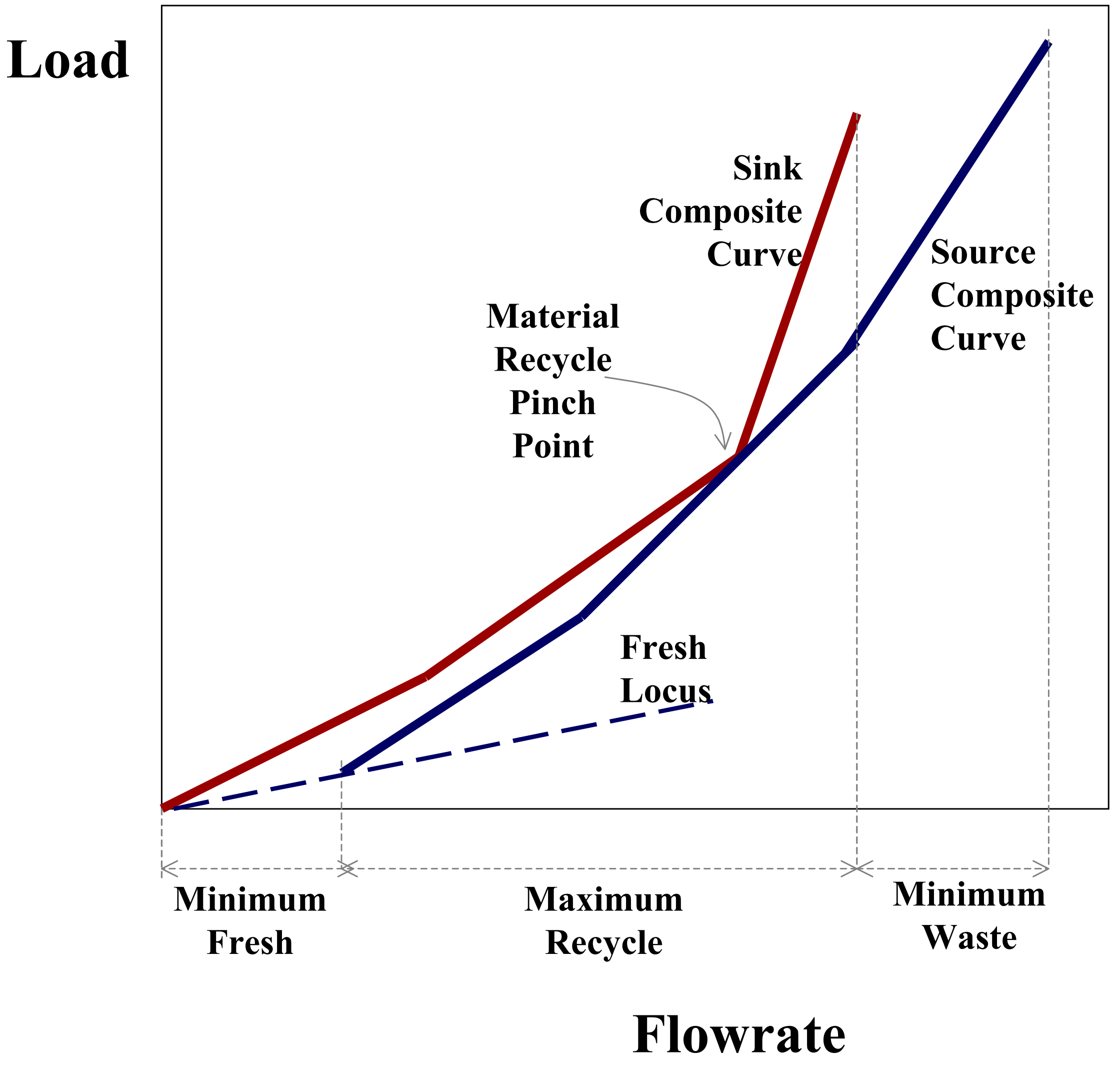

Figure 3.25: Material Recycle Pinch Diagram when Fresh Resource is Impure

INSIGHTS ON PROCESS MODIFICATIONS

The material-recycle pinch diagram and the associated design rules can be used to guide the engineer in making process modifications to enhance material reuse; for instance, the observation that below the pinch there is deficiency of recyclable sources, whereas above the pinch there is a surplus of sources. Therefore, sinks can be moved from below the pinch to above the pinch and sources can be moved from above the pinch to below the pinch to reduce the usage of fresh resources and the discharge of waste. Moving a sink from below the pinch to above the pinch can be achieved by increasing the upper bound on the composition constraint of the sink given by inequality (3.55). Conversely, moving a source from above the pinch to below the pinch can be accomplished by reducing its composition through changes in operating conditions or by adding an "interception" device (e.g., separator, reactor, etc.) that can lower the composition of impurities. The design of interception networks will be handled in several chapter in this book. Figure 3.26a illustrates an example when a flowrate β is intercepted to reduce its content of impurities down to a composition similar to that of the fresh. Therefore, this flowrate is moved from above the pinch to below the pinch. Compared to the nominal case without interception, two benefits accrue as a result of this movement across the pinch: both the usage of fresh resource and the discharge of waste are reduced by β.

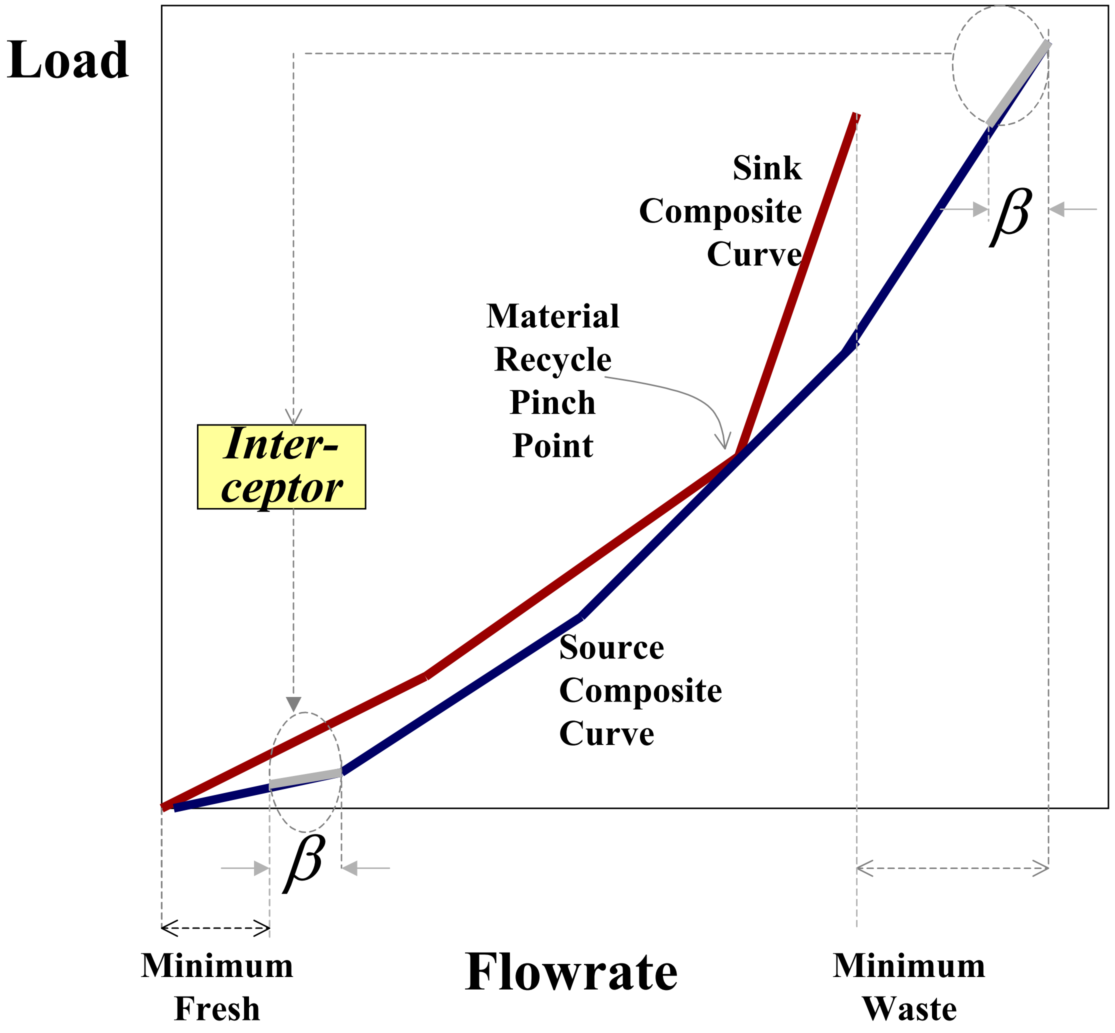

Fig. 3.26a. Insights for Process Modification: Moving a Source across the Pinch

Another alternative is to reduce the load of a source below the pinch (again by altering operating conditions or adding an interception device). Consequently, the cumulative load of the source composite decreases and allows an additional recycle of process sources with the result of decreasing both the fresh consumption and waste discharge. Figure 3.26b illustrates the material-recycle pinch diagram before interception. Then, the second source is intercepted to remove the load protruding above the pinch. As the intercepted load is removed, the slope of the second source decreases. The new slope is the composition of the intercepted source.

Consequently, the source composite curve can be slid to the left to reduce (or in this case to eliminate) the use of fresh resource as shown in Fig. 3.26c.

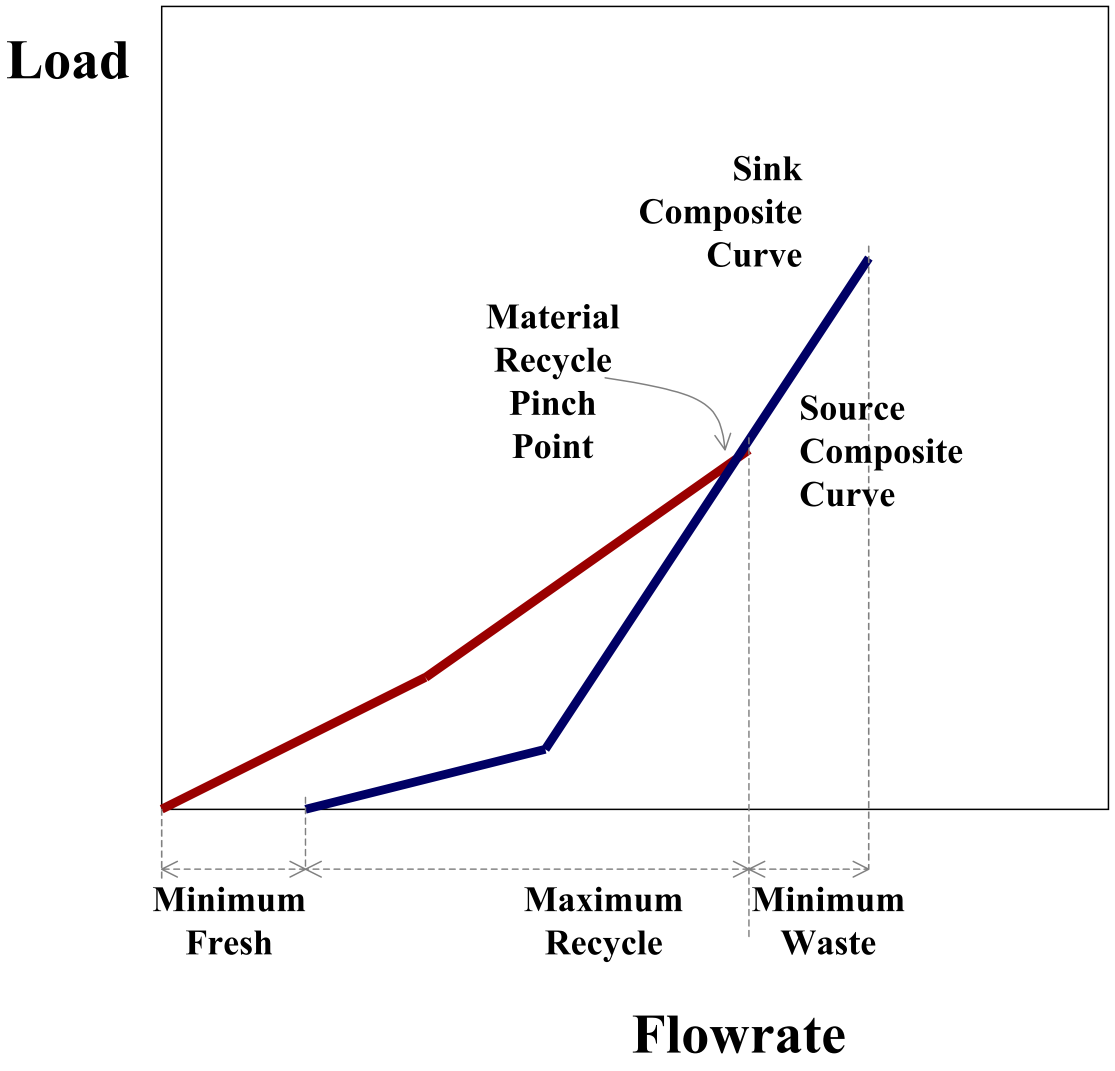

Fig. 3.26b. Example of a Material-Reuse Pinch Diagram before Interception

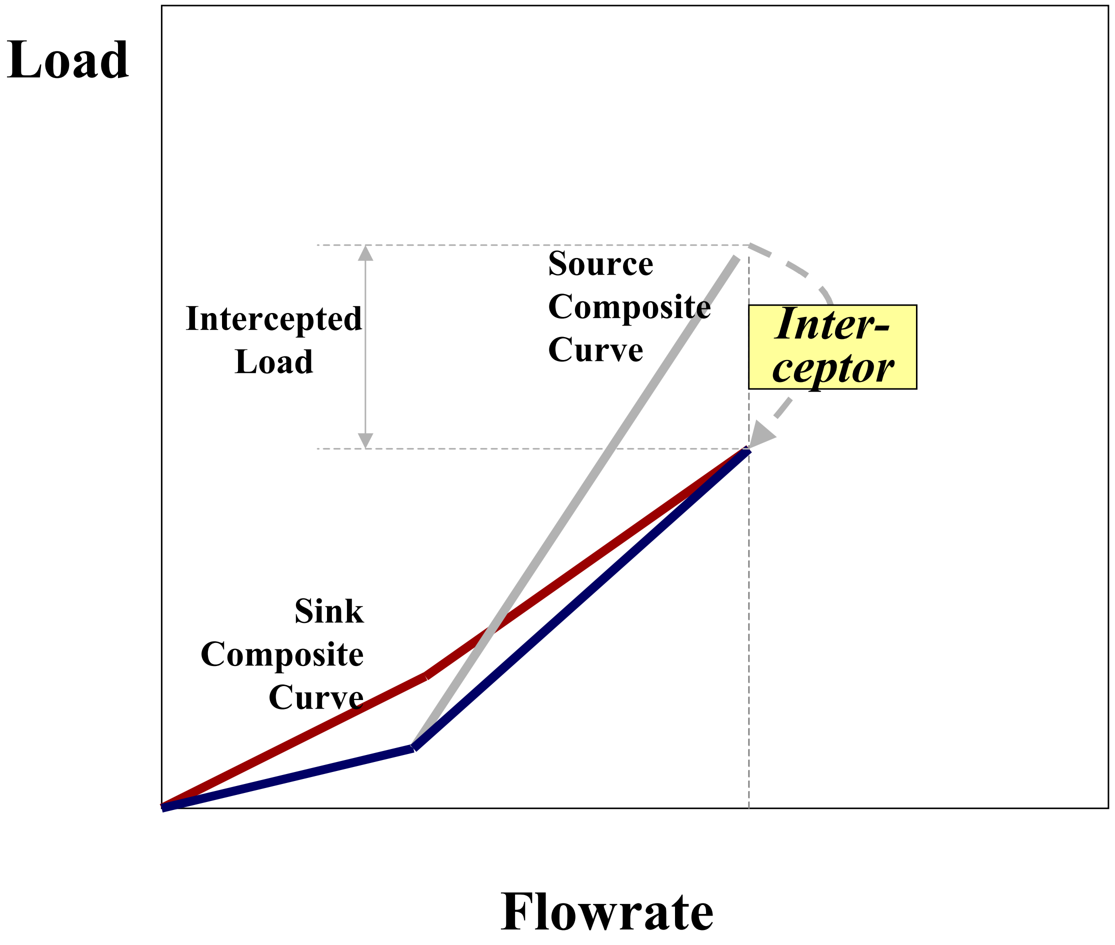

Fig. 3.26c. Insights for Process Modification: Lowering the Slope of Second Source through Interception

EXAMPLE 3.4. TARGETING FOR THE VINYLA ACETATE CASE STUDY

Let us revisit the vinyl acetate case study described earlier in Example 3.2. The relevant problem data are summarized in Tables 3.1 and 3.2. The sinks and sources are ranked in ascending order of composition. Next, the sink and source composite curves are constructed as shown in Figs. 3.27 and 3.28. Next, the source composite curve is slid horizontally to the right till it touches the sink composite curve. The material reuse pinch diagram is shown by Fig. 3.29. The targets for minimum fresh usage and minimum waste discharge are found to be $9.6\text{x}10^3$ and

4.8×10^3 kg/hr, respectively. These are the same results obtained by the detailed design of the source sink mapping diagram as shown in the results of Fig. 3.17.

Table 3.1. Sink Data for the Vinyl Acetate Example

Sink	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Absorber I	5,100	0.05	255
Acid Tower	10,200	0.10	1,020

Table 3.2. Source Data for the Vinyl Acetate Example

Source	Flowrate kg/hr	Inlet Mass Fraction	Inlet Load, kg/hr
Bottoms of Absorber II	1,400	0.14	196
Bottoms of Primary Tower	9,100	0.25	2,275

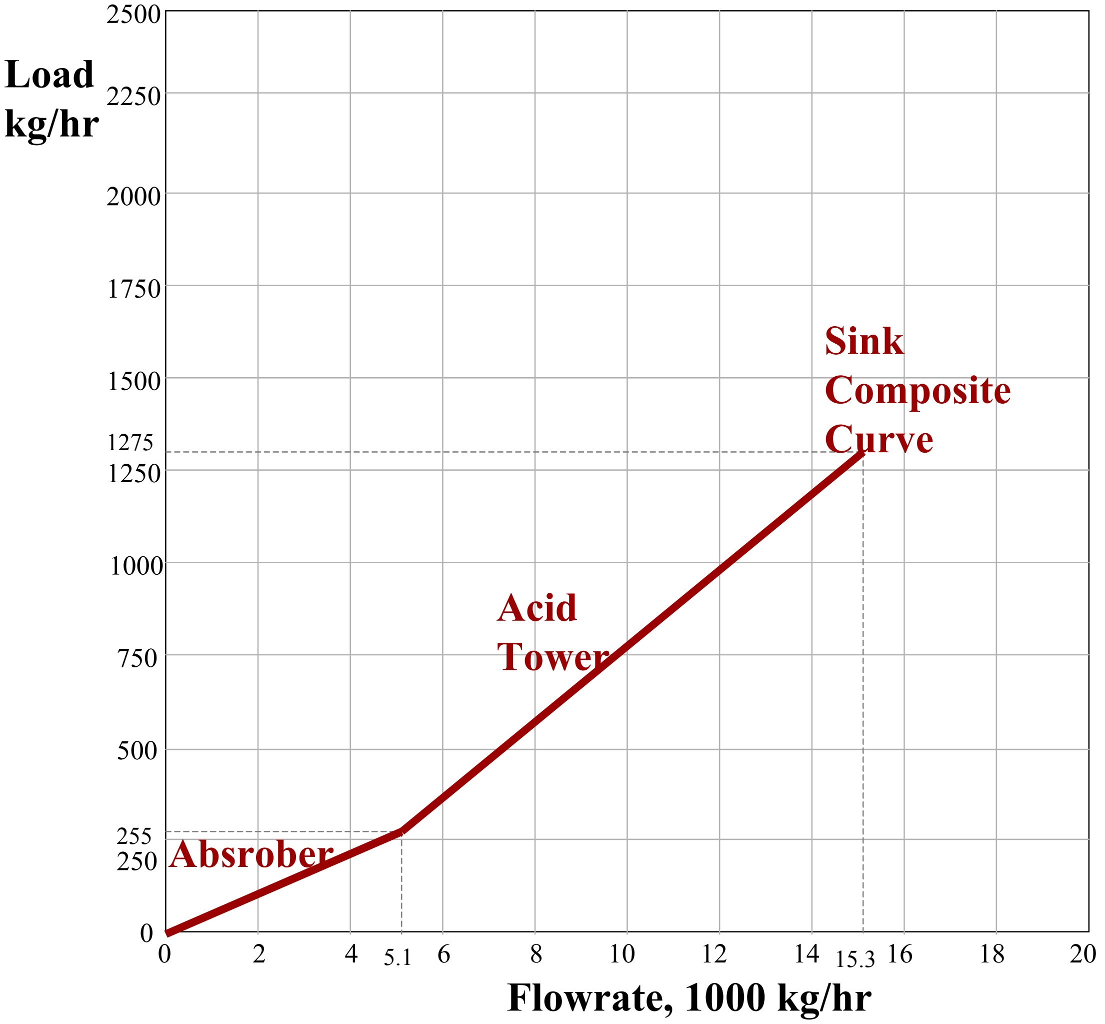

Fig. 3.27. Sink Composite Curve for the Vinyl Acetate Case Study

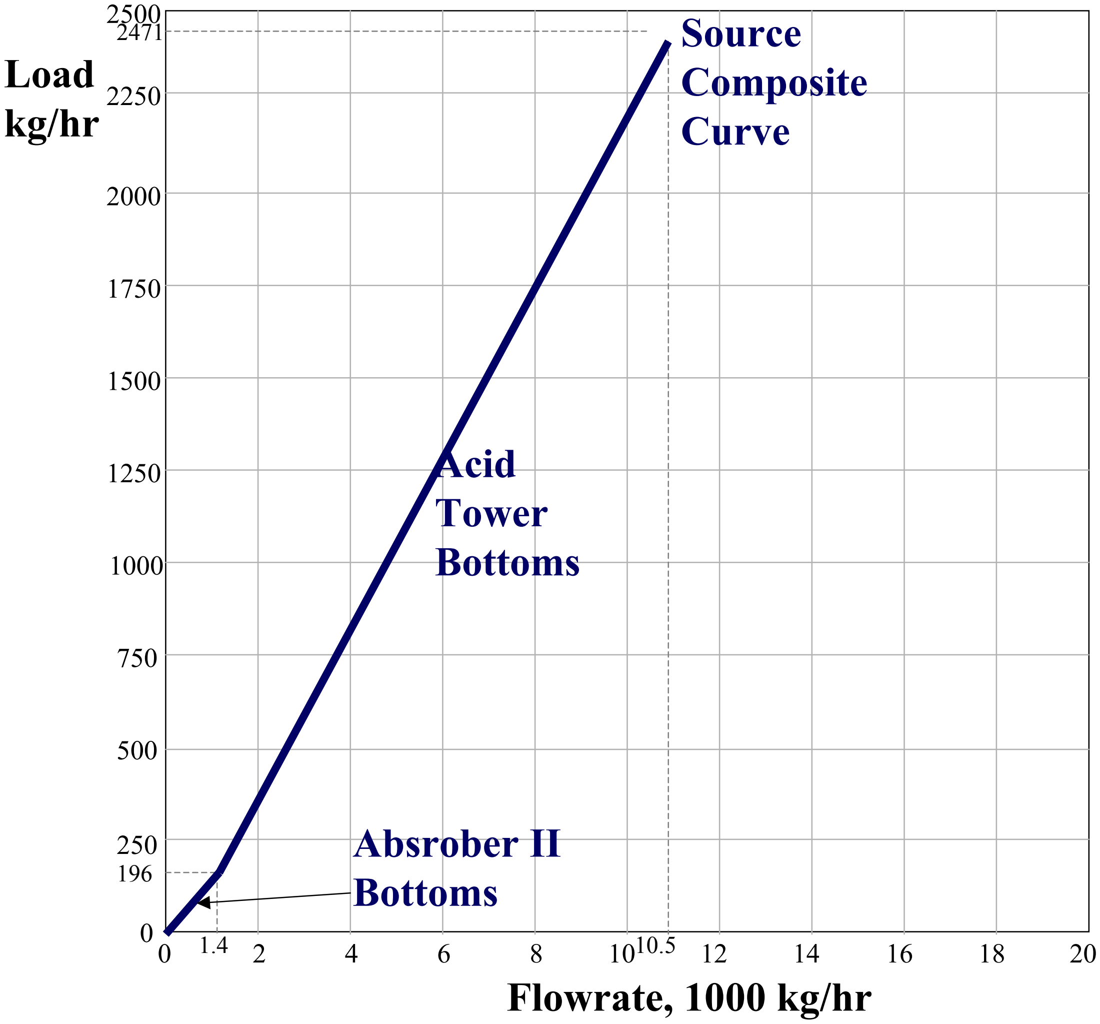

Fig. 3.28. Source Composite Curve for the Vinyl Acetate Case Study

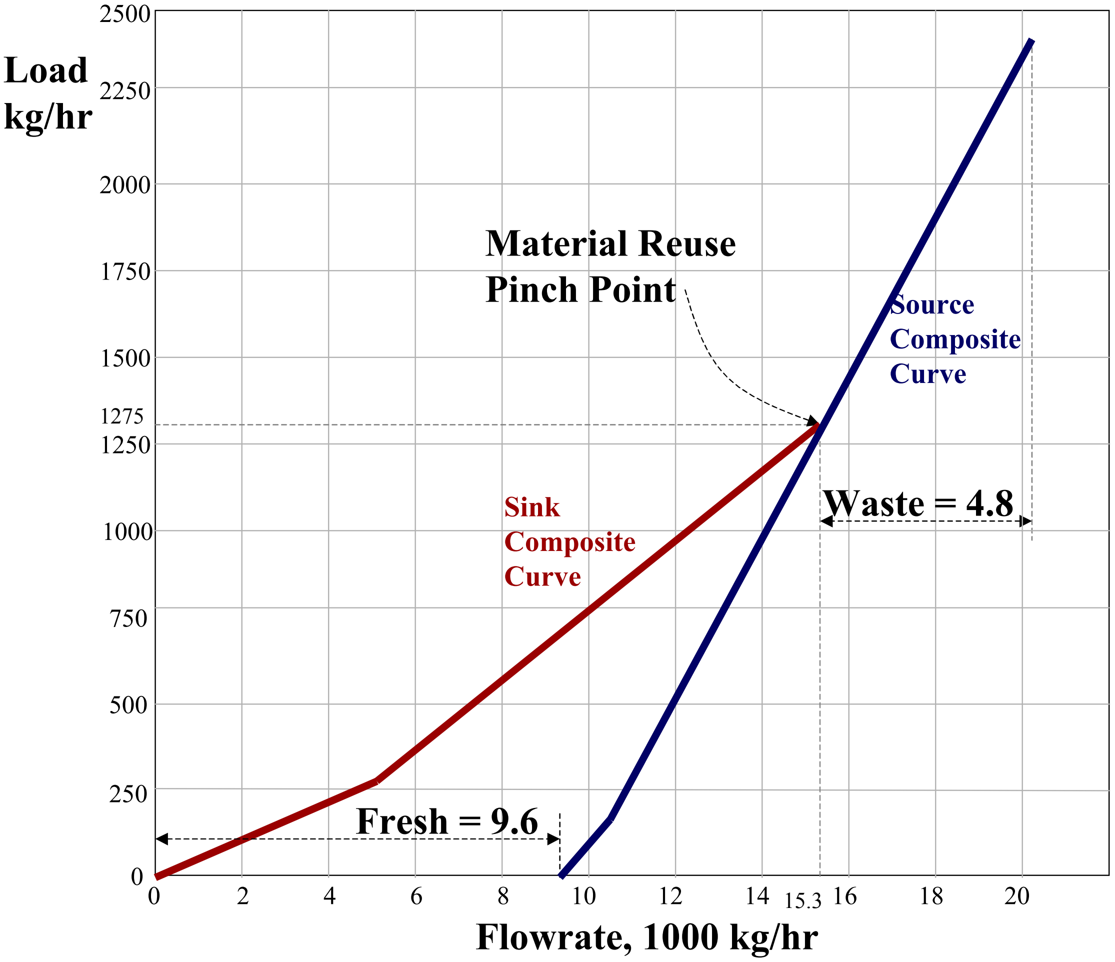

Fig. 3.29. Material-Reuse Pinch Diagram for the Vinyl Acetate Case Study

EXAMPLE 3.5. HYDROGEN RECYCLE IN A REFINERY.

Hydrogen is a critical commodity in a petroleum refinery. Alves and Towler (2002) describe a case study involving the optimization of a hydrogen distribution system within a refinery, and it is comprised of four sinks and six sources. The pertinent information regarding these sinks and sources can be seen in Tables 3.3. and 3.4.

Table 3.3. Sink Data for Hydrogen Problem (Alves and Towler, 2002)

Sinks	Flow (mol/s)	Maximum Inlet	Load

		Impurity Concentration (mol %)	**(mol/s)**
1	2495	19.39	483.8
2	180.2	21.15	38.1
3	554.4	22.43	124.4
4	720.7	24.86	179.2

Table 3.4. Source Data for the Hydrogen Problem (Alves and Towler, 2002)

Sources	**Flow (mol/s)**	**Impurity Concentration (mol %)**	**Load (mol/s)**
1	623.8	7	43.7
2	415.8	20	83.2
3	1801.9	25	450.5
4	138.6	25	34.7
5	346.5	27	93.6
6	457.4	30	137.2

In this case study, the fresh hydrogen is available with a 5 mol/mol% impurity content. Identify the target for minimum usage of fresh hydrogen and minimum discharge of gaseous waste.

Solution:

Using the information in Tables 3.3 and 3.4, and by plotting a locus for fresh hydrogen (slope being 0.05), the material recycle pinch diagram can be developed and the sopurce composite curve is slid on the fresh locus. The results are shown in Fig. 3.30.

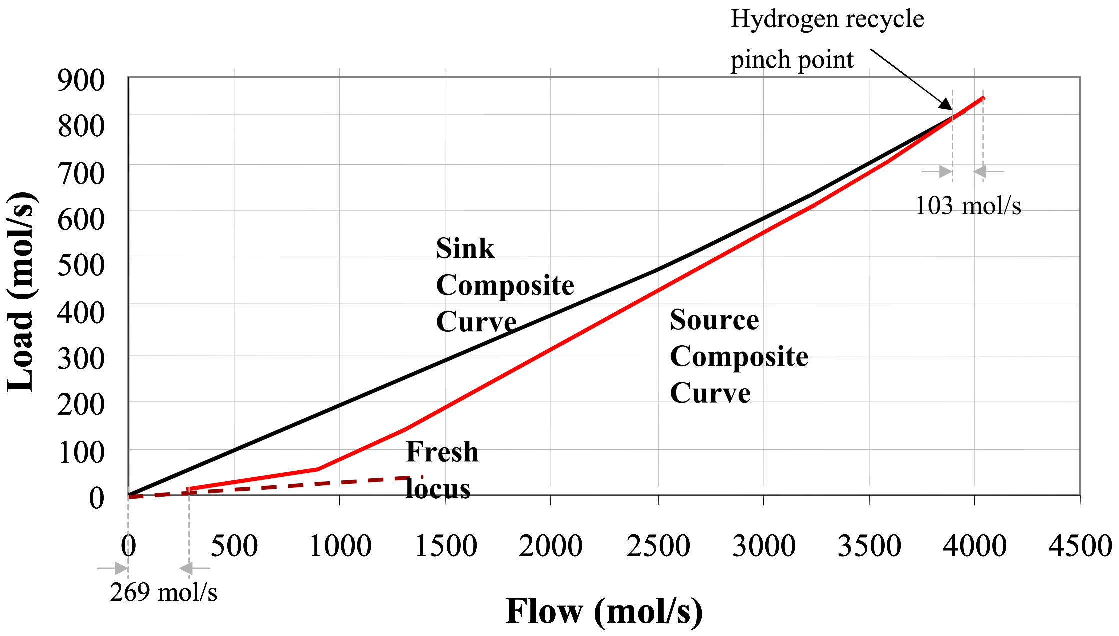

Figure 3.30. Hydrogen Reuse Pinch Diagram (El-Halwagi et al., 2003)

From Fig. 3.30, the minimum hydrogen required and waste hydrogen to be discharged are 269 mol/s and 103 mol/s respectively.

EXAMPLE 3.6. WATER RECOVERY IN A FOOD PROCESS

Consider the food processing plant shown in the simplified flowsheet of Fig. 3.31. The primary feedstocks are first pre-washed then processed throughout the facility. The gaseous waste of the process is cleaned in a water scrubber prior to discharge. Therefore, the process has two sinks that consume fresh water: the washer and the scrubber. Table 3.5 provides the data for these two sinks. The process results in two aqueous streams that are sent to biotreatment but may be considered for recycle: condensate I from the evaporator and condensate II from the stripper. The data for the two process sources are given in Table 3.6.

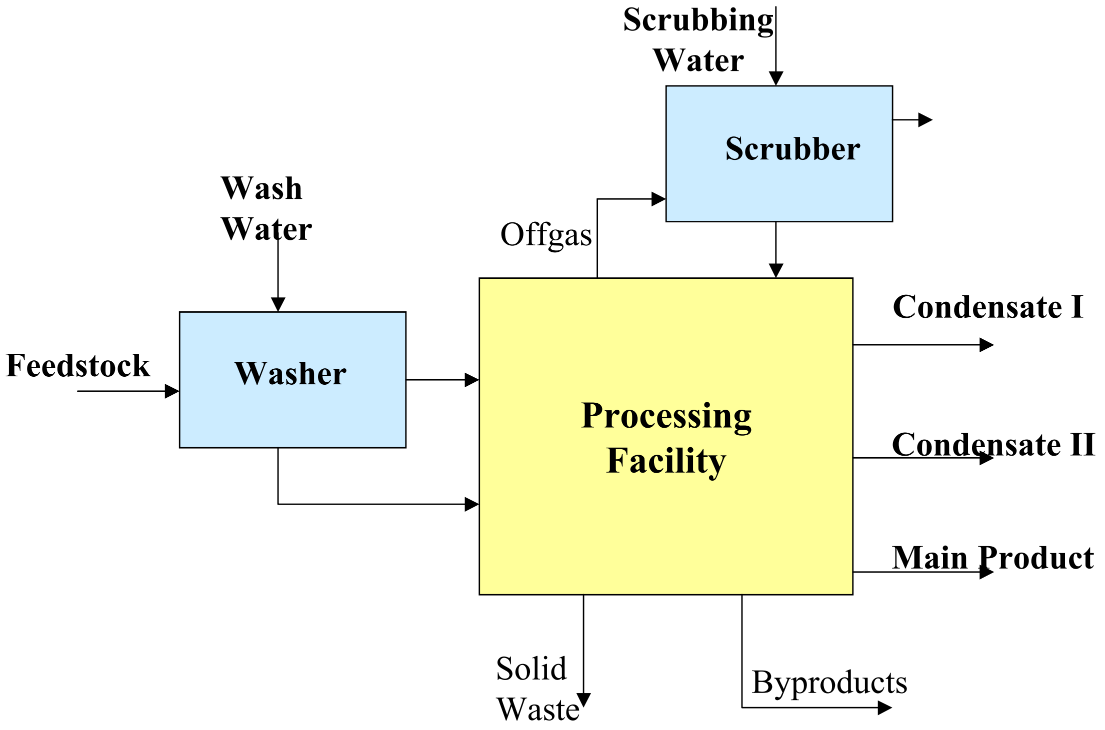

Fig. 3.31. A Simplified Flowsheet of the Food Processing Plant

Table 3.5. Sink Data for the Food Processing Example

Sink	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Washer	8,000	0.03	240
Scrubber	10,000	0.05	500

Table 3.6. Source Data for the Food Processing Example

Source	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Condensate I	10,000	0.02	200
Condensate II	9,000	0.09	810

At present, the plant uses fresh water for the washer and the scrubber. In order to reduce the usage of fresh water and discharge of wastewater (condensate), the plant has decided to adopt direct-recycle strategies. An engineer has proposed that Condensate I be recycled to the scrubber (Fig. 3.32). The result of this project is to eliminate the need for fresh water in the scrubber, reduce overall fresh water consumption to 8,000 kg/hr, and reduce wastewater discharge (Condensate II) to 9,000 kg/hr. Critique this proposed project.

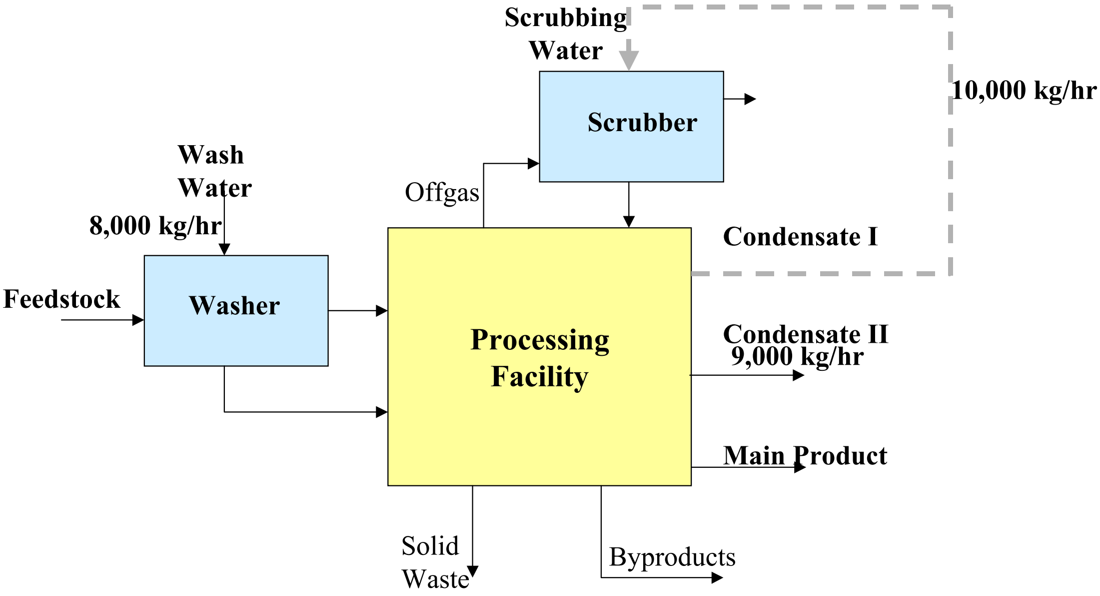

Fig. 3.32. Proposed Recycle Project

Solution:

Before examining the details of recycle strategies, it is beneficial to establish the targets for minimum water usage and discharge. These benchmarks are obtained from the material-recycle pinch diagram shown in Fig. 3.33. As can be seen from the pinch diagram, the target for minimum fresh water usage is 2,000 kg/hr while the target for minimum wastewater discharge is

3,000 kg/hr[2]. Since these targets are much better than the proposed solution, we need to closely examine the suggested recycle strategy.

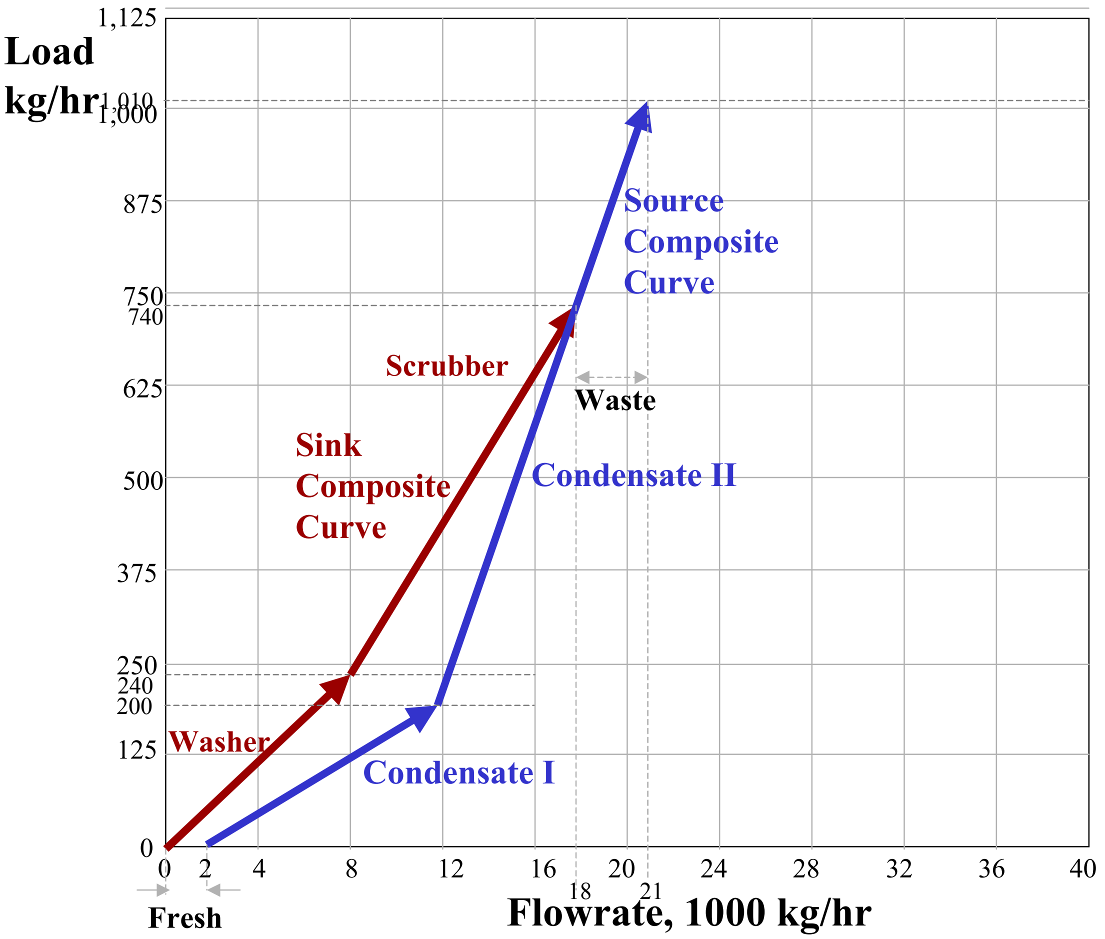

Fig. 3.33 Pinch Diagram for Food Processing Example (Targets for Fresh and Waste are 2,000 and 3,000 kg/hr, respectively)

Next, we represent the proposed solution on the material-recycle pinch diagram as shown in Fig. 3.34. Since Condensate I is matched with the scrubber, it is plotted directly below the

---

[2] It is worth noting that in this problem, there are infinite recycle strategies that satisfy the targets for minimum fresh usage and minimum waste discharge. Can you identify some of these alternatives?

scrubber. This is a feasible solution since the flowrate is satisfied and the load of Condensate I is less than the maximum admissible load for the scrubber. However, we notice that this solution results in passing 6,000 kg/hr through the pinch. Therefore, we expect to see a 6,000 kg/hr increase in fresh usage and waste discharge. Indeed, this is the case (fresh water usage is 8,000 kg/hr compared to the target of 2,000 kg/hr and waste discharge of 9,000 kg/hr compared to the target of 3,000 kg/hr). Additionally, we notice that proposed recycle does not follow the sink-composition rule which calls for the maximization of the inlet composition to the sink (the proposed solution has the inlet to the scrubber being 2% as compared to 5%).

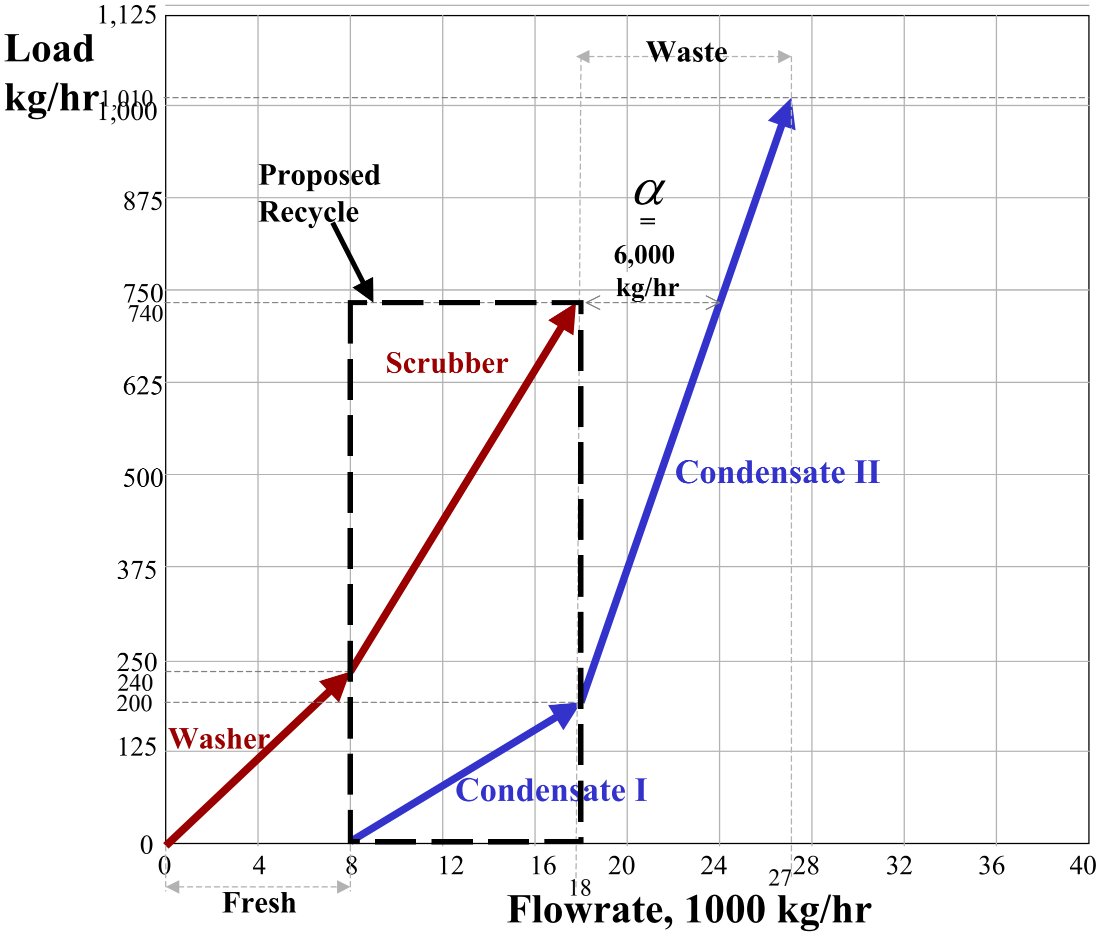

Fig. 3.34. Representation of Proposed Recycle on Pinch Diagram (Proposed Project Results in Passing 6,000 kg/hr through the Pinch)

The above discussion indicates that the proposed project should not be implemented. Instead, an integrated solution consistent with the identified targets (Fig. 3.33) should be recommended. Nonetheless, if the engineer insists on implementing the proposed recycle project, there is still an opportunity to improve upon this situation. The fact that the concentration of impurities in Condensate II is higher than the admissible concentration to the washer does not prevent us from pursuing partial recycle. Figure 3.35 is the pinch diagram for the remaining source and sink in the problem. As can be seen from the diagram, if Condensate I is used in lieu of the scrubber water, then the target for the remaining source (Condensate II) and sink (Washer) is 5,300 kg/hr in fresh water usage and 6,300 kg/hr in wastewater discharge. The foregoing discussion underscores the importance of ensuring that a short-term project be compatible with an overall integrated strategy. An individual project which is seemingly flawless may be detrimental to the overall performance of the whole process and may prevent the process from ever reaching its true target. Finally, a big-picture approach such as the material recycle pinch diagram yields insights that may not be seen by detailed engineering focusing on individual units and streams.

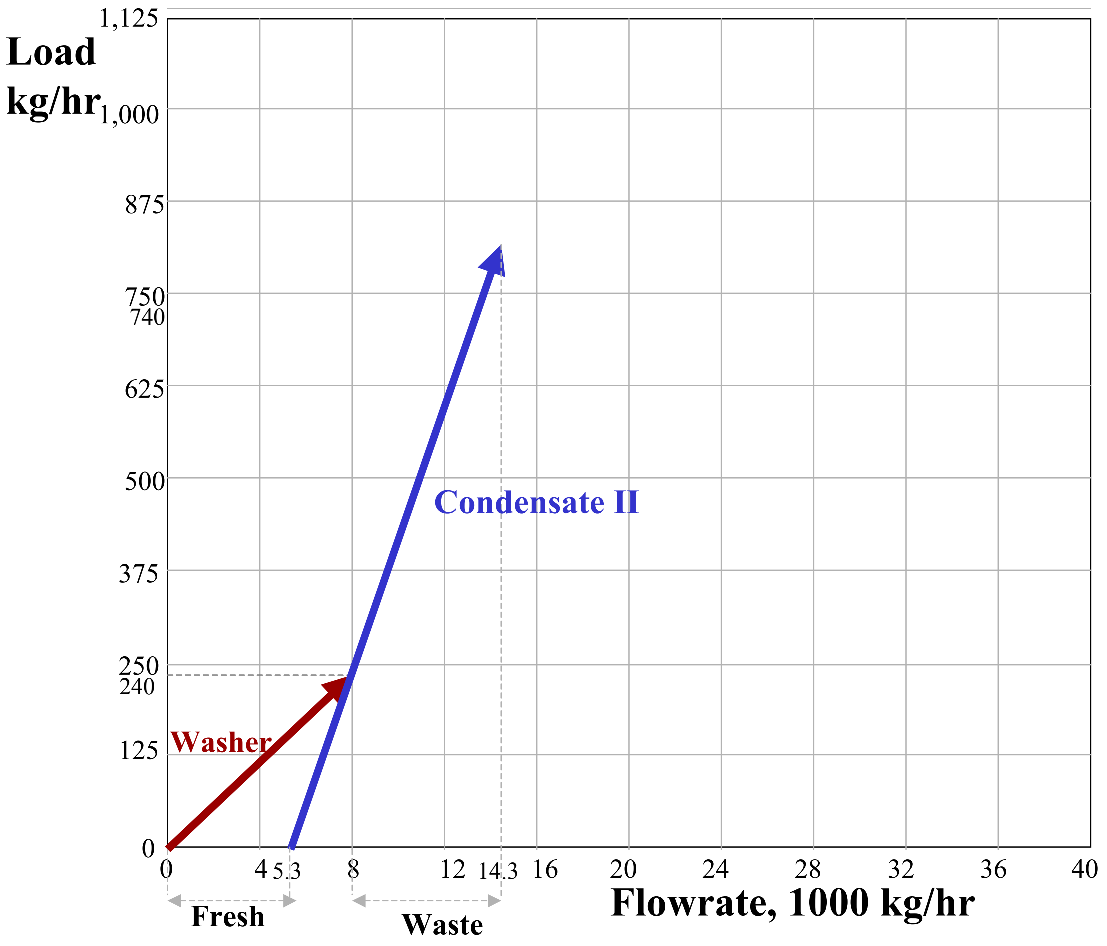

Fig. 3.35 Pinch Diagram if Condensate I and the Scrubber are Taken Out of the Problem (Targets for Fresh and Waste are 5,300 and 6,300 kg/hr, respectively)

MULTICOMPONENT SOURCE-SINK MAPPING DIAGRAM

The source-sink diagram can be extended to represent ternary (three-component) systems. Figure 3.36 is a ternary diagram for components A, B, and C. Each apex of the equilateral triangle represents 100% of a component. The opposite base corresponds to 0% of that component. Each line parallel to the base is a locus of a constant percentage of that component. Figure 3.36 shows the loci for various percentages of component A. The horizontal base of the triangle is the locus of any stream containing 0% of A. The other horizontal lines show the loci for compositions ranging from 10 to 90% A. Figure 3.37 illustrates the representation of a source containing 20% A, 30% B, and 50% C. Clearly, it is sufficient to represent the loci of two compositions (e.g., 20% A and 30% B) and locate the source at their intersection. The third composition is determined by passing a line parallel to the 0%-C base through the source.

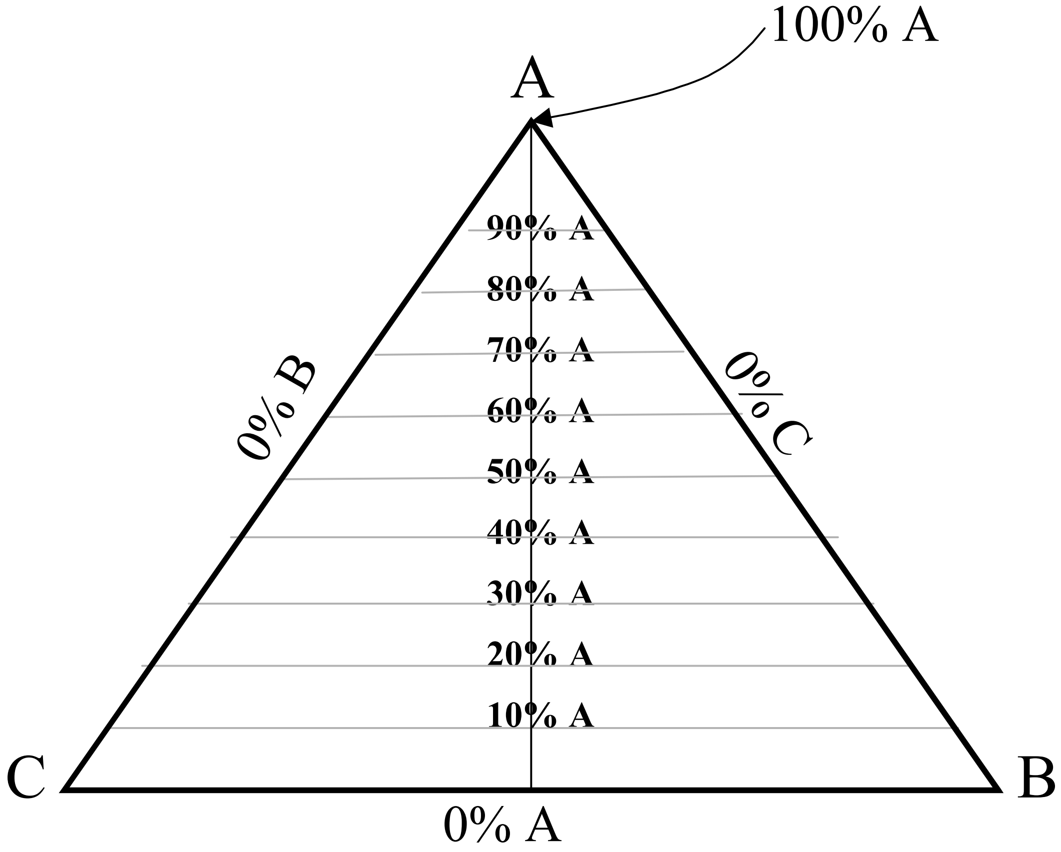

Fig. 3.36 Ternary Composition Representation

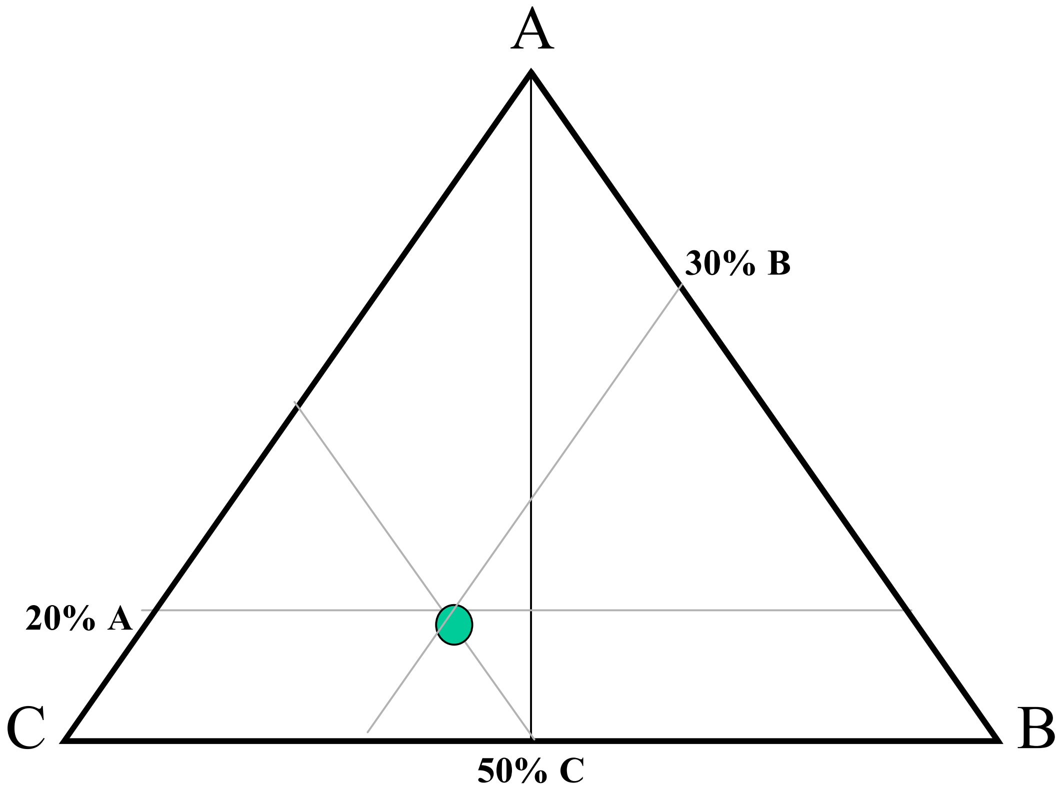

Fig. 3.37 Representation of a Ternary Mixture

Composition constraints in the sinks can be represented on the ternary diagram. For instance, consider a sink with the following constraints:

0.30 ≤ mass fraction of A in stream entering the sink ≤ 0.70 (3.61a)

0.20 ≤ mass fraction of B in stream entering the sink ≤ 0.50 (3.61b)

0.10 ≤ mass fraction of C in stream entering the sink ≤ 0.60 (3.61c)

The sink constraints are represented by Fig. 3.38. Any point within the shaded region is a feasible feed to the sink. The ternary source-sink diagram has the same rules as the sink optimality and source prioritization (e.g., Parthasarathy and El-Halwagi, 2000). For instance, when two process sources i and i+1 are considered for recycle by mixing with a fresh resource, the lever arms should be first calculated. As can be seen from Fig. 3.39, the lever arm rules can be expressed as follows:

$$\frac{\text{Fresh usage when source i is recycled}}{\text{Feed flowrate of sink}} = \frac{\beta_{F,i}}{\beta_{F,i} + \beta_i}$$

and

$$\frac{\text{Fresh usage when source i + 1 is recycled}}{\text{Feed flowrate of sink}} = \frac{\beta_{F,i+1}}{\beta_{F,i+1} + \beta_{i+1}}$$

Since source i has a shorter relative arm than that of i+1, it should be used first. Source i+1 is only used after source i has been completely recycled. This is the same concept used in source prioritization previously described in the single-component source-sink representation.

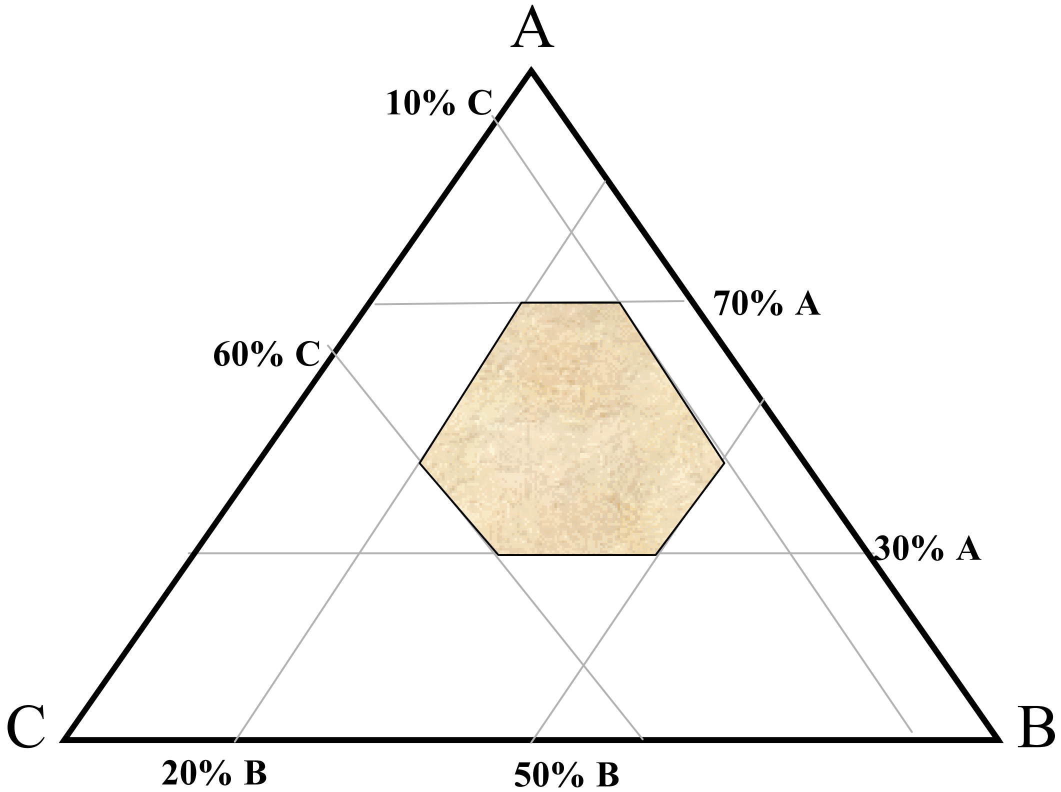

Fig. 3.38 Representation of a Sink with Ternary Constraints

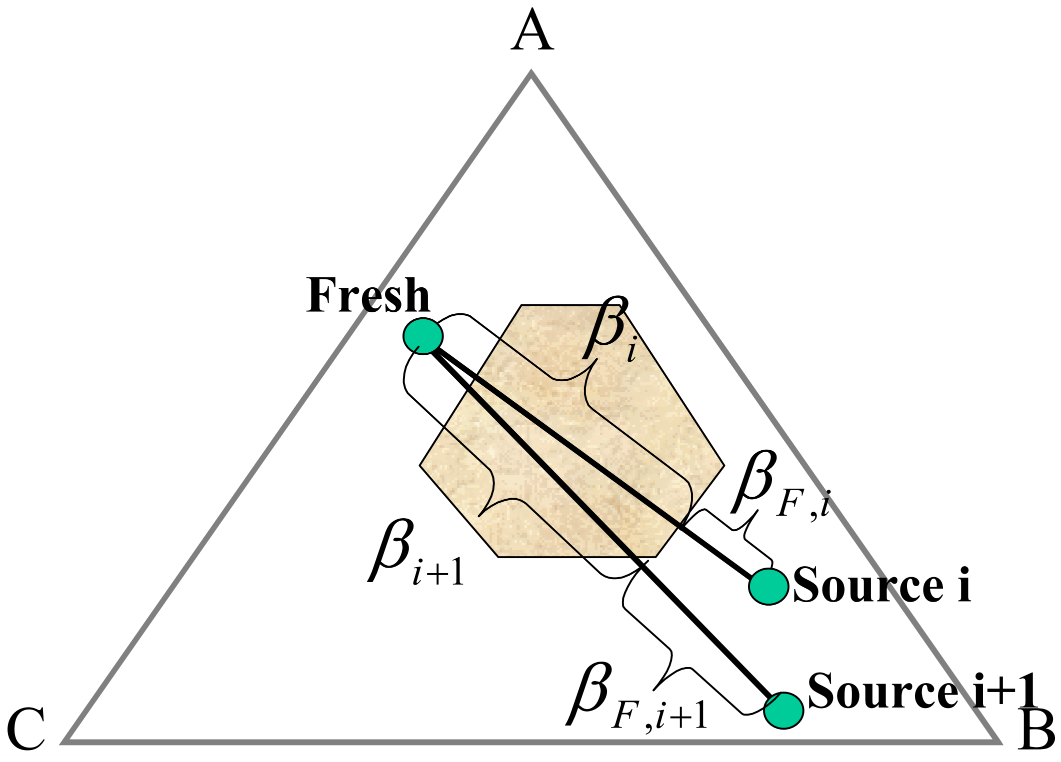

Fig. 3.39 Level Arm Rule for a Ternary Source-Sink Diagram

ADDITIONAL READINGS

Over the past decade, several design techniques have been developed to minimize the usage of fresh resources using network synthesis and analysis. Recent reviews can be found in literature (e.g., El-Halwagi et al., 2003; Dunn and El-Halwagi, 2003). An important variation of MENs, wastewater minimization, was introduced by Wang and Smith (1994). They proposed a graphical approach to target the minimum fresh water consumption and wastewater discharged by the transfer of contaminants from process streams to water streams. Dhole et al. (1996) and El-Halwagi and Spriggs (1996) addressed the problem of material reuse and discharge through a source (supply)-sink (demand) representation. Dhole et al. (1996) created a graphical technique that represents concentration versus flowrate and creates a supply composite and a demand composite. When the two composites touch, a bottleneck (water pinch) is identified and can be eliminated by mixing of source streams. Even though the methodology had great impact on the concept for water minimization, it has its drawbacks. The key limitation is that Dhole et al. did not provide a systematic method for elimination of pinch points by mixing. In order to overcome this limitation, Polley and Polley (2000) proposed a set of rules for sequencing mixing and recycle options. Additionally, Sorin and Bedard (1999) proposed an algebraic method called the evolutionary table which is based on locating the global pinch based on mixing source streams with closer concentration differences first, and then going to the stream with the next nearest concentration. Alves (1999), Alves and Towler (2002) and Hallale (2002) developed a surplus diagram with a graphical representation of purity versus flowrate. Both methods rely on extensive calculations to create the surplus diagram in order to target minimal consumption of resources (water in the case of Hallale (2002) and hydrogen in the case of Alves and Towler (2002)). Manan et al. (2004) extended the surplus diagram by developing a non-iterative targeting procedure for mater reuse. Mann and Liu (2000) provided a comprehensive coverage of the subject particularly for water reuse.

HOMEWORK

3.1. Consider a process with six sinks and five sources (Sorin and Bedard, 1999). The process data are given in Tables 3.7 and 3.8 Fresh water is used in the sinks and it is desired to replace as much fresh water as possible using direct recycle of process sources. Determine the target for minimum usage of fresh water and waste discharge after direct recycle. How many material recycle pinch points are there? What is their significance?

Table 3.7. Sink information for Problem 3.1. (Sorin and Bedard, 1999)

Sink	Flow (tonnes/hr)	Maximum Inlet Concentration (ppm)	Load (kg/hr)
1	120	0	0
2	80	50	4
3	80	50	4
4	140	140	19.6
5	80	170	13.6
6	195	240	46.8

Table 3.8. Source information for Problem 3.1. (Sorin and Bedard, 1999)

Sources	Flow (tonnes/hr)	Concentration (ppm)	Load (kg/hr)
1	120	100	12
2	80	140	11.2
3	140	180	25.2
4	80	230	18.4
5	195	250	48.75

3.2. Consider the wastewater minimization problem described by Polley and Polley (2000). The process has four sources and four sinks and information concerning them can be seen below in Tables 3.8 and 3.9.

a. Find the targets for minimum fresh water and minimum wastewater discharge after direct recycle.
b. Develop a recycle strategy that attains the identified targets.

Table 3.8. Sink Data for Problem 3.2. (Polley and Polley, 2000)

Sinks	**Flow (tonnes/hr)**	Maximum Inlet **Concentration (ppm)**	**Load (kg/hr)**
1	50	20	1
2	1000	50	5
3	80	100	8
4	70	200	14

Table 3.9. Source Data for Problem 3.2. (Polley and Polley, 2000)

Sources	**Flow (tonnes/hr)**	**Concentration (ppm)**	**Load (kg/hr)**
1	50	50	2.5
2	100	100	10
3	70	150	10.5
4	60	250	15

3.3. A thermomechanical pulp and newsprint mill consisting of 54 sinks and 10 sources (Jacob et al., 2002). The source and sink data can be seen in Tables 3.10 and 3.11.

Table 3.10. Sink Data for the Pulp and Newsprint Problem (Jacob et al., 2002)

Sink	**Flow (L/min)**	**Max. Allowable**	**Load**

		Fines Concentration (%)	**(L/min)**
1	200	1.000	2.0
2	400	1.000	4.0
3	355	0.020	0.1
4	150	1.000	1.5
5	13000	1.000	130.0
6	4250	1.000	42.5
7	2800	1.000	28.0
8	4580	1.000	45.8
9	1950	1.000	19.5
10	500	1.000	5.0
11	1000	1.000	10.0
12	3000	1.000	30.0
13	435	1.000	4.4
14	310	1.000	3.1
15	60	1.000	0.6
16	1880	1.000	18.8
17	4290	1.000	42.9
18	9470	1.000	94.7
19	6500	1.000	65.0
20	620	1.000	6.2
21	55	1.000	0.6
22	70	1.000	0.7
23	320	1.000	3.2
24	1050	1.000	10.5
25	73000	1.000	730.0
26	1765	1.000	17.7
27	235	1.000	2.4

28	95	1.000	1.0
29	20	1.000	0.2
30	180	0.000	0.0
31	160	0.018	0.0
32	30	0.018	0.0
33	20	0.018	0.0
34	315	0.000	0.0
35	315	0.000	0.0
36	930	0.018	0.2
37	460	0.018	0.1
38	30	0.018	0.0
39	30	0.018	0.0
40	315	0.000	0.0
41	315	0.000	0.0
42	110	0.018	0.0
43	110	0.018	0.0
44	190	0.000	0.0
45	190	0.000	0.0
46	100	0.000	0.0
47	20	0.000	0.0
48	15	0.000	0.0
49	60	0.018	0.0
50	30	0.018	0.0
51	100	0.000	0.0
52	20	0.000	0.0
53	100	0.000	0.0
54	20	0.000	0.0

Table 3.11. Source Data for the Pulp and Newsprint Mill (Jacob et al., 2002)

Source	**Flow (L/min)**	**Fines Concentration (%)**	**Load (L/min)**
TMP clear water	25000	0.07	17.5
TMP cloudy water	39000	0.13	50.7
Inclined screen water	5980	0.50	29.9
Press header water	2840	0.49	13.9
Save-all clear water	6840	0.08	5.5
Save-all clear water	3720	0.1	3.7
Silo water	73000	0.39	284.7
Machine chest whitewater	8585	0.34	29.2
Vacuum pump overflow	2570	0.00	0.0
Residual showers	1940	0.13	2.5

Identify a target for minimum water usage and minimum waste discharge.

Hint: To simplify the problem, notice that for the sinks there are only four concentration levels of interest. Therefore, the sinks can be lumped into four sinks with fine concentrations (%) of 0.000 , 0.018, 0.020 and 1.000.

3.4. Consider the plastic processing facility described in Problem 2.3. In addition to the information given in Problem 2.3, the following constraints are imposed on feeds to process sinks (Hamad and El-Halwagi, 1998).

Sorting/Drying Unit:

$45{,}000 \leq$ hot gas flowrate (kg/hr) $\leq 60{,}000$ kg/hr

Composition of butane in gas entering sorting unit $\leq 4{,}000$ ppmw

Furnace:

380,000 ≤ Total flowrate entering furnace (kg/hr) ≤ 400,000

10.0 w/w% ≤ Composition of butane in gas entering furnace ≤ 10.5 w/w%

Flowrate of air = 340,000 kg/hr

On a source-sink mapping diagram, the depolymerization off-gas has the shortest arm w.r.t. sorter/dryer. Therefore, the depolymerization off-gas is to be mixed with the hot gas (containing no butane) and recycled to the sorter/dryer. What is the maximum flowrate (kg/hr) of the depolymerization off-gas that can be recycled to the sorter/dryer?

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