

CHAPTER FIVE

VISUALIZATION TECHNIQUES FOR THE DEVELOPMENT OF DETAILED MASS INTEGRATION STRATEGIES

Chapter Two provided holistic techniques for identifying overall targets for benchmarking mass consumption and discharge. These targets are determined ahead of detailed design. Once a target is determined it is necessary to develop cost-effective strategies to reach the target. For a given target, there are numerous design decisions that must be judiciously made. These include addressing the following challenging questions:

- What are the optimum stream-rerouting strategies?
- Should any streams be segregated, mixed, or rerouted? Which ones?
- Which streams should be recycled/reused? To what units?
- Should design variable and/or operating conditions of existing units be altered? Which ones? To what extent?
- Is there a need to add/replace units? Which ones? Where to add/replace?
- Should interception (e.g., separation) devices be added? Which streams should be intercepted? To remove what? To what extent?
- Which separating agents should be selected for interception?
- What is the optimal flowrate of each separating agent?
- How should these separating agents be matched with the rich streams (i.e. stream pairings)?

Because of the prohibitively large number of alternatives involved in answering these questions, a systematic procedure is needed to extract the optimum solution(s) without enumerating them. This is the role provided by mass integration. Mass integration is a holistic and systematic methodology that provides a fundamental understanding of the global flow of mass within the process and employs this understanding in identifying performance targets and optimizing the allocation, separation, and generation of streams and species. Mass integration is based on fundamental principles of chemical engineering combined with system analysis using graphical

and optimization-based tools. In order to develop detailed mass-integration strategies, let us represent the process flowsheet from a species viewpoint (e.g. El-Halwagi and Spriggs, 1998; El-Halwagi et al., 1996) as shown in Fig. 5.1. For each targeted species, there are sources (streams that carry the species) and process sinks (units that can accept the species). Process sinks include reactors, separators, heaters/coolers, biotreatment facilities, and discharge media. Streams leaving the sinks become, in turn, sources. Therefore, sinks are also generators of the targeted species. Each sink/generator may be manipulated via design and/or operating changes to affect the flowrate and composition of what each sink/generator accepts and discharges.

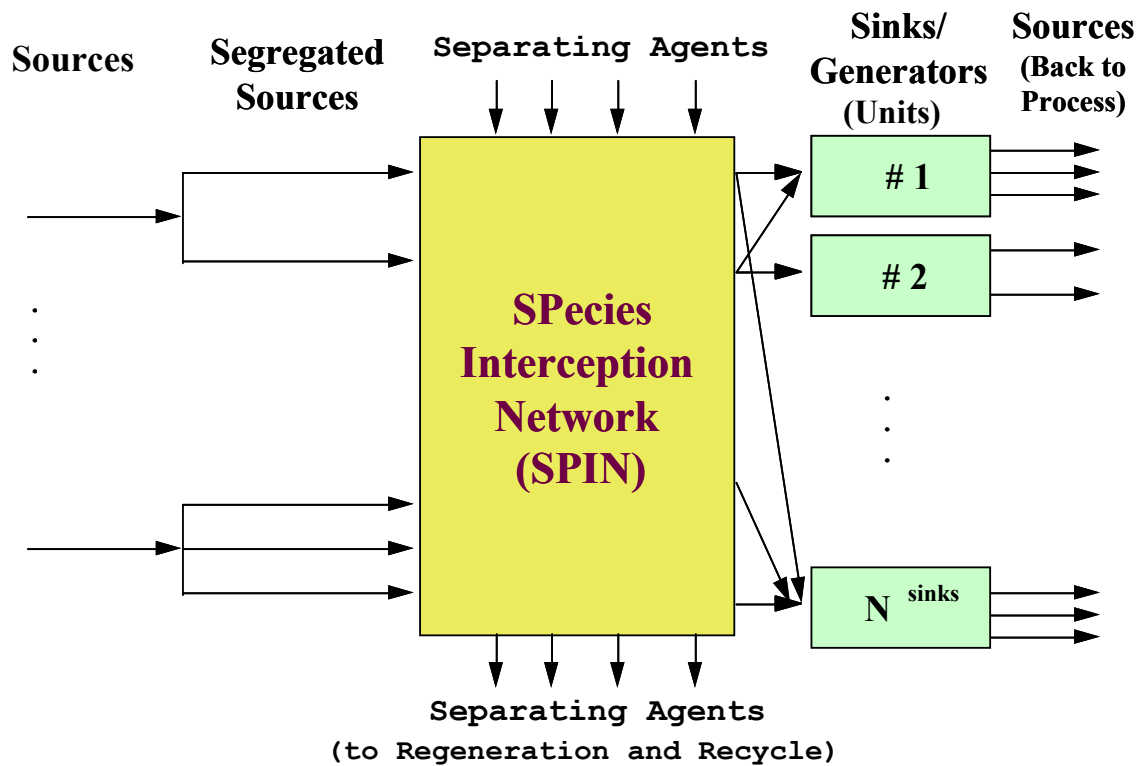


Fig. 5.1. Process from a Species Perspective
(El-Halwagi et al., 1996; Garrison et al., 1995)

Properties of sources (e.g. flowrate, composition, pressure, temperature, etc.) can be modified by adding new units that intercept the streams prior to being fed to the process sinks

and condition their properties to the desired values. This is performed a species-interception network (SPIN) that may use mass- and energy-separating agents.

There are three main factors used in screening candidate mass-integration strategies; economics, impact, and acceptability. Economics can be assessed by a variety of criteria such as cost, return on investment, payback period, etc. Impact is a measure of the extent of the solution strategy to (partially) attain the desired target. Acceptability is a measure of how likely the proposed strategies to be accepted and implemented by the plant. This factor is plant based as it differs from one company to the other depending on their operating policies, corporate environment, and level of comfort within the plant to adopt process modifications. Based on these factors, one can classify candidate strategies via mass integration into three categories (Fig. 5.2):

- No/Low Cost Changes
- Moderate Cost Modifications, and
- New Technologies

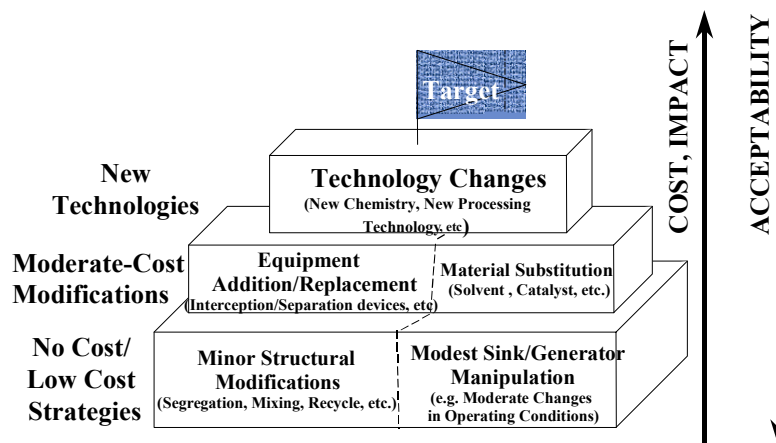


Fig. 5.2 Hierarchy of Mass-Integration Strategies

These strategies are typically in ascending order of cost and impact and in descending order of acceptability. The following sections provide more details on these strategies.

Low/No Cost Strategies

These strategies can be broadly classified into two categories: structural and parametric modifications. The structure-based changes pertain to low/now cost in process configuration such as stream rerouting (e.g. segregation and recycle) which involves piping and pumping primarily. Parametric changes include moderate adjustments in process variables and operating conditions (e.g. temperature, pressure, etc.) which require no or modest capital expenditure. Let us further define these strategies:

Segregation simply refers to avoiding the mixing of streams. In many cases, segregating waste streams at the source renders several streams environmentally acceptable and hence reduces the pollution-prevention cost. Furthermore, segregating streams with different compositions avoids unnecessary dilution of streams. This may reduce the cost of removing the targeted species from the segregated streams. It may also provide composition levels that allow the streams to be recycled directly to process units.

Recycle refers to the utilization of a process stream (a source) in a process unit (a sink). As described in Chapter Three, each sink has a number of constraints on the characteristics (e.g. flowrate and composition) of feed that it can process. If a source satisfies these constraints it may be directly recycled to or reused in the sink. However, if the source violates these constraints segregation, mixing, and/or interception may be used to prepare the stream for recycle. Source-sink mapping diagram and material recycle pinch diagram can be used to determine targets and detailed options for fresh usage, recycle/reuse, and waste discharge.

Modest Changes in Process Variables and Operating Conditions

In order to relate process performance with changes in operating conditions, it is necessary to use an analytical tool that simulates the input-output relations of selected units and can track components in the process and determine what design and operating condition changes are required to meet process targets.

Medium-Cost Strategies and Main Technology Changes

In addition to the aforementioned low-cost strategies, it is attain the target by replacing or adding new equipment and using alternative species. Substantial technology changes can also be implemented. These include major changes in processing scheme including the application of new chemical pathways and core changes in process chemistry. Alternative reactions and molecular design techniques will be discussed later. Here, we focus on equipment addition along with their associated material utilities (e.g., separating agents). *Interception* denotes the utilization of new unit operations to adjust the composition, flowrate and other properties of certain process streams to make them acceptable for existing process sinks. A particularly important class of interception devices is separation systems. These separations may be induced by the use of mass-separating agents (MSAs) and/or energy separating agents (ESAs). A systematic technique is needed to screen the multitude of separating agents and separation technologies to find the optimal separation system. The synthesis of MSA-induced physical-separation systems has been covered in Chapter Four through the synthesis of mass-exchange networks (MENs). Other interception systems are covered throughout the book. The MEN can be used to prepare sources for recycle. When MSAs are used for interception, Fig. 5.1 is revised as shown in Fig. 5.3 by placing a MEN instead of the SPIN.

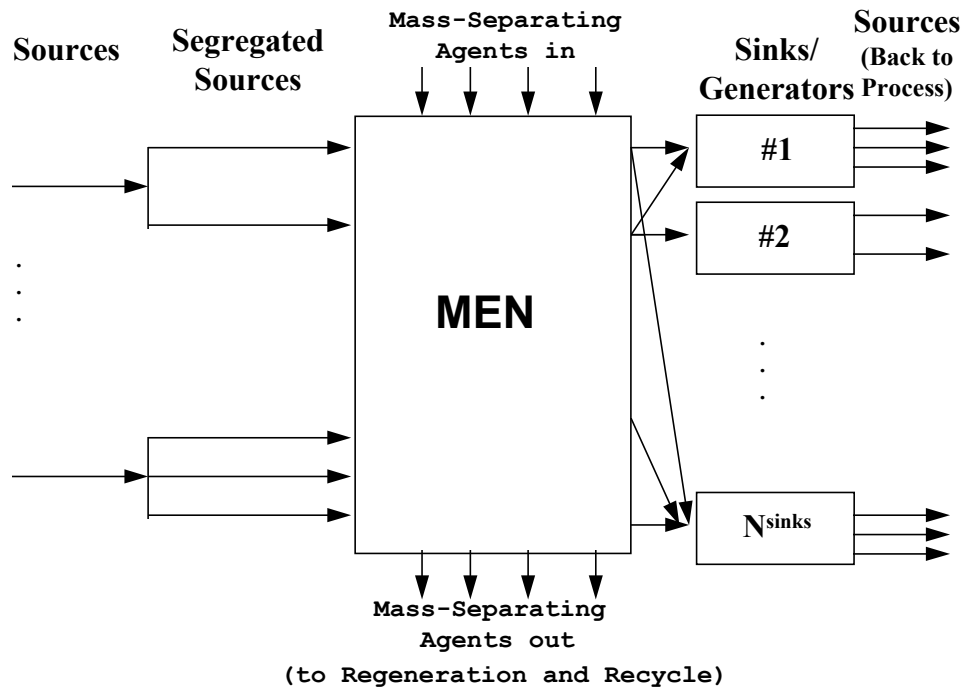
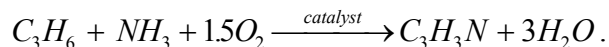


Fig. 5.3. A Process from a Species Viewpoint when MSAs are Used for Interception

Example 5.1: APPLICATION OF MASS INTEGRATION TO DEVOTTLENECK AN ACRYLONITRILE PROCESS AND REDUCE WATER USAGE AND DISCHARGE (El-Halwagi, 1997):

Acrylonitrile (AN , C_3H_3N) is manufactured via the vapor-phase ammoxidation of propylene:



The reaction takes place in a fluidized-bed reactor in which propylene, ammonia, and oxygen are catalytically reacted at 450°C and 2 atm. The reaction is a single pass with almost complete conversion of propylene. The reaction products are cooled using an indirect-contact heat exchanger which condenses a fraction of the reactor off-gas. The remaining off-gas is scrubbed with water, then decanted into an aqueous layer and an organic layer. The organic layer is fractionated in a distillation column under slight vacuum which is induced by a steam-jet ejector. Figure 5.4 shows the process flowsheet along with pertinent material balance data.

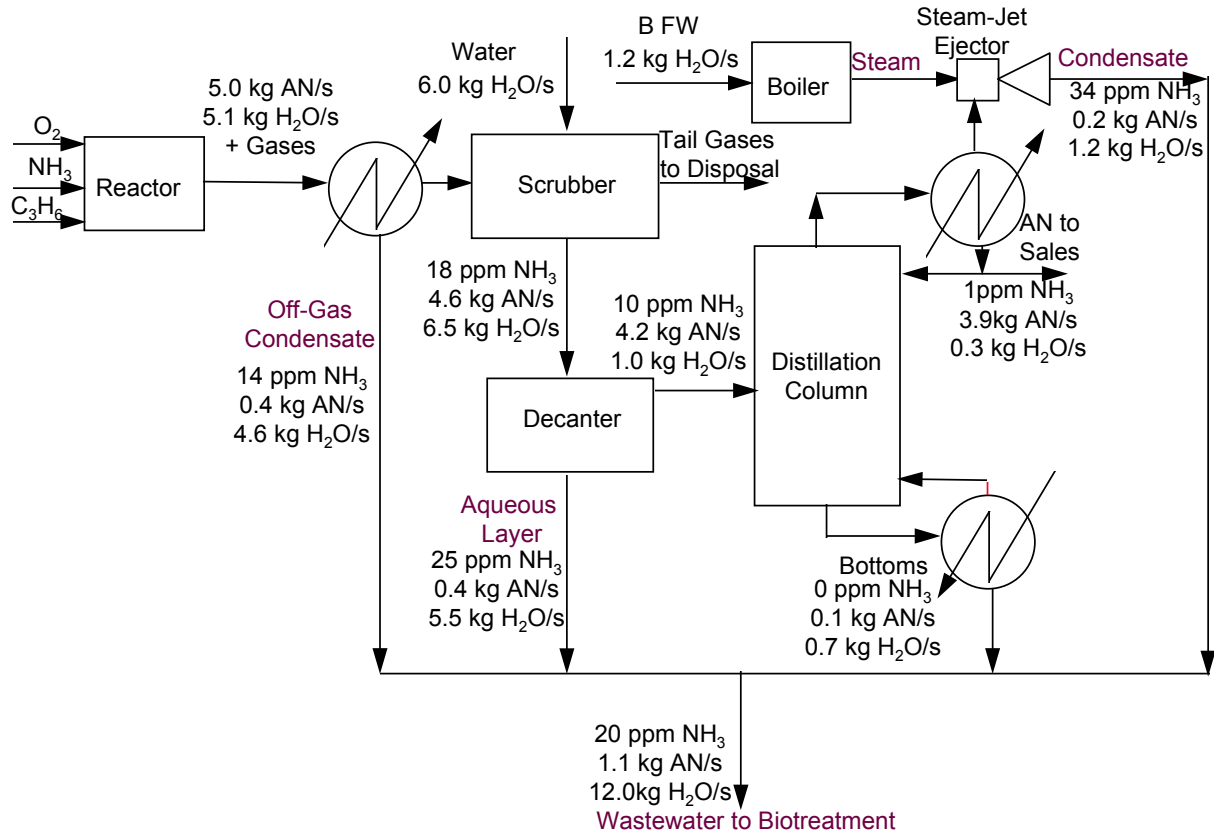


Fig. 5.4. Flowsheet of AN production (El-Halwagi, 1997).

The wastewater stream of the plant is composed of the off-gas condensate, the aqueous layer of the decanter, the bottom product of the distillation column, and the condensate from the steam-jet ejector. This wastewater stream is fed to the biotreatment facility. Since the biotreatment facility is currently operating at full hydraulic capacity, it constitutes a bottleneck for the plant. Plans for expanding production of AN are contingent upon debottlenecking of the biotreatment facility by reducing its influent or installing an additional treatment unit. The new biotreatment facility will cost about \$4 million in capital investment and \$360,000/yr in annual operating cost, leading to a TAC of \$760,000/yr with a 10-yr linear depreciation. The objective of this case study is to use mass integration techniques to devise cost-effective strategies to debottleneck the biotreatment facility.

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

Scrubber

- $5.8 \leq \text{flowrate of wash feed (kg/s)} \leq 6.2$ (5.1)

- $0.0 \leq \text{ammonia content of wash feed (ppm NH}_3) \leq 10.0$ (5.2)

Boiler Feed Water (BFW)

- Ammonia content of BFW (ppm NH₃)=0.0 (5.3)

- AN content of BFW (ppm AN)=0.0 (5.4)

Decanter

- $10.6 \leq \text{flowrate of feed (kg/s)} \leq 11.1$ (5.5)

Distillation Column:

- $5.2 \leq \text{flowrate of feed (kg/s)} \leq 5.7$ (5.6)

- $0.0 \leq \text{Ammonia content of feed (ppm NH}_3) \leq 30.0$ (5.7)

- $80.0 \leq \text{AN content of feed (wt.\% AN)} \leq 100.0$ (5.8)

Furthermore, for quality and operability objectives the plant does not wish to recycle the AN product stream (top of distillation column), the feed to the distillation column and, the feed to the decanter.

Three external MSAs are considered for removing ammonia from water; air (S₁), activated carbon (S₂) and an adsorbing resin (S₃). The data for the candidate MSAs are given in Table 5.1. The equilibrium data for the transfer of the pollutant from the waste stream to the jth MSA is given by,

$$y_l = m_j x_j, \quad (5.9)$$

where y_l and x_j are weight-based parts per million of ammonia in the wastewater and the jth MSA, respectively.

Table 5.1. Data for MSAs of the AN Problem

Stream	Upper bound on flowrate L_j^c	Supply composition (ppmw) x_j^s	Target composition (ppmw) x_j^t	m_j	ϵ_j ppmw	C_j \$/kg MSA	C_j^r \$/kg NH ₃ removed
S ₁	∞	0	6	1.4	2	0.004	667
S ₂	∞	10	400	0.02	5	0.070	180
S ₃	∞	3	1100	0.01	5	0.100	91

Solution

The first step in the analysis is to identify the target for debottlenecking the biotreatment facility. An overall water balance for the plant (Fig. 5.5a) can be written as follows:

$$\text{Water in} + \text{Water generated by chemical reaction} = \text{Wastewater out} + \text{Water losses}$$

Since the wastewater discharge is larger than fresh water flowrate, it is possible, in principle, to bring wastewater to a quality that can substitute fresh water using segregation, mixing, recycle and interception. Furthermore, sink/generator manipulation can be employed to reduced flowrate of fresh water. Hence, fresh-water usage in this example can in principle be completely eliminated, and for the same reaction conditions and water losses, the target for wastewater discharge can be calculated from the overall water balance as follows (Fig. 5.5b):

$$\begin{aligned} \text{Target of minimum discharge to biotreatment} &= 5.1 - 0.3 \\ &= 4.8 \text{ kg water/s.} \end{aligned} \tag{5.10}$$

As can be seen from Fig. 5.5b, the corresponding target for minimum usage of fresh water is potentially zero.

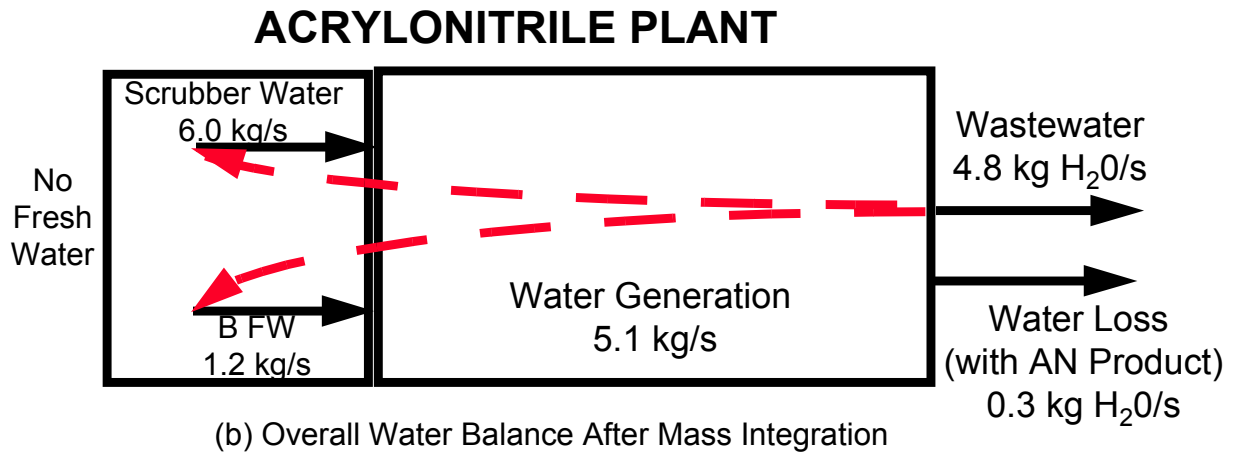
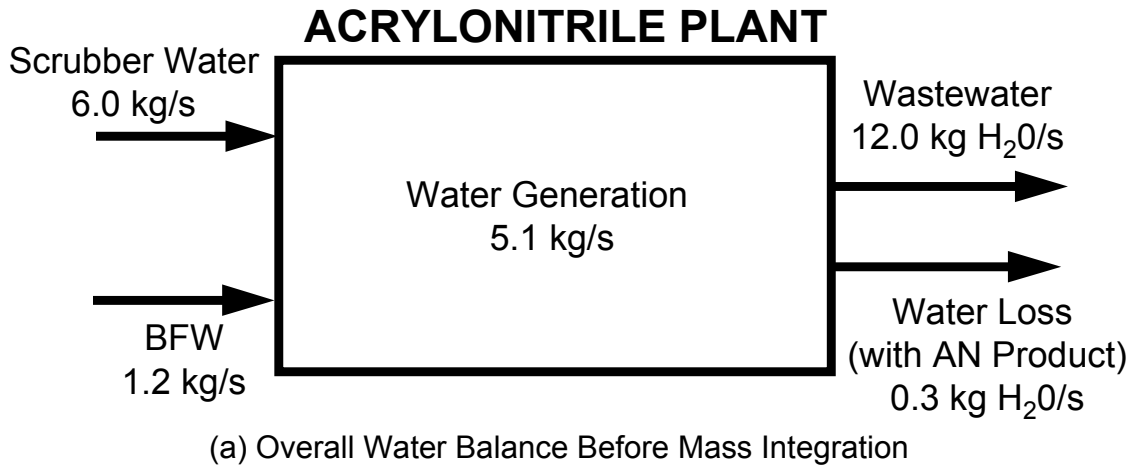


Fig. 5.5. Establishing targets for biotreatment influent: overall water balance (a) before and (b) after mass integration (El-Halwagi, 1997).

Figure 5.6 illustrates the gap between current process performance and benchmarked mass targets. Having identified this target, let us now determine how to best attain the target. It is also necessary to sequence and integrate the solution strategies.

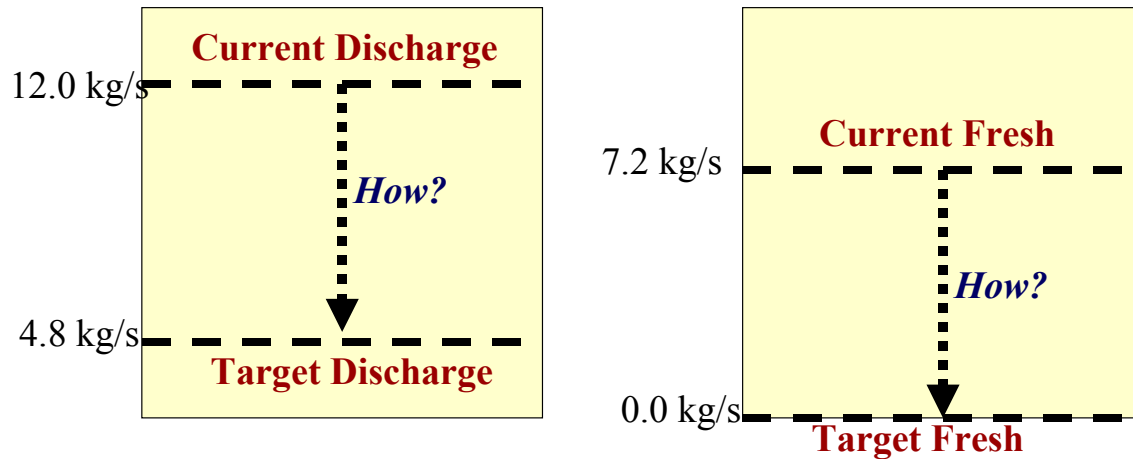


Fig. 5.6 Benchmarking Water Usage and Discharge

First, we develop no/low cost strategies starting with minor process modifications. An operating parameter that can be altered to reduce fresh water usage (and consequently wastewater discharge) is the flowrate of the feed to the scrubber. As given by constraint (5.1), the flowrate of fresh water fed to the first scrubber may be reduced to 5.8 kg/s. This is a minor process modification which involves setting the flow control valve. Compared to the current usage of 6.0 kg/s, the net result is a reduction of 0.2 kg/s in water usage (and discharge). These results are shown in Fig. 5.7. To track water, the wastewater discharge is described in terms of kg H₂O/s (not as total flowrate of wastewater including other species).

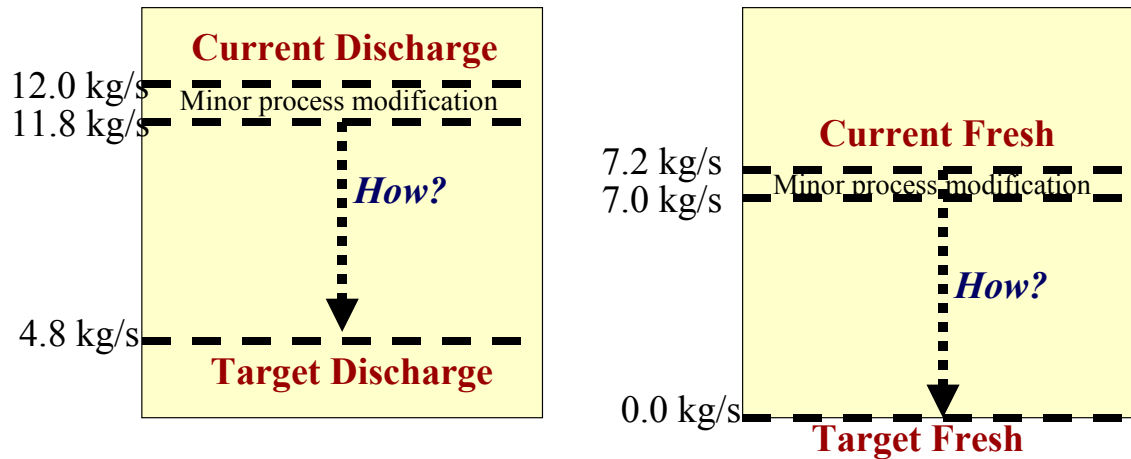


Fig. 5.7 Reduction in Water Usage and Discharge (Expressed as kg H₂O/s) after Minor Process Modification

Next, we consider other no/low cost strategies including segregation, mixing, and direct recycle opportunities. First, we identify the relevant sources and sinks. Once the streams composing the terminal wastewater are segregated, we get four sources that can be potentially recycled. Fresh water used in the scrubber and the boiler provides two more sources. In order to reduce wastewater discharge to biotreatment, fresh water must be reduced. Hence, we should focus our attention on recycling opportunities to sinks that employ fresh water, namely, the scrubber and the boiler. Figure 5.8 illustrates the sources and sinks involved in the analysis.

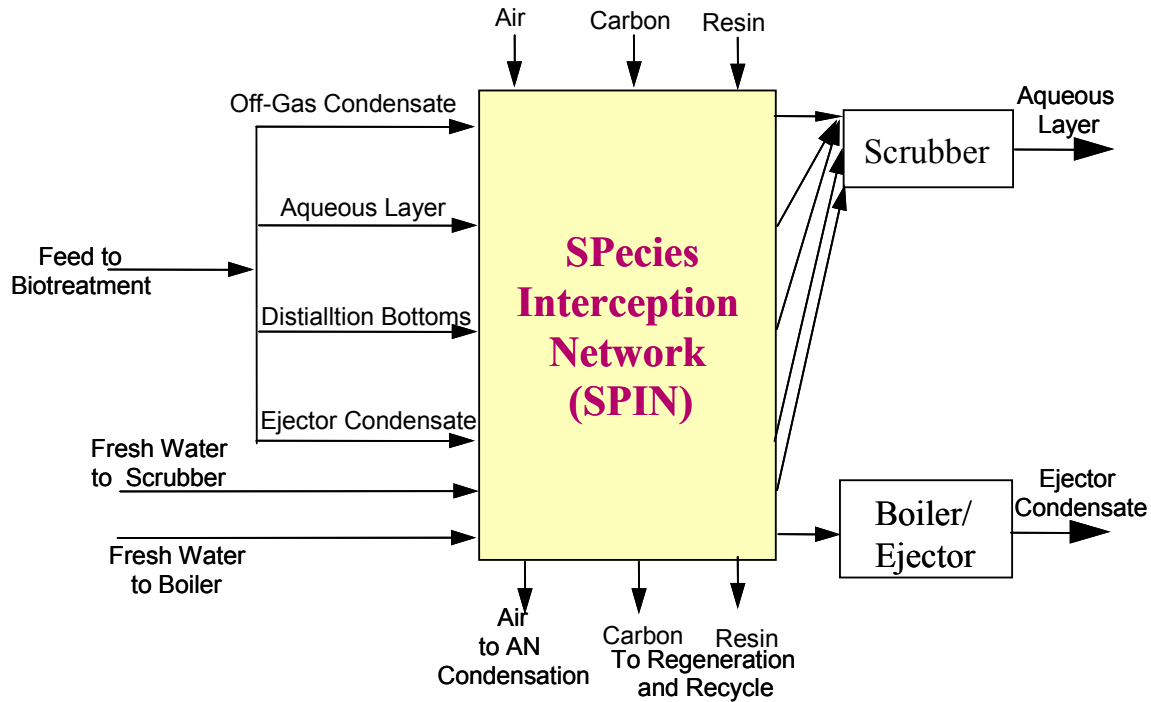


Fig. 5.8. Segregation, mixing, interception and recycle Representation for the AN Case Study (El-Halwagi, 1997)

Direct recycle strategies are based on segregating, rerouting, and mixing of sources without the use of new equipment. Hence, there is no SPIN involved in direct recycle. Therefore, for direct recycle Fig. 5.8 is revised by eliminating the SPIN as shown in Fig. 5.9. Because of the stringent limitation on the BFW (no ammonia or AN), no recycled stream can be used in lieu of fresh water (segregation, mixing, recycle and interception can reduce, but not eliminate, ammonia/AN content). Consequently, in Fig. 5.9 none of the process sources are allocated to the boiler.

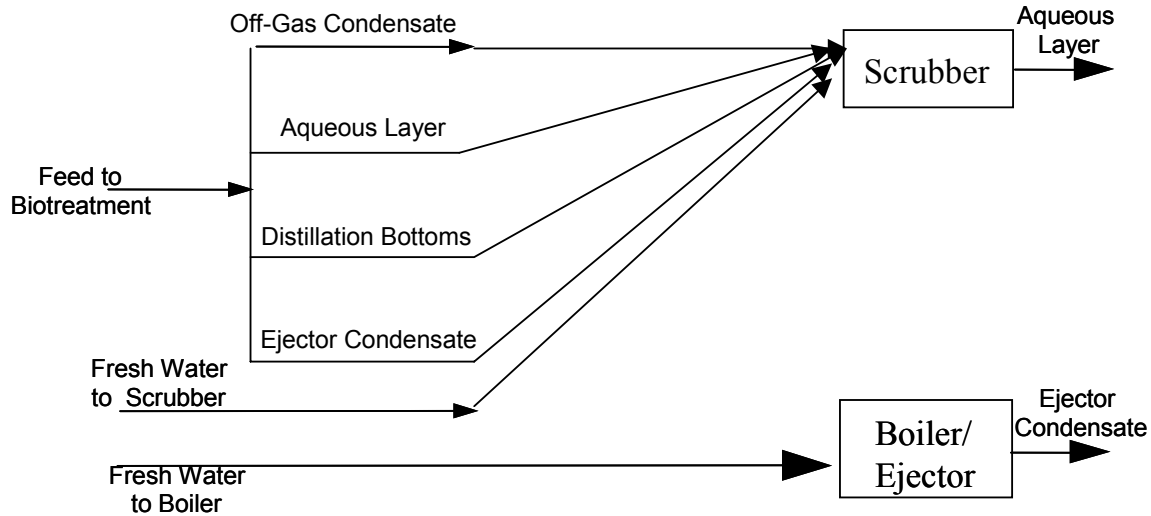


Fig. 5.9. Schematic Representation of Segregation, Direct Recycle, and Mixing for the AN Example (El-Halwagi, 1997)

Because of the stringent limitation on the BFW (no ammonia or AN), no recycled stream can be used in lieu of fresh water (segregation, mixing, recycle and interception can reduce, but not eliminate, ammonia/AN content). Hence, the boiler should not be considered as a sink for recycle (with or without interception). Instead, it should be handled at the stage of sink/generator manipulation. This leaves us with the five segregated sources and two sinks (boiler and scrubber). The data for the sources and sinks are summarized in Tables 5.2 and 5.3, respectively. Using these data, the material-recycle pinch diagram is constructed by first developing the sink composite curve (Fig. 5.10), then the source composite curve (Fig. 5.11), and the material-recycle pinch diagram (Fig. 5.12). As can be seen from Fig. 5.12, when direct recycle is used the following targets can be obtained:

$$\text{Minimum fresh water} = 2.1 \text{ kg/s} \quad (5.11a)$$

$$\text{Maximum direct recycle} = 4.9 \text{ kg/s} \quad (5.11b)$$

$$\text{Minimum waste discharge} = 8.0 \text{ kg/s} \quad (5.11c)$$

As mentioned earlier, to track water it is useful to express the flowrate of waste discharge as kg H₂O/s (not as total flow including other species). This can be readily calculated by noting that the reduction in fresh water usage is equal to the reduction in wastewater discharge (expressed as kg H₂O/s). Since,

$$\text{Reduction in fresh water usage} = 7.2 - 2.1 = 5.1 \text{ kg/s} \quad (5.11d)$$

We have

$$\begin{aligned} \text{Minimum waste discharge (expressed as kg H}_2\text{O)/s)} &= 12.0 - 5.1 \\ &= 6.9 \text{ kg H}_2\text{O/s}^1 \end{aligned} \quad (5.11e)$$

Table 5.2. Sink Data for the AN Example

Sink	Flowrate kg/s	Maximum Inlet Composition of NH ₃ ppm	Maximum Inlet Load, 10 ⁻⁶ kg NH ₃ /s
BFW	1.2	0.0	0.0
Scrubber	5.8	10.0	58.0

Table 5.3. Source Data for the AN Example

Source	Flowrate kg/s	Inlet Composition of NH ₃ ppm	Inlet Load, 10 ⁻⁶ kg NH ₃ /s
Distillation Bottoms	0.8	0.0	0.0
Off-Gas Condensate	5.0	14	70.0
Aqueous Layer	5.7 ²	25	142.5
Jet-Ejector Condensate	1.4	34	47.6

¹ The difference between the wastewater discharge expressed as total flowrate (8.0 kg/s) versus that expressed in terms of H₂O (6.9 kg/s) accounts for the 1.1 kg/s of collective AN losses in the wastewater.

² Since the flowrate of the feed to the scrubber has been reduced by 0.2 kg/s as a result of minor process modification, the flowrate of the aqueous layer is assumed to decrease from 5.9 to 5.7 kg/s.

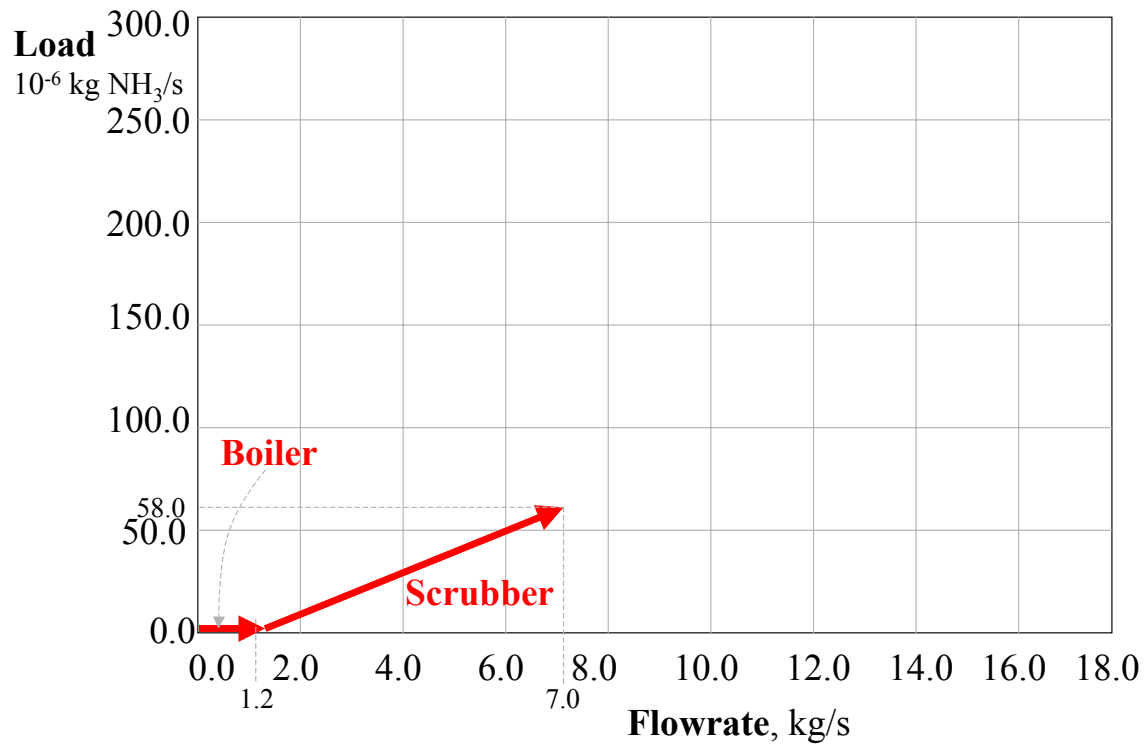


Fig. 5.10. Sink Composite Diagram for the AN Example

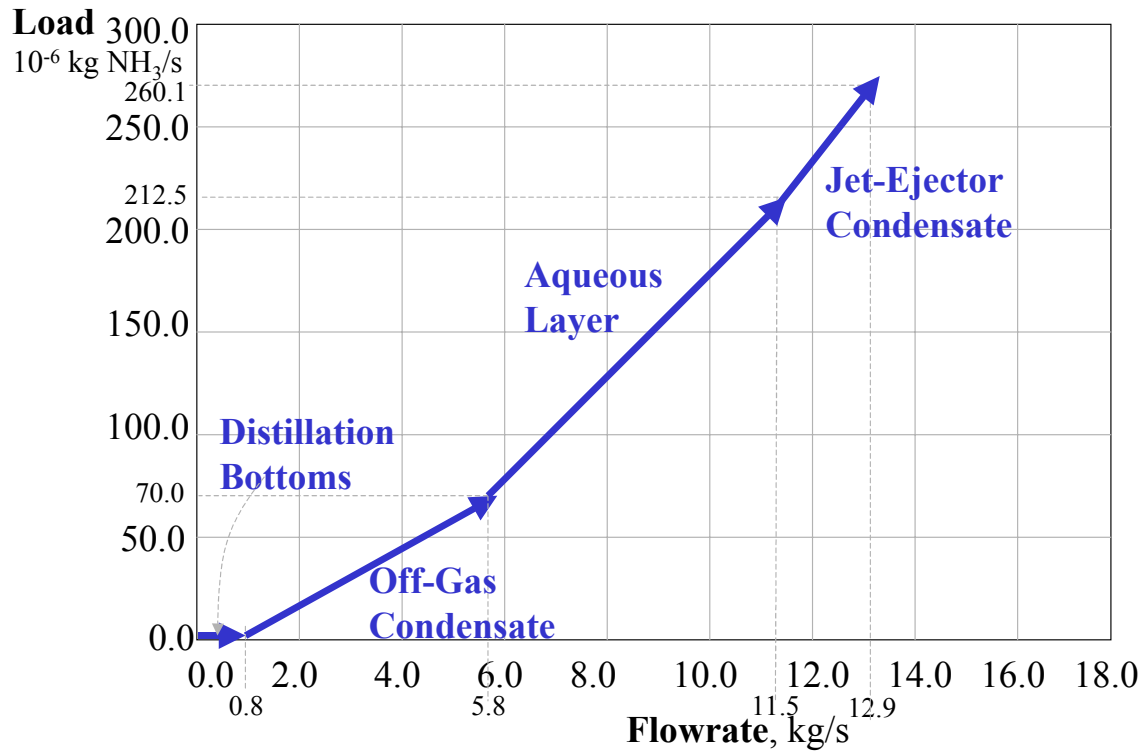


Fig. 5.11. Source Composite Diagram for the AN Example

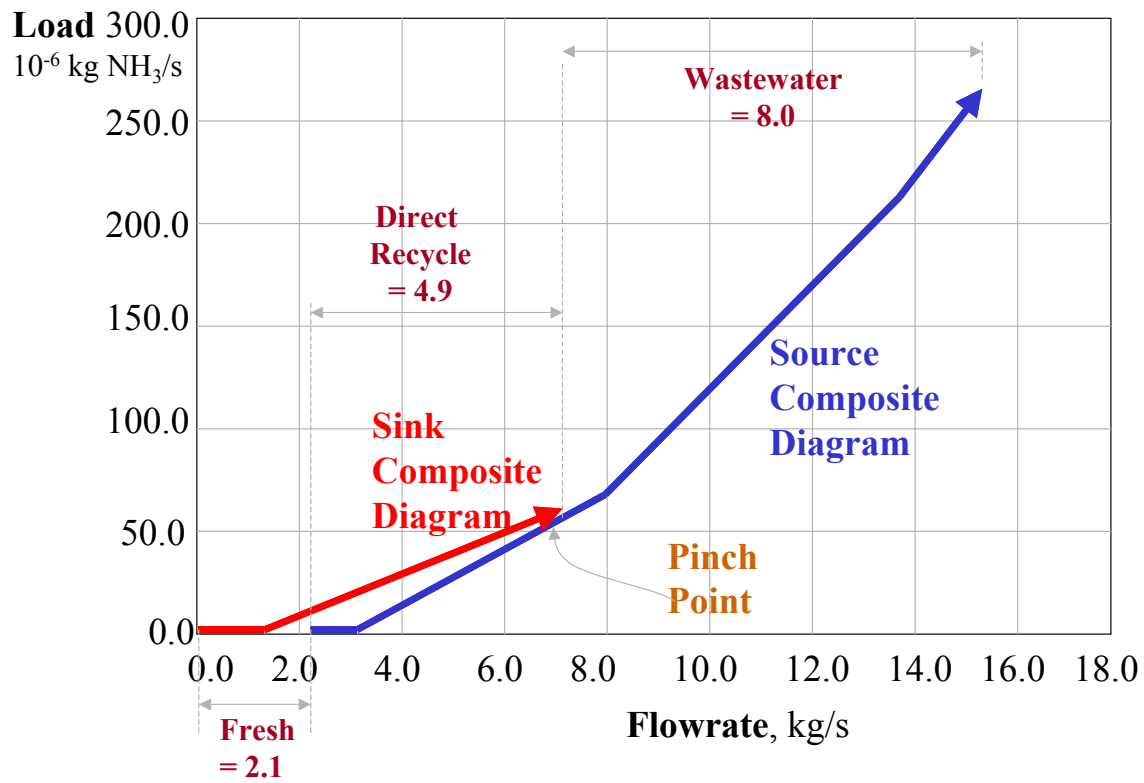


Fig. 5.12. Material Recycle Pinch Diagram for the AN Example

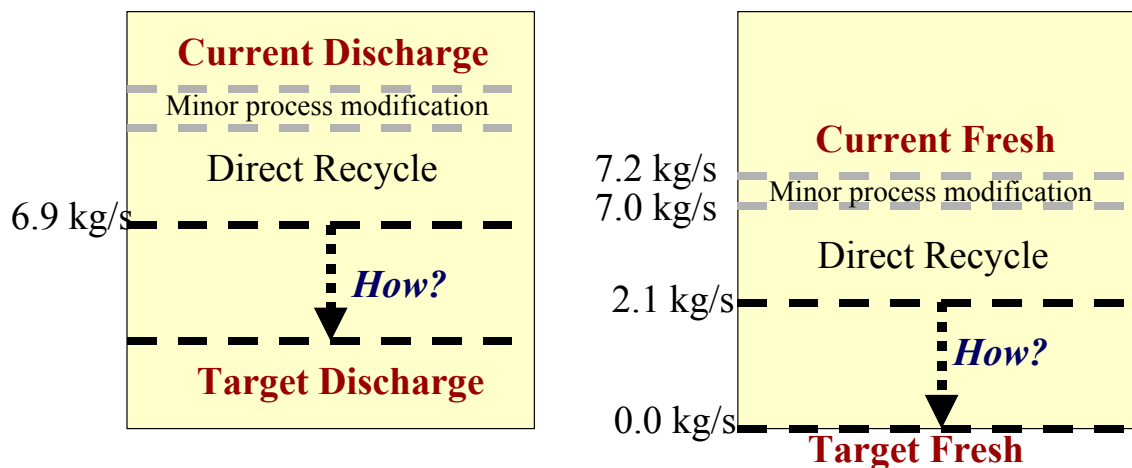


Fig. 5.13 Reduction in Water Usage and Discharge (Expressed as kg H₂O/s) after Minor Process Modification and Direct Recycle

It is beneficial to detail the direct-recycle strategies to attain the identified targets. Towards that end, the source-sink mapping diagram can be used to identify which sources should be recycled to which sinks. Figure 5.14 is a source-sink mapping representation of the problem. As mentioned earlier, because of the stringent requirements on the feed to the boiler sink (0.0 composition of any pollutant), it is not possible to replace any of the feed to the boiler through recycle (even with interception). Consequently, we will not represent the boiler sink on the source-sink mapping diagram. Following the lever arm rules including sink-feed conditions and source-prioritization rules described in Chapter Three, the following statements can be made:

- The composition of the feed to the boiler should be set to its maximum value (10 ppm)
- The use of the sources should be prioritized as follows: distillation bottoms, off-gas condensate, aqueous layer, then jet-ejector condensate.

Hence, we start by considering the use of the first two sources (shortest fresh arms): distillation bottoms and off-gas condensate. The flowrate resulting from combining these two

sources (5.8 kg/s) is sufficient to run the scrubber. However, its ammonia composition³ as determined by the lever-arm principle is 12.1 ppm, which lies outside the zone of permissible recycle to the scrubber. As shown by Fig. 5.15, the maximum flowrate of the off-gas condensate to be recycled to the scrubber⁴ is determined as follows:

$$\frac{\text{Arm of Gas Condensate}}{\text{Total Arm}} = \frac{\text{Flowrate of Recycled Gas Condensate}}{\text{Flowrate of Scrubber Feed}}$$

i.e., (5.12)

$$\frac{10 - 0}{14 - 0} = \frac{\text{Flowrate of Recycled Gas Condensate}}{5.8}$$

Hence, flowrate of recycled gas condensate = 4.1 kg/s and the flowrate of fresh water is 0.9 kg/s (5.8 - 0.8 - 4.1). Therefore, direct recycle can reduce the fresh-water consumption (and consequently the influent to biotreatment) by 5.1 kg/s. This is exactly the same target identified from the material recycle pinch analysis as described by Eq. (5.11d).

³ Algebraically, this composition can be calculated as follows: $\frac{(5.0\text{kg/s})(14 \text{ ppm } NH_3) + 0}{5.8\text{kg/s}} = 12.1 \text{ ppm } NH_3$

⁴ Again, algebraically this flowrate can be calculated as follows:
 $\frac{\text{Flowrate of recycled off - Gas condensate} \times 14 \text{ ppm } NH_3 + 0 + 0}{5.8 \text{ kg / s}} = 10 \text{ ppm } NH_3.$

where the numerator represents the ammonia in recycled off-gas condensate, distillation bottoms (none) and fresh water (none). Hence, flowrate of recycled off-gas condensate = 4.14 kg/s.

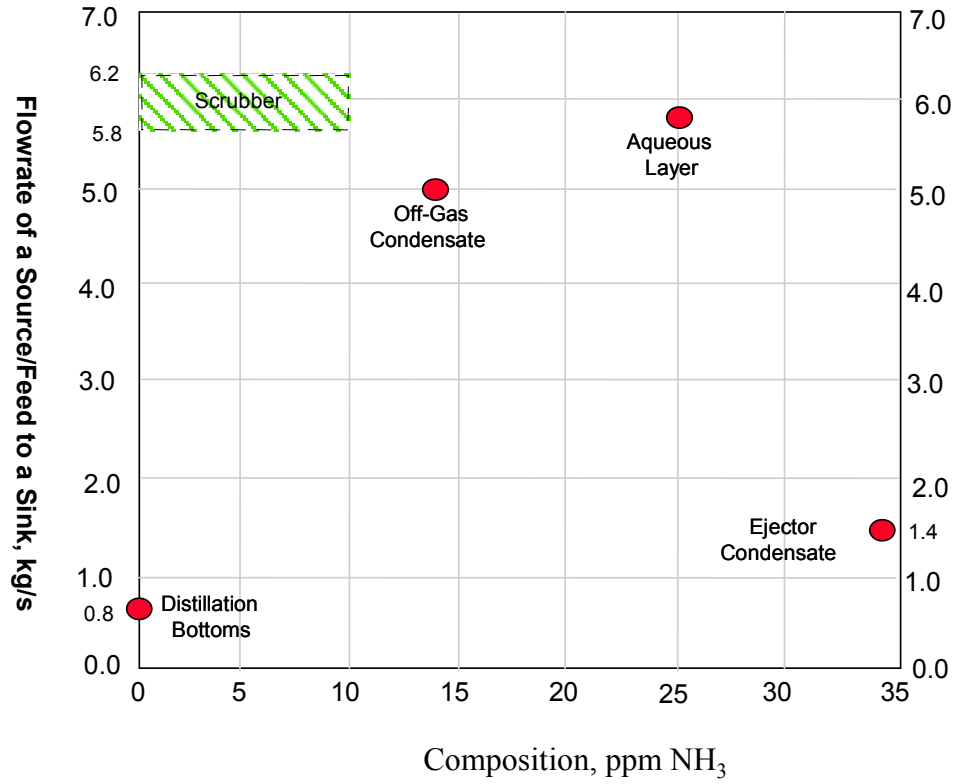


Fig. 5.14 Source-Sink Mapping Diagram for the AN Example (El-Halwagi, 1997)

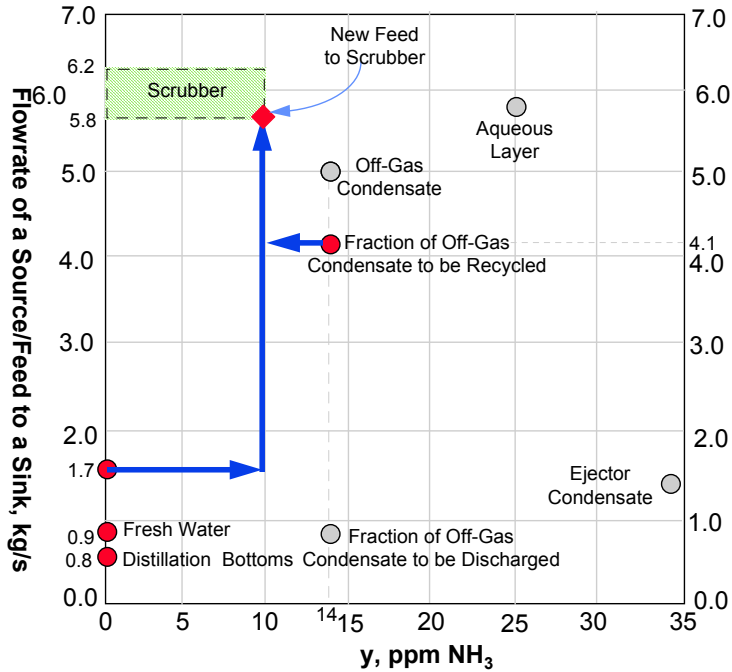


Fig. 5.15 Direct-Recycle Strategies for the AN Example (El-Halwagi, 1997)

With the details of the direct-recycle strategies determined, it is possible to determine the implementation cost. The primary cost of direct recycling is pumping and piping. Assuming that the TAC for pumping and piping is $\frac{\$80}{\text{m} \cdot \text{yr}}$ and assuming that the total length of piping is 600 m, the TAC for pumping and piping is \$48,000/yr.

Since not all the off-gas condensate has been recycled, there is not need to consider recycle from any other source (since they have longer fresh arms). Therefore, there are no more direct-recycle opportunities and we have exhausted the no/low cost strategies. Next, we move to adding new units and we consider interception.

Before screening interception devices, it is necessary to determine the interception task. For all of the off-gas condensate to be recycled to the boiler, its ammonia content has to be reduced. As can be seen from Fig. 5.16, in order to fully recycle the off-gas condensate the

ammonia load to be removed is $12 \cdot 10^{-6}$ kg/s. The composition of the intercepted off-gas condensate is the slope of the intercepted stream which is 11.6 ppm. Therefore, the interception task is to reduce the composition of ammonia in the off-gas condensate from 14.0 ppm to 11.6 ppm. The same result can be obtained algebraically as follows:

$$\text{Load removed from off-gas condensate} = \text{flowrate of off-gas condensate} \cdot (\text{supply composition} - \text{target composition}) \quad (5.13a)$$

i.e.,

$$12 \cdot 10^{-6} = 5.0 \cdot (14.0 - \text{target composition})$$

Therefore,

$$\text{Target (intercepted) composition of ammonia in off-gas condensate} = 11.6 \text{ ppm} \quad (5.13b)$$

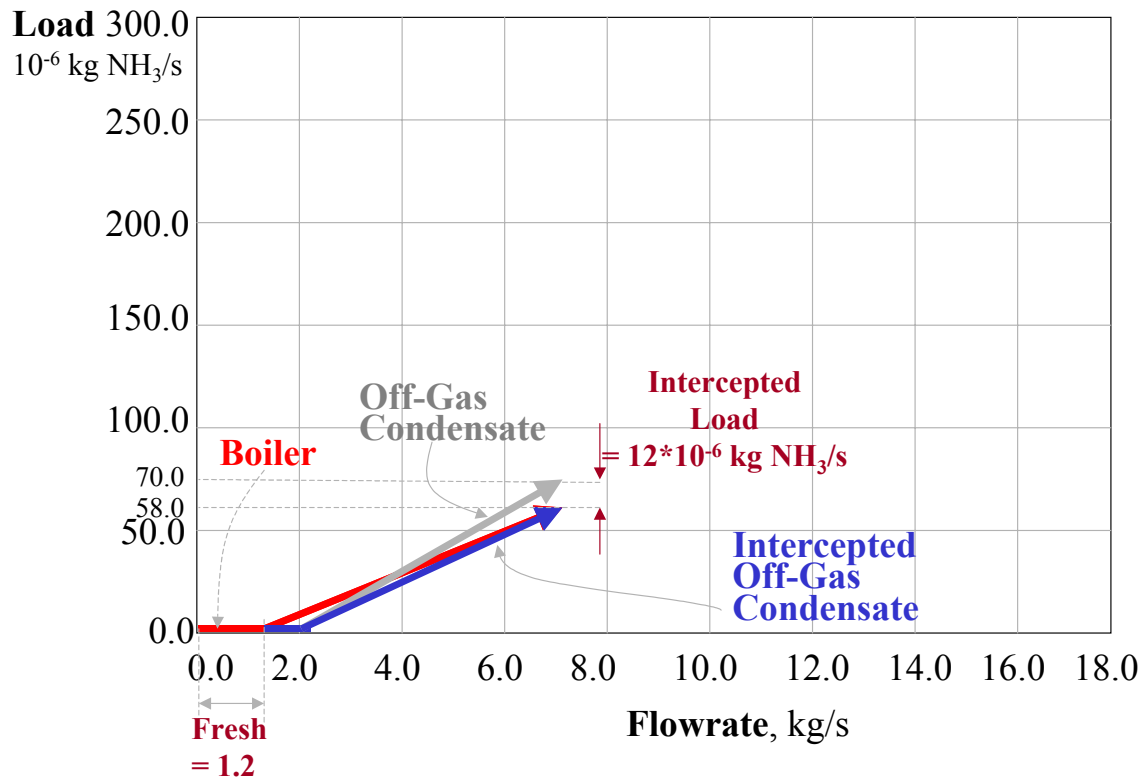


Fig. 5.16. Intercepting the Off-Gas Condensate

The same result may also be obtained through the source-sink mapping diagram as shown in Fig. 5.17. Alternatively, it may be calculated as follows:

$$\frac{(5.0 \text{ kg / s}) y^t \text{ ppm } NH_3 + 0}{5.8 \text{ kg / s}} = 10.0 \text{ ppm } NH_3$$

i.e., $y^t = 11.6 \text{ ppm}$. (5.13)

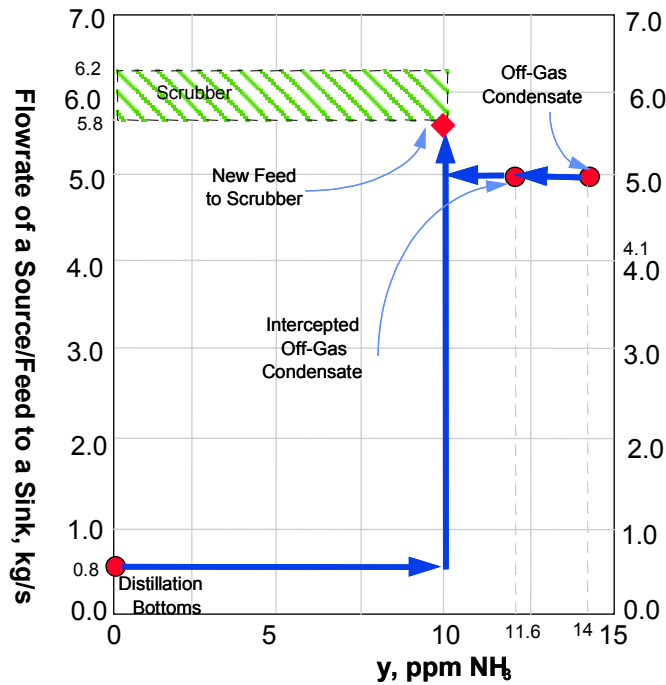


Fig. 5.17. Determination of Interception Task for the Off-Gas Condensate (El-Halwagi, 1997)

In order to synthesize an optimal MEN for intercepting the off-gas condensate, we construct the pinch diagram as shown in Fig. 5.18. Since the three MSA's lie completely to the left of the rich stream, they are all thermodynamically feasible. Hence, we choose the one with

the least cost (\$/kg NH₃ removed); namely the resin. The annual operating cost for removing ammonia using the resin is:

$$5 \frac{\text{kg Liquid}}{\text{s}} * (14.0 * 10^{-6} - 11.6 * 10^{-6}) \frac{\text{kg NH}_3}{\text{kg Liquid}} * 91 \frac{\$}{\text{kg NH}_3} * 3600 * 8760 \frac{\text{s}}{\text{yr}} = \$34,437 / \text{yr} . \quad (5.14)$$

The annualized fixed cost of the adsorption column along with its ancillary equipment (e.g. regeneration, materials handling, etc.) is estimated to be about \$85,000/yr. Therefore, the TAC for the interception system is \$119,437/yr.

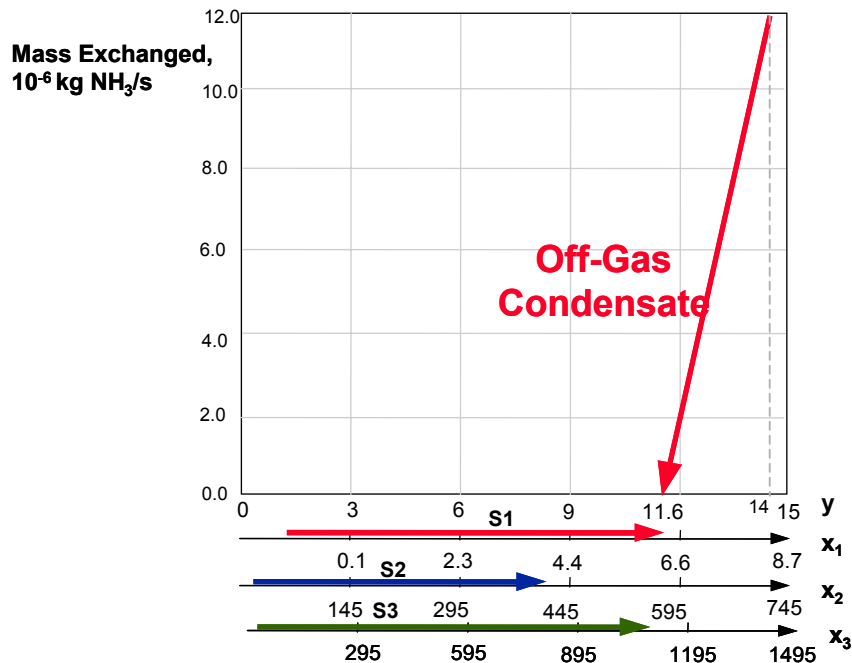


Fig. 5.18. The pinch diagram for the AN case study (El-Halwagi, 1997)

As a result of minor process modification, segregation, interception, and recycle, we have eliminated the use of fresh water in the scrubber, leading to a reduction in fresh water consumption (and influent to biotreatment) by 6.0 kg/s. Therefore, the target for segregation, interception, and recycle has been realized.

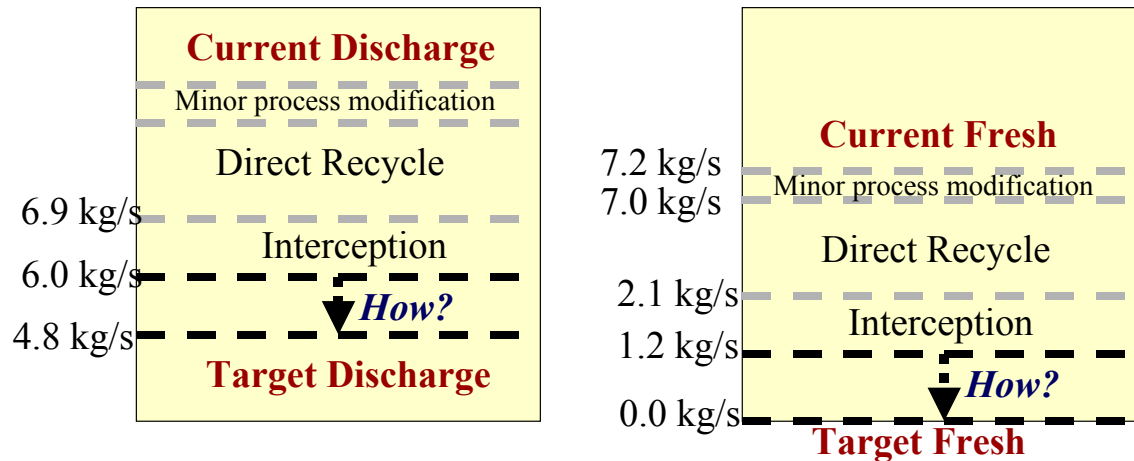


Fig. 5.19 Reduction in Water Usage and Discharge (Expressed as kg H₂O/s) after Minor Process Modification, Direct Recycle, and Interception

Next, we focus our attention on sink/generator manipulation to remove fresh-water consumption in the steam-jet ejector. The challenge here is to alter the design and/or operation of the boiler, the ejector, or the distillation column to reduce or eliminate the use of steam. Several solutions may be proposed including:

- Replacing of the steam-jet ejector with a vacuum pump. The distillation operation will not be affected. The operating cost of the ejector and the vacuum pump are comparable. However, a capital investment of \$75,000 is needed to purchase the pump. For a five-year linear depreciation with negligible salvage value, the annualized fixed cost of the pump is \$15,000/year.
- Operating the column under atmospheric pressure, thereby eliminating the need for the vacuum pump. Here a simulation study is needed to examine the effect of pressure change.
- Relaxing the requirement on BFW quality to a few parts per million of ammonia and AN. In this case, recycle and interception techniques can be used to significantly reduce the fresh water feed to the boiler and, consequently, the net wastewater generated.

Figure 5.20 illustrates the revised flowsheet with segregation, interception, recycle and sink/generator manipulation. As can be seen from the figure, the flowrate of the terminal wastewater stream has been reduced to 4.8 kg H₂O/s. This is exactly the same *target* predicted in

Fig. 5.5b. In order to refine the material balance throughout the plant, a simulation study is needed, as discussed in Chapter 1.

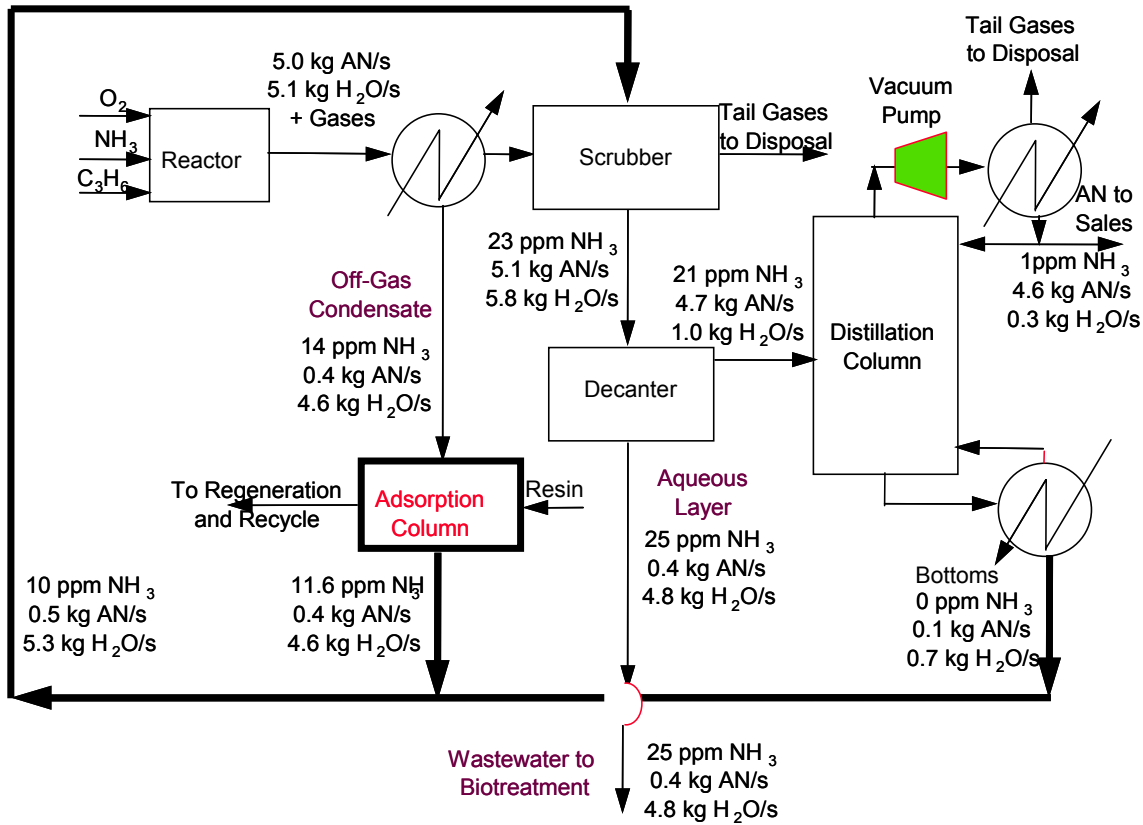


Fig. 5.20 Optimal solution to the AN case Study (El-Halwagi, 1997)

Figures 5.21 and 5.22 are impact diagrams (sometimes referred to as Pareto charts) for the reduction in wastewater and the associated TAC. These figures illustrate the cumulative impact of the identified strategies on biotreatment influent and cost.

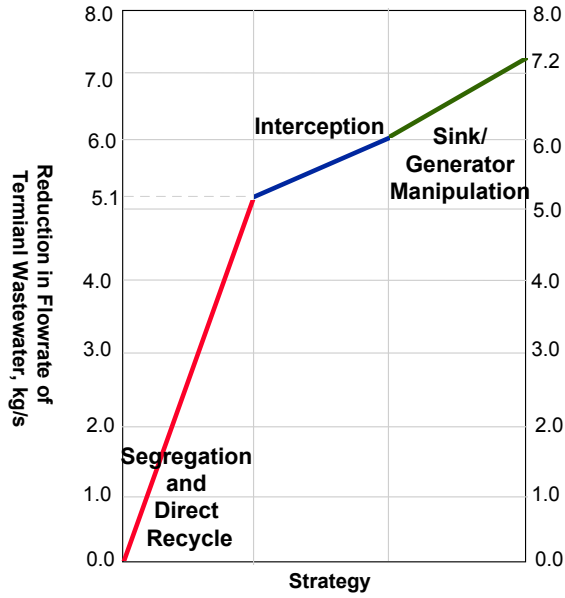


Fig. 5.21 Impact Diagram for Reducing Biotreatment Influent (El-Halwagi, 1997)

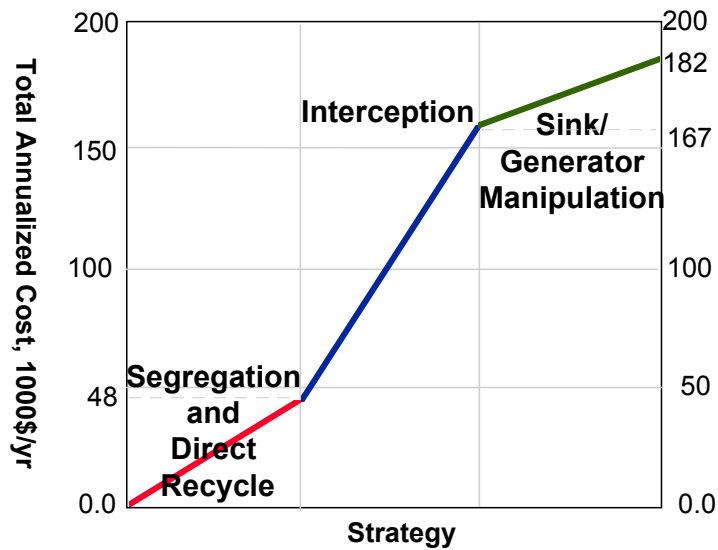


Fig. 5.22 Impact Diagram for TAC of Identified Solutions (El-Halwagi, 1997)

We are now in a position to discuss the merits of the identified solutions. As can be inferred from Fig. 5.20, the following benefits can be achieved:

- Acrylonitrile production has increased from 3.9 kg/s to 4.6 kg/s, which corresponds to an 18% yield enhancement for the plant. This production increase is a result of better allocation

of process streams; the essence of mass integration. For a selling value of \$0.6/kg of AN, the additional production of 0.7 kg AN/s can provide an annual revenue of \$13.3 million/yr!

- Fresh-water usage and influent to biotreatment facility are decreased by 7.2 kg/s. The value of fresh water and the avoidance of treatment cost are additional benefits.
- Influent to biotreatment is reduced to 40% of current level. Therefore, the plant production can be expanded 2.5 times the current capacity before the biotreatment facility is debottlenecked again.

Clearly, this is a superior solution to the installation of an additional biotreatment facility.

It is instructive to draw some conclusions from this case study and emphasize the design philosophy of mass integration. First, the target for debottlenecking the biotreatment facility was determined ahead of design. Then, systematic tools were used to generate optimal solutions that realized the target. Next, an analysis study was performance needed to refine the results. This is an efficient approach to understanding the global insights of the process, setting performance targets, realizing these targets, and saving time and effort by focusing on the big picture first and dealing with the details later. This is a fundamentally different approach than using the designer's subjective decisions to alter the process and check the consequences using detailed analysis. It is also different from using simple end-of-pipe treatment solutions. Instead, the various species are optimally allocated throughout the process. Therefore, objectives such as yield enhancement, pollution prevention, and cost savings can be simultaneously addressed. Indeed, pollution prevention (when undertaken with the proper techniques) can be a source of profit for the company, not an economic burden.

PROBLEMS

5.1. Let us revisit the tire-to-fuel process described in Problem 4.1. Figure 5.23 is a more detailed flowsheet. Tire shredding is achieved by using high-pressure water jets. The shredded tires are fed to the process while the spent water is filtered. The wet cake collected from the filtration system is forwarded to solid waste handling. The filtrate is mixed with 0.20 kg/s of fresh water makeup to compensate for water losses with the wet cake (0.08 kg water/s) and the shredded tires (0.12 kg water/s). The mixture of filtrate and water makeup is fed to a high-pressure compression station for recycle to the shredding unit. Due to the pyrolysis reactions, 0.08 kg water/s are generated.

The plant has two primary sources for wastewater; the decanter (0.20 kg water/s) and the seal pot (0.15 kg/s). The plant has been shipping the wastewater for off-site treatment. The cost of wastewater transportation and treatment is \$0.01/kg leading to a wastewater treatment cost of approximately \$110,000/yr. The plant wishes to stop off-site treatment of wastewater to avoid cost of off-site treatment (\$110,000/yr) and alleviate legal-liability concerns in case of transportation accidents or inadequate treatment of the wastewater. The objective of this problem is to eliminate or reduce to the extent feasible off-site wastewater treatment. For capital budget authorization, the plant has the following economic criterion:

$$\text{Payback period} = \frac{\text{Fixed capital investment}}{\text{Annual savings}} \leq 3 \text{ years} \quad (5.15)$$

where

Annual Savings = Annual avoided cost of off-Site treatment - Annual operating cost of on-site system

In addition to the information provided by Problem 3.1., the following data are available:

Economic Data

- Fixed cost of extraction system associated with S_2 , \$ = 120,000 (Flowrate of wastewater, kg/s)^{0.58}

- Fixed cost of adsorption system associated with S_3 , \$ = 790,000 (Flowrate of wastewater, kg/s)^{0.70}
- Fixed cost of stripping system associated with S_4 , \$ = 270,000 (Flowrate of wastewater, kg/s)^{0.65}
- A biotreatment facility that can handle 0.35 kg/s wastewater has a fixed cost of \$240,000 and an annual operating cost of \$60,000/yr.

Technical Data

Water may be recycled to two sinks; the seal pot and the water-jet compression station. The following constraints on flowrate and composition of the pollutant (heavy organic) should be satisfied:

Seal Pot:

- $0.10 \leq \text{Flowrate of feed water (kg / s)} \leq 0.20$
- $0 \leq \text{Pollutant content of feed water (ppmw)} \leq 500$

Makeup to Water-Jet Compression Station

- $0.18 \leq \text{Flowrate of makeup water (kg / s)} \leq 0.20$
- $0 \leq \text{Pollutant content of makeup water (ppmw)} \leq 50$

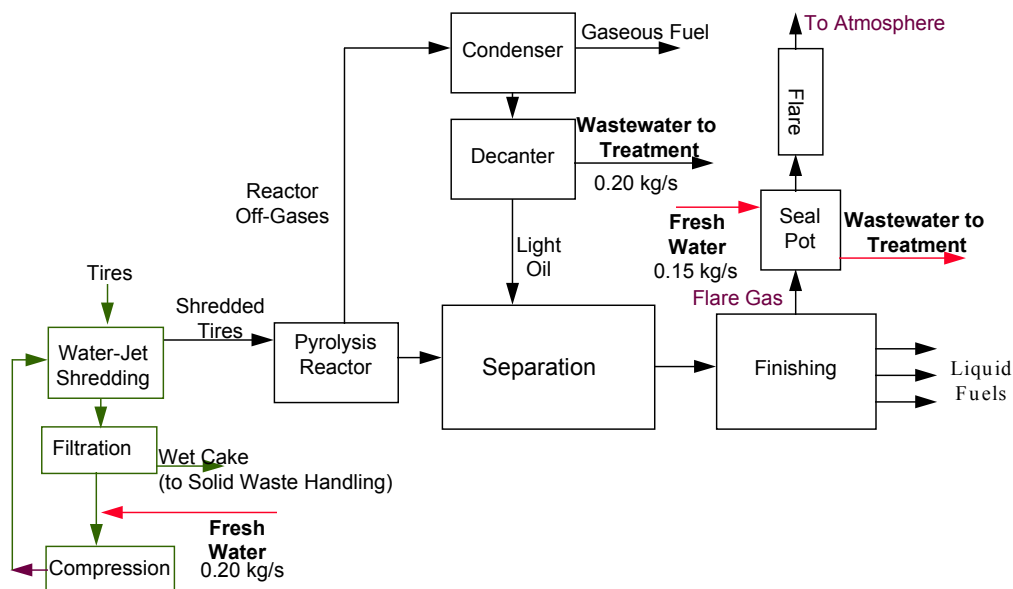


Fig. 5.23. Schematic flowsheet of tire-to-fuel process (El-Halwagi, 1997)

4.2. Consider the magnetic-tape manufacturing process previously described by problem 4.7. In this process (Dunn et al., 1995), 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.

Three MSAs can be used to remove the solvent from the gaseous emission. The equilibrium data for the transfer of the organic solvent to the j th lean stream is given by $y = m_j x_j$ where the values of m_j are given in Table 5.5. Throughout this problem, a minimum allowable composition difference, of 0.001(kg organic solvent)/(kg MSA) is to be used.

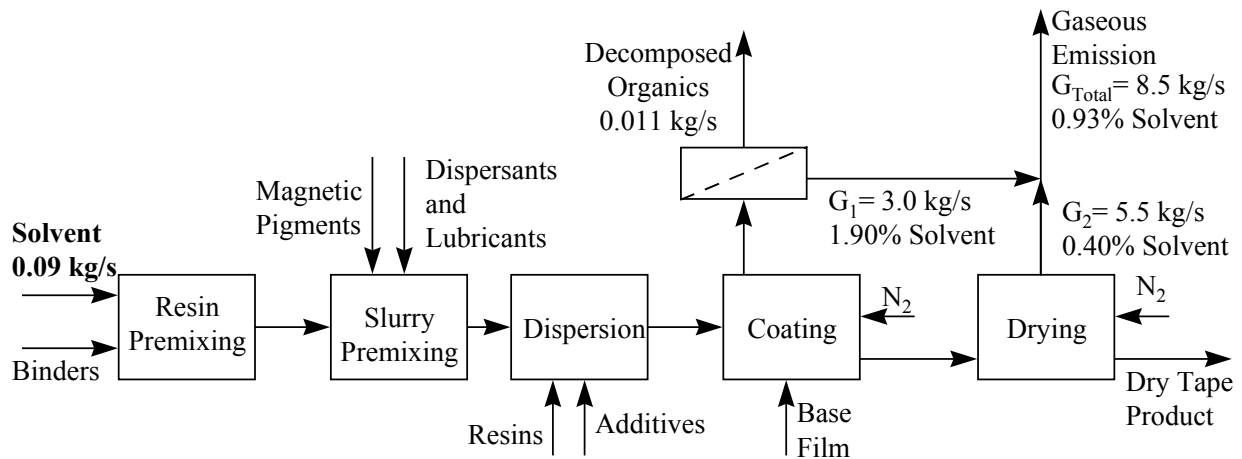


Fig. 5.24. Schematic representation of a magnetic tape manufacturing process (Dunn et al., 1995, El-Halwagi, 1997)

Table 5.5. Data for the MSAs

Stream	Upper Bound	Supply	Target	m_j	ϵ_j	C_j
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	on Flowrate L_j^c kg/s	Composition (mass fraction) x_j^s	Composition (mass fraction) x_j^t		mass fraction	\$/kg MSA
S₁	∞	0.014	0.040	0.4	0.001	0.002
S₂	∞	0.020	0.080	1.5	0.001	0.001
S₃	∞	0.001	0.010	0.1	0.001	0.002

The annualized fixed cost of a mass exchanger, \$/yr, may be approximated by 18,000 (Gas Flowrate, kg/s)^{0.65}. The value of the recovered solvent is \$0.80/kg of organic solvent.

In addition to the environmental problem, the facility is concerned about the waste of resources, primarily in the form of used solvent (0.09 kg/s) that costs about \$2.3 million/yr. It is desired to undertake a mass-integration analysis to optimize solvent usage, recovery and losses. It may be assumed that outlet gas composition from the coating and the dryer chambers are independent of the entering gas compositions.

Develop a minimum-cost solution which minimizes the usage of fresh solvent in the process. The solution strategies may include segregation, mixing, recycle and interception. Evaluate the payback period for your solution.

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