.4 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:

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

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

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

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

$$0 \leq M_j^{\text{sink}} \leq M_j^{\max} \quad \text{where } j = 1, 2, \ldots, N_{\text{sinks}} \tag{3.57}$$

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.,*

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

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,

$$z_1^{\max} \le z_2^{\max} \le \ldots z_j^{\max} \ldots \le z_{N_{\text{sinks}}}^{\max}$$

2. Rank sources in ascending order of impurities composition, i.e.,

$$y_1 < y_2 < \ldots y_i \ldots < y_{N_{\text{sources}}}$$

3. Plot the maximum admissible load of impurities in each sink ($M_j^{\text{sink,max}} = G_j z_j^{\max}$) versus its flowrate. Therefore, each sink is represented by an arrow whose vertical distance is $M_j^{\text{sink,max}} = G_j z_j^{\max}$, 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 *sink composite curve* (Figure 3-18).

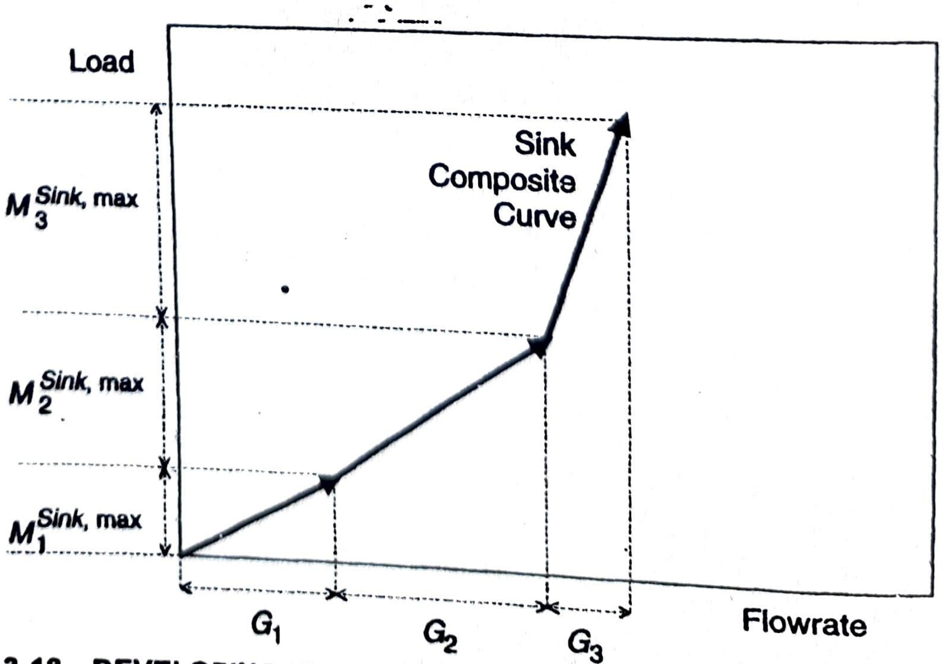


FIGURE 3-18 DEVELOPING SINK COMPOSITE DIAGRAM

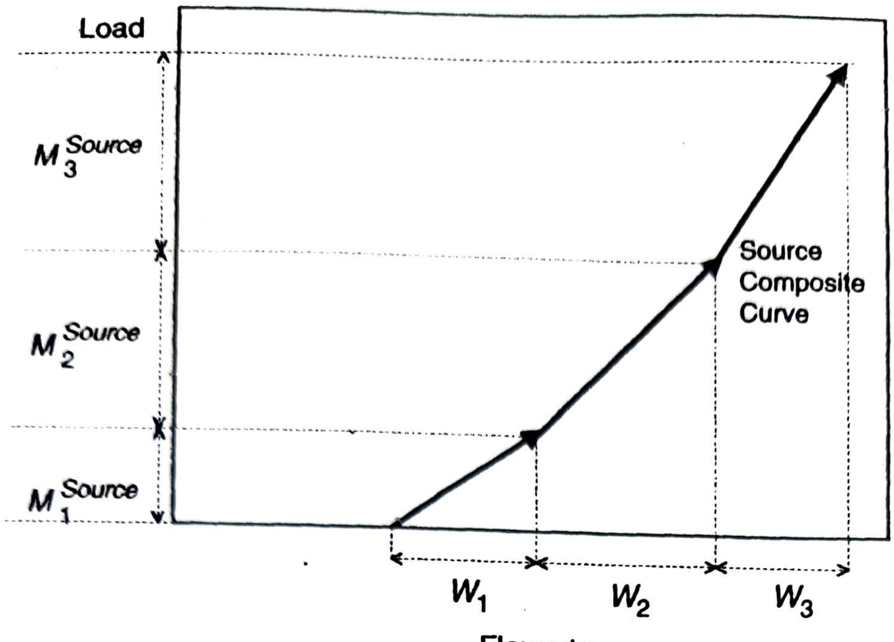


FIGURE 3-19 DEVELOPING SOURCE COMPOSITE DIAGRAM

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 i^{th} 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 Figure 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 (Figure 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 (Figure 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 Figure 3-22.

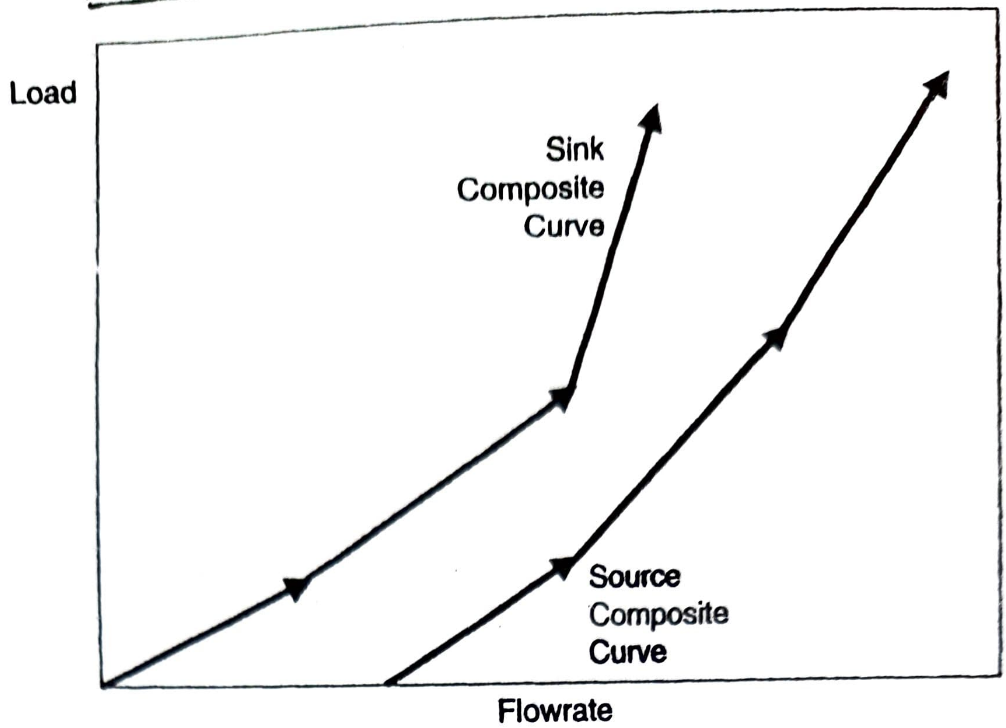


FIGURE 3-20 SINK AND SOURCE COMPOSITE DIAGRAMS

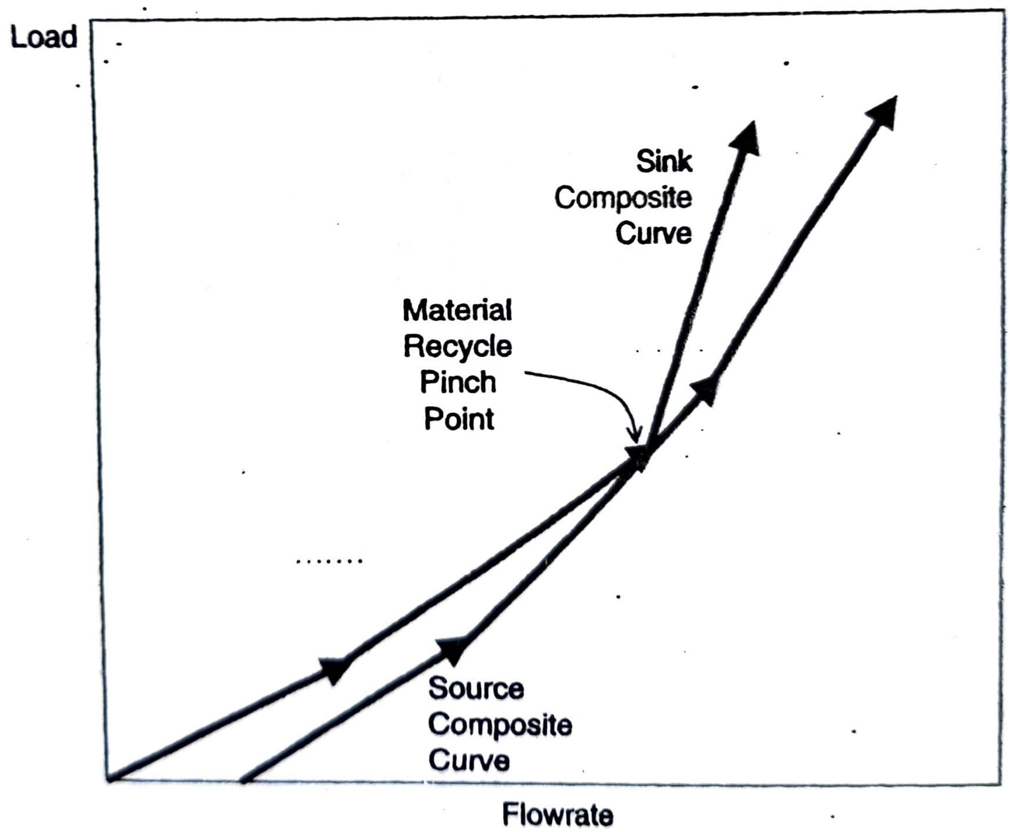


FIGURE 3-21 MATERIAL RECYCLE PINCH DIAGRAM (EL-HALWAGI ET AL., 2003)

3.5 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

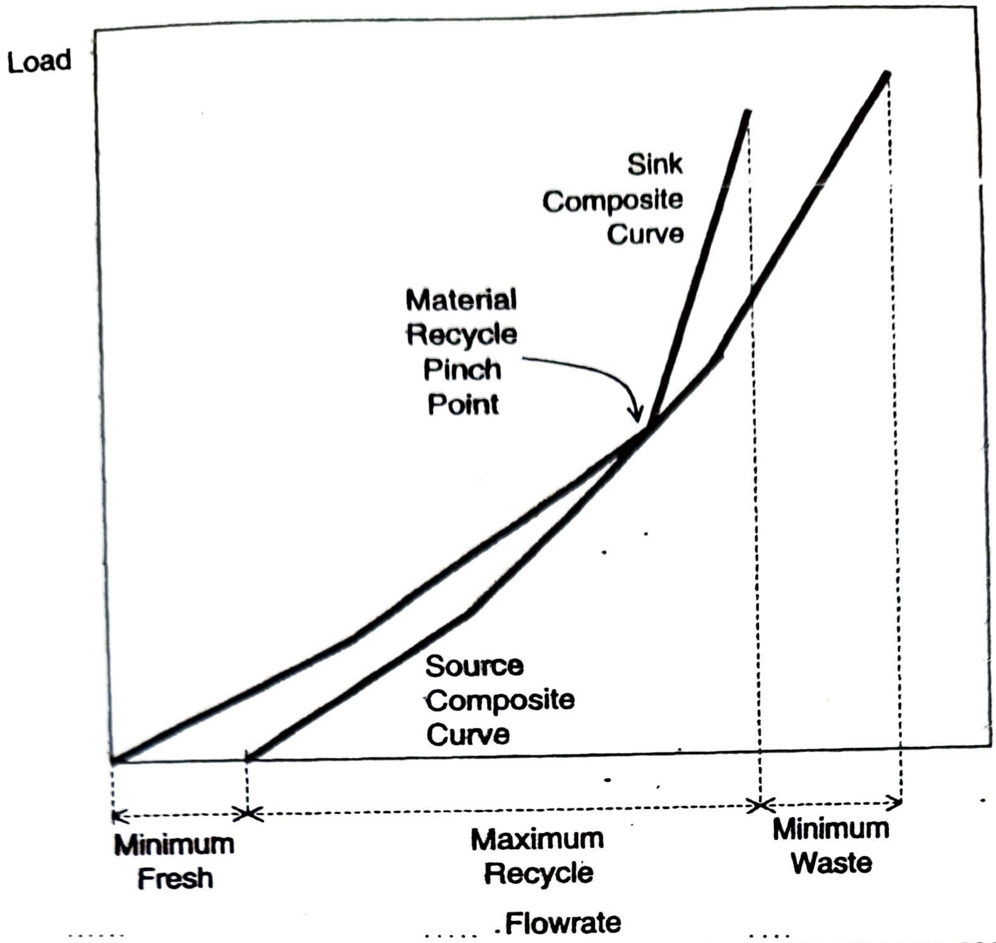


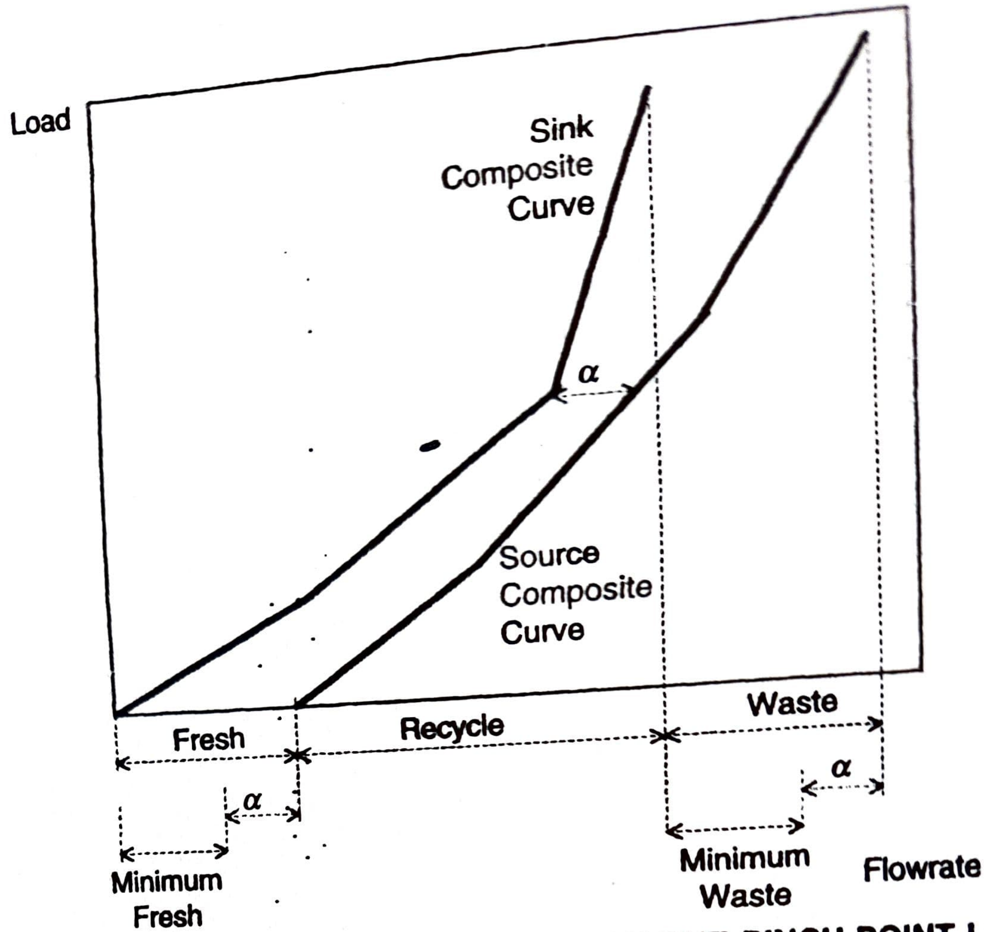
FIGURE 3-22 IDENTIFYING TARGETS FOR MINIMUM FRESH USAGE, MAXIMUM DIRECT RECYCLE, AND MINIMUM WASTE DISCHARGE (EL-HALWAGI ET AL., 2003)

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 right, 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 Figure 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 Figure (3-24).

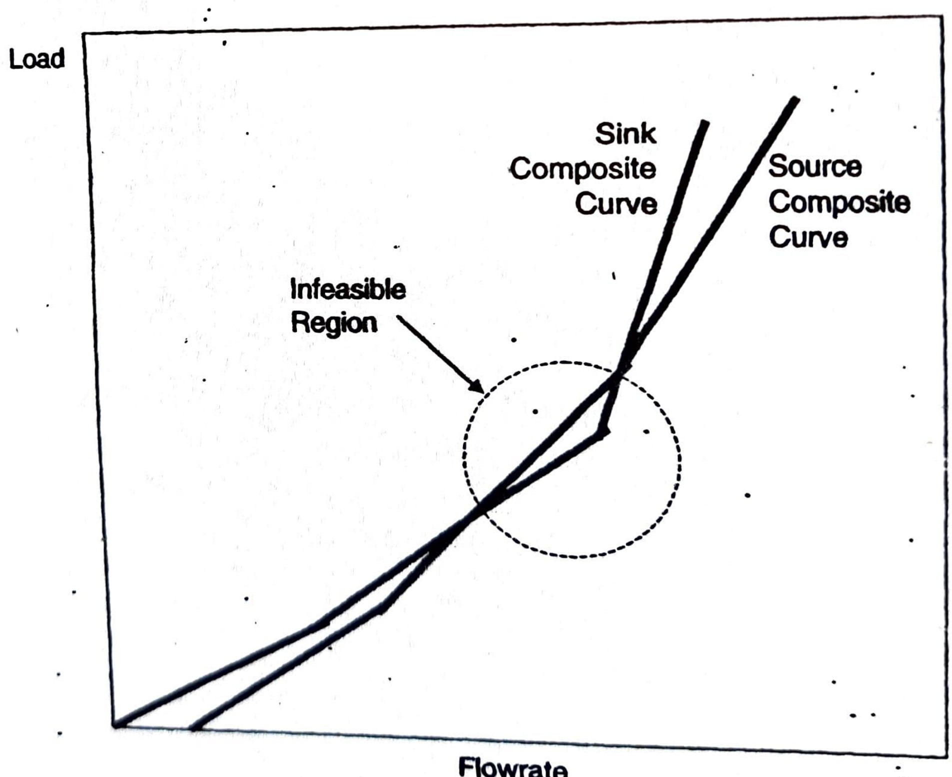
The above discussion indicates that in order to achieve the minimum usage of fresh resources, maximum reuse of the process sources, and minimum discharge of waste, the following *three design rules* are needed:

- 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



[redacted] FIGURE 3-23 PASSING FLOWRATE (α) THROUGH THE PINCH POINT LEADS TO LESS INTEGRATION



[redacted] FIGURE 3-24 VIOLATING PINCH POINT LEADS TO INFEASIBILITY

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.).

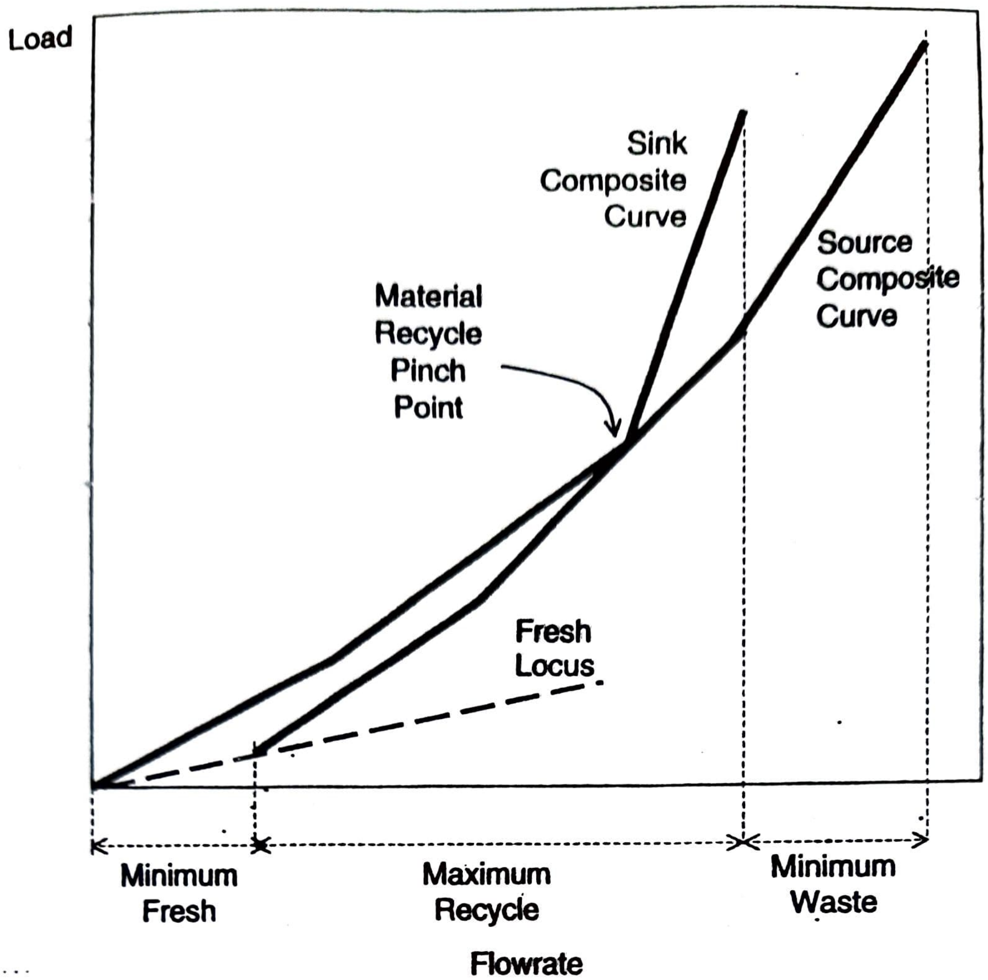


FIGURE 3-25 MATERIAL RECYCLE PINCH DIAGRAM WHEN FRESH RESOURCE IS IMPURE

3.5.1 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 reason for this is that with no impurities in the fresh, it does not contribute to 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 Figure 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.

3.5.2 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 is 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 Chapter Four, Seven, Thirteen, and Fourteen 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.

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

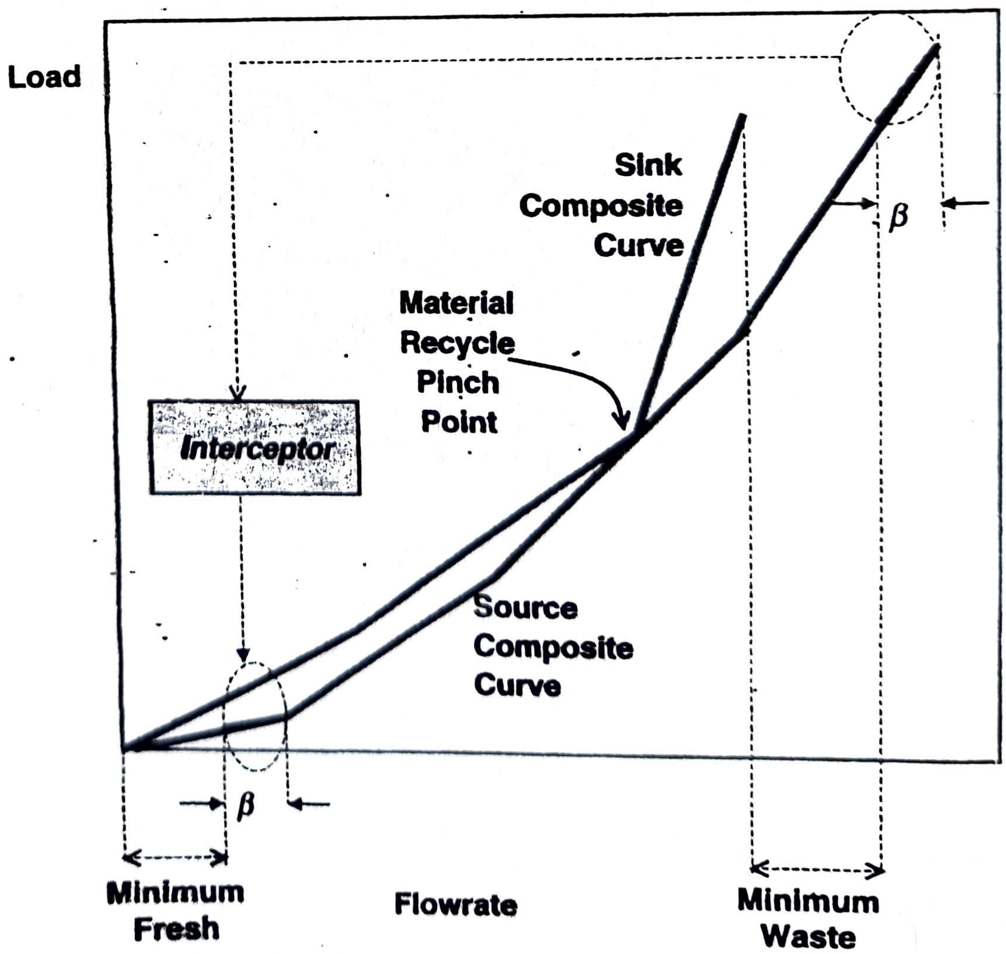


FIGURE 3-26a INSIGHTS FOR PROCESS MODIFICATION: MOVING A SOURCE ACROSS THE PINCH

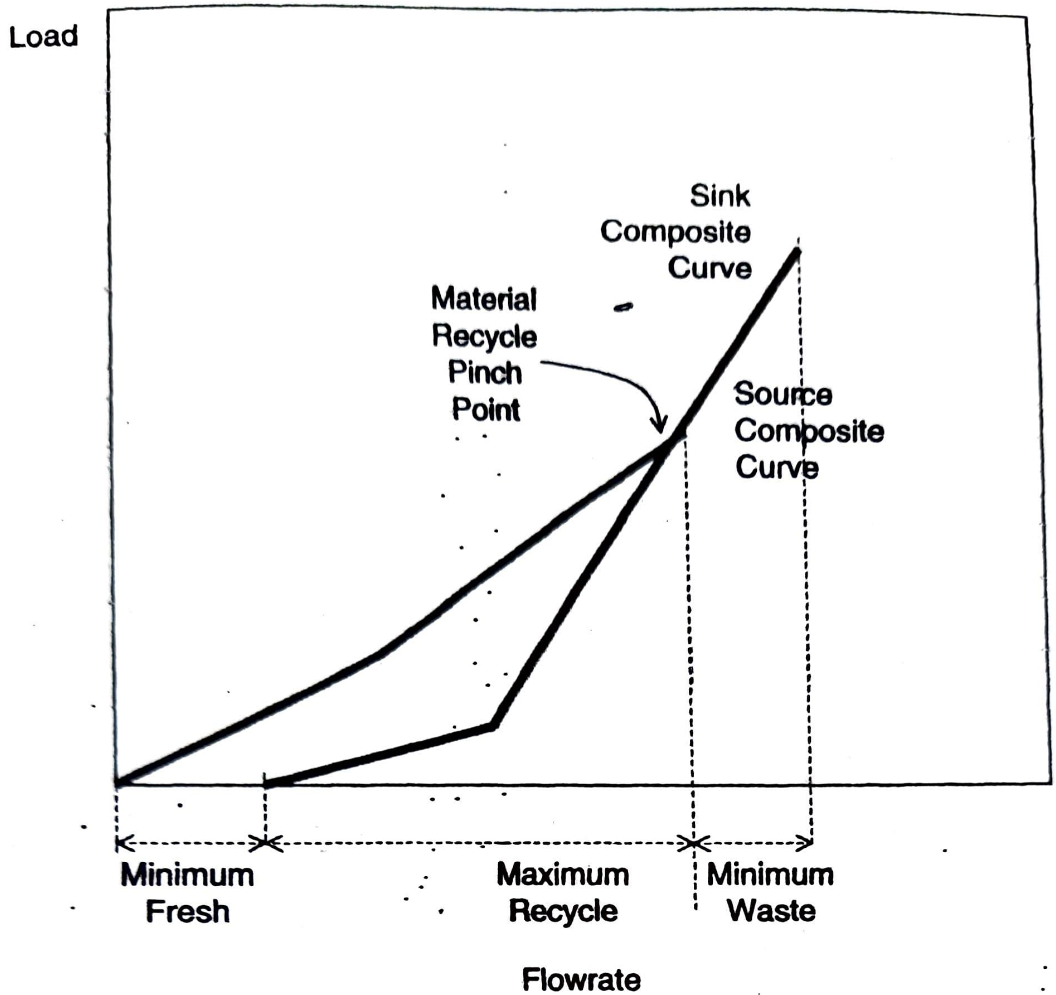


FIGURE 3-26b EXAMPLE OF A MATERIAL RECYCLE PINCH DIAGRAM BEFORE INTERCEPTION

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 Figure 3-26c.