Segregated Targeting for Multiple Resource Networks Using Decomposition Algorithm

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A generalized decomposition technique is presented for determining optimal resource usage in segregated targeting problems with single quality index (e.g., concentration, temperature, etc.) through pinch analysis. The latter problems are concerned with determining minimal resource requirements of process networks characterized by the existence of multiple zones, each consisting of a set of demands and using a unique external resource. However, all the zones share a common set of internal sources. The decomposition algorithm allows the problem to be decomposed into a sequence of subproblems, each of which can in turn be solved using any established graphical or algebraic targeting methodology to determine the minimum requirement of respective resource. This article presents a rigorous mathematical proof of the decomposition algorithm, and then demonstrates its potential applications with case studies on carbon-constrained energy sector planning, interplant water integration, and emergy-based multisector fuel allocation. © 2009 American Institute of Chemical Engineers *AIChE J,* 56: 1235–1248, 2010

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Introduction

Concerns about environmental sustainability, rising costs of raw material and waste treatment, as well as increasingly stringent emission regulations are among factors that drive the process industries to move forward to more sustainable resource conservation practices in recent years. Process integration techniques such as pinch analysis are among the widely accepted tools developed for resource conservation. The technique was originally developed for the systematic design of heat recovery systems in process plants[1–3] and was later extended for applications in mass and property integration.[4,5] More specifically, recently developed techniques have been focusing on resource conservation based on the source-sink allocation model, where sources represent processes that discharge potentially useful streams that may be reused/recycled; whereas the sinks refer to process units where these sources can be fed. A bipartite superstructure representation, such as the one shown in Figure 1, is often used to illustrate the source-sink model. Specific applications of the source-sink allocation model include that of water recovery,[6–12] hydrogen integration,[13–15] property-based material recovery,[16,17] and energy sector planning with various environmental footprint constraints.[18–21] Provided that

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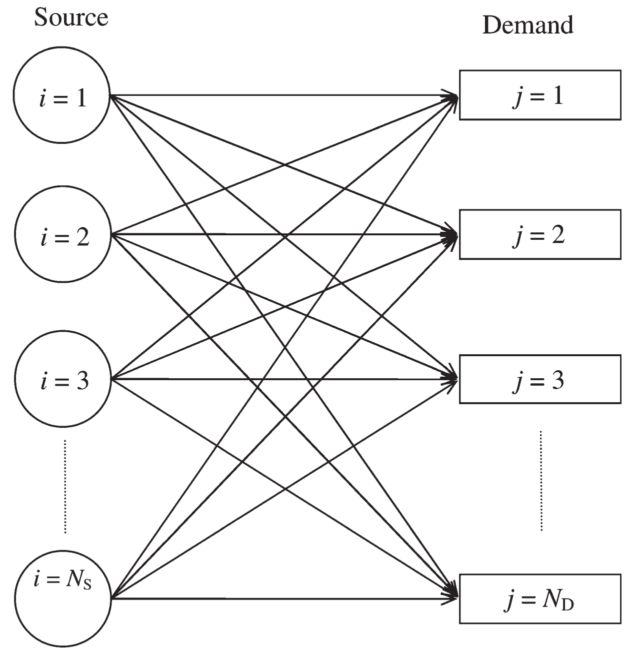

Figure 1. Superstructure representation for the source-sink allocation model.

process streams are characterized by a single overall index of quality (e.g., concentration, temperature, etc.) problems can be solved through pinch analysis techniques that are known to be equivalent to a linear programming optimization model.[6–9]

In most cases, targeting is only performed for a single set of sinks and sources for resource conservation. However, the recent work of Lee et al.[20] showed that there are cases where individual resource targets are needed for different subsystems or zones (termed as *segregated targeting*). Figure 2 illustrates the general segregated targeting problem; note that the key characteristic is that each zone has its own unique external resource, but the internal sources are shared by all the zones. The authors demonstrated a case in carbon-constrained energy sector planning where external low-carbon resources are targeted individually in different geographical regions that nevertheless share common fossil fuel resources. An automated targeting approach is adopted to find the fresh resource targets.[20] In this article, the same problem is reworked using a novel decomposition algorithm. Furthermore, it can be seen that the general segregated targeting problem can be applied by analogy to other domains that are structurally similar. Hence, apart from carbon-constrained energy sector planning, two other resource conservation problems are also solved to demonstrate the versatility of the newly proposed procedure. The second case study involves an interplant water reuse or recycle problem, whereas the third case study extends the methodology to fuel allocation planning across multiple zones using the concept of emergy. A rigorous mathematical proof of the decomposition algorithm is also provided.

Problem Statement and Mathematical Formulation

The general problem of segregated targeting for multiple resources using the decomposition algorithm may be mathematically stated as follows. A set of N_s sources is given. Each source i ($i = 1, 2\ldots N_s$) produces a flow F_{si} with a given quality q_{si}. Multiple sets or processes known as zones (with a cardinality of N_k), each having N_{dk} demands are also given, to where source streams may be allocated for reuse/recycle. Each individual demand j ($j = 1, 2\ldots N_{dk}$) in each zone k ($k = 1, 2\ldots N_k$) accepts a flow F_{djk} with a quality that has to be less than a predetermined maximum limit q_{djk}. The unused sources will be discharged as waste, without any quality and flow limitation. There is a set of N_k external resources, each with a quality of q_{rk}, and without flow limitation. Each external resource is available to only one corresponding zone, such that the kth external resource can only be supplied to the kth zone. No such restriction is imposed on the internal sources, which are shared by all zones. Flows are denoted by nonnegative real numbers. Stream quality is defined by a nonnegative real number, and it follows an inverse scale. A value of 0 indicates the highest possible quality and on the other hand, larger numerical values indicate lower quality.[15] It may be noted that the flow and quality load limitations on waste generation may be imposed by the environmental regulations. However, such restrictions are relaxed in the present problem definition, similar to many other resource conservation problems.[6–10,14,22,23] Because of relaxation of additional restrictions on waste, no additional constraint is associated with the waste in the mathematical formulation of the problem. The objective of this work is to develop an algorithmic decomposition procedure that will identify an optimum strategy for integrating sources and demands to minimize the total external resource requirement. Note that different targeting techniques may be applied

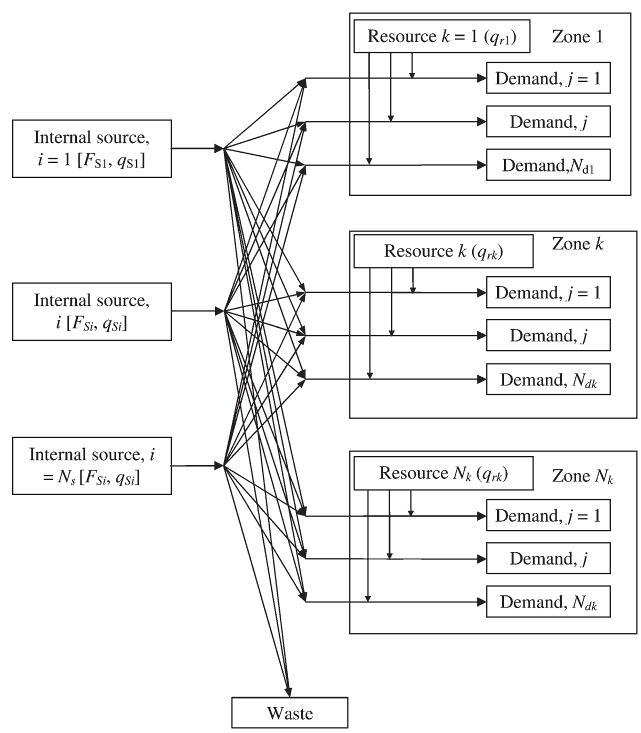

Figure 2. Superstructure representation for the segregated targeting problem.

within the algorithmic decomposition framework to obtain the same results.

Before developing an appropriate mathematical formulation for the earlier problem, the conservation equations for flows and qualities may be defined.[15] Note that two streams with flows F_1 and F_2 and quality levels q_1 and q_2, respectively, may be mixed to produce a stream with flow F_3 and quality q_3. The product of quality with flow may be defined as quality load (Q). Then, flows and quality loads are conserved when the following relationships that constitute linear mixing rules are satisfied.

$$F_1 + F_2 = F_3 \tag{1}$$

$$F_1 q_1 + F_2 q_2 = F_3 q_3 \tag{2}$$

Now, let f_{ijk} denotes the flow transferred from source i to demand j of zone k. Similarly, let f_{rjk} and f_{iw} represent the flow transferred from external resource r to demand j of zone k and flow transferred from source i to waste, respectively. Because of the flow conservation in Eq. 1, the flow balance for every internal source and for every internal demand may be written as follows:

$$\sum_{jk=1}^{N_{dk}} f_{ijk} + f_{iw} = F_{si} \qquad \text{for every source } i \in \{1, 2 \ldots N_s\} \tag{3}$$

$$f_{rjk} + \sum_{i=1}^{N_s} f_{ijk} = F_{djk} \quad \text{for every demand } j \in \{1, 2 \ldots N_{dk}\} \text{ in zone } k \in \{1, 2 \ldots N_k\} \tag{4}$$

By definition, every demand accepts a flow F_{djk} with a quality that has to be less than a predetermined maximum limit q_{djk}. Using the quality load conservation in Eq. 2, the quality requirement for any internal demand may be mathematically expressed as follows:

$$f_{rjk} q_{rk} + \sum_{i=1}^{N_s} f_{ijk} q_{si} \le F_{djk} q_{djk}$$
$$\text{for every demand } j \in \{1, 2 \ldots N_{dk}\} \text{ in zone } k \in \{1, 2 \ldots N_k\} \tag{5}$$

It may be noted that the quality levels for every source and every resource are known by definition. Therefore, Eq. 5 is linear in terms of flow variables.

The total requirement of resources may be calculated to be

$$\sum_{k=1}^{N_k} \sum_{jk=1}^{N_{dk}} f_{rjk} = R \tag{6}$$

The objective is to minimize R subject to the constraints given by Eqs. 3–5. As all the constraints and the objective function are linear, this is a linear programming problem.

A novel decomposition method is now illustrated to solve the earlier linear programming problem in a sequential manner. Because different targeting techniques may be used to solve the same problem, the decomposition algorithm and the proposed segregated targeting procedure will be illustrated in conjunction with different pinch analysis approaches for three illustrative examples that follow.

The Decomposition Algorithm

The decomposition algorithm proposed for the segregated targeting problem is a generic procedure that can be applied in conjunction with any of the established pinch-based targeting techniques developed for the resource conservation problems that is described by the source-sink problem. The steps of the proposed algorithm are summarized as a flow chart in Figure 3 and are illustrated as follows:

1. The zones of the system are first ranked in descending order, based on the quality levels of their respective external resources (q_{rk}). In case of any ties, the sequence may be determined arbitrarily.
2. The decomposition procedure begins with the zone with the poorest quality external resource (i.e., with maximum q_{rk}). The minimum external resource requirement of this zone is determined using any of the existing graphical or algebraic targeting techniques.
3. The zone being analyzed will have regions with quality index levels that are higher and lower than that of its pinch quality index. Essentially, the pinch quality index

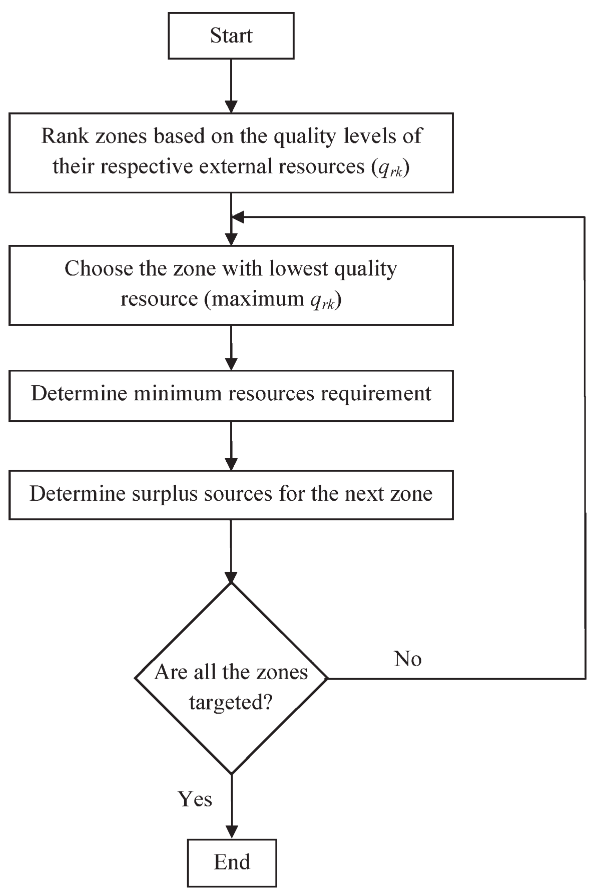

Figure 3. Flow chart of the proposed decomposition algorithm for segregated targeting.

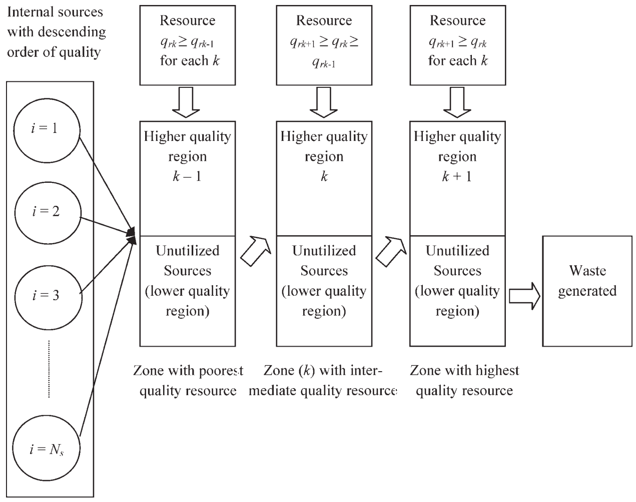

Figure 4. Graphical representation of the decomposition algorithm.

divides the entire zone into two regions: region with higher quality indices (lower quality region) and region with lower quality indices (higher quality region). For the demands or sinks in the (higher quality region), there is no flexibility with respect to allocation of streams, as any changes will alter the external resource target determined previously. In the lower quality region, however, the stream allocation is changed to maximize the total load within the zone. Note that this shift may create multiple pinch points and a terminal pinch point at the end of the composite curves or the last quality index level in the algebraic targeting techniques.[11,20]

4. The demands drawn by the current zone from the shared pool of internal sources are then deducted from the amounts originally available. There are two possibilities here. First, the current zone may consume all of the available internal source streams, leaving no surplus for other zones in the system. Alternatively, the current zone may only require a portion of an available source for its own use, in which case any excess can be left to be used by the other zones. All that is necessary to determine the surplus is to deduct the consumption of the current zone from the currently available source. The adjusted quantities represent the internal sources still available for use by the remaining zones.

5. Steps 2–4 are repeated for the different zones following the sequence previously determined in Step 1, until all the external resource targets have been determined. The combined resource demand of all the zones is then the optimal target for the entire system.

The proposed decomposition algorithm is illustrated graphically through Figure 4.

Mathematical proof of the decomposition algorithm

The mathematical proof of the proposed decomposition algorithm is presented in this subsection. Using the perturbation method, it is illustrated that the proposed algorithm gives an optimum solution. Without loss of generality, two zones are assumed with $q_{r1} > q_{r2}$. The proposed algorithm suggests that after satisfying the first zone (because $q_{r1} > q_{r2}$), remaining surplus sources may be passed to the second zone. Let δ be the incremental flow from any source supplied to the second zone without using it in the first zone. It will be shown that by doing this total resource requirement (R) will not be reduced.

Pillai and Bandyopadhyay[22] proved that for a resource allocation problem, minimization of the external resource requirement (R) is equivalent to the minimization of the total waste generation (W). Therefore, it is sufficient to prove that the total waste generation is not reduced by the proposed flow perturbation and hence, the proposed algorithm produces a local optimal solution.

It is possible to perturb the current solution by an incremental flow of magnitude δ that may be transferred from sources from different quality regions of the first zone:

Case (1): δ is transferred from a source at the pinch or the higher quality region of the first zone, and

Case (2): δ is transferred from a source at the lower quality region.

Case 1. Let δ be the incremental amount of flow from source S_i in the first zone, with quality q_{si} (such that $q_{si} \le q_{p1}$, where q_{p1} is the pinch quality of the first zone) transferred to the second zone. Now to satisfy the demands of the first zone, δ_1 of flow with quality q_{sj} (such that $q_{sj} > q_{si}$) and δ_2 of flow with quality q_{sk} (such that $q_{sk} < q_{si}$) are to be used in the first zone. Because all sources in the higher quality region are completely used, δ_2 of flow has to be supplied from the external resource (i.e., $q_{sk} = q_{r1}$). As the original requirement from source S_i is replaced by two other sources, the flow and the quality load balances may be expressed as follows:

$$\delta_1 + \delta_2 = \delta \tag{7}$$

$$\delta_1 q_{sj} + \delta_2 q_{r1} = \delta q_{si} \tag{8}$$

Values of δ_1 and δ_2 can be determined by solving the earlier-mentioned equations. Because of perturbation of the source flows to the second zone (δ increased at q_{si} and δ_1 reduced at q_{sj}), the waste generation from the second zone also changes. To calculate the change in the waste flow, expression for minimum waste generation by a resource allocation problem, as derived by Pillai and Bandyopadhyay[22] is used.

$$W = \sum_{\substack{i=1\\ q_{si}>q_p}}^{N_s} F_{si} - \sum_{\substack{j=1\\ q_{dj}>q_p}}^{N_d} F_{dj} + \sum_{\substack{i=1\\ q_{si}\le q_p}}^{N_s} F_{si}\frac{(q_{si}-q_{rs})}{(q_p-q_{rs})} - \sum_{\substack{j=1\\ q_{dj}\le q_p}}^{N_d} F_{dj}\frac{(q_{dj}-q_{rs})}{(q_p-q_{rs})} \tag{9}$$

It may be noted that the change in waste production depends on the pinch quality of the second zone (q_{p2}). Based on Eq. 9, the change in waste production due to flow perturbation may be calculated as follows:

$$\Delta W = \begin{cases} \delta\dfrac{q_{si}-q_{r2}}{q_{p2}-q_{r2}} - \delta_1\dfrac{q_{sj}-q_{r2}}{q_{p2}-q_{r2}} & \text{when } q_{sj} \le q_{p2} \\ \delta\dfrac{q_{si}-q_{r2}}{q_{p2}-q_{r2}} - \delta_1 & \text{when } q_{sj} > q_{p2} \end{cases} \tag{10}$$

Using the expression for δ_1, obtained by solving Eqs. 7 and 8, Eq. 10 may be simplified as:

$$\Delta W = \begin{cases} \delta \dfrac{(q_{sj} - q_{si})(q_{r1} - q_{r2})}{(q_{p2} - q_{r2})(q_{sj} - q_{r1})} & \text{when } q_{sj} \leq q_{p2} \\ \delta \dfrac{(q_{sj} - q_{si})(q_{si} - q_{r2}) - (q_{p2} - q_{si})(q_{si} - q_{r1})}{(q_{p2} - q_{r2})(q_{sj} - q_{r1})} & \text{when } q_{sj} > q_{p2} \end{cases} \tag{11}$$

It may be easily seen that ΔW is always positive. Hence, by transferring excess flows from the pinch or the higher quality region of the first zone, the overall objective function deteriorates

Case 2. Similar to the previous case, let δ be the incremental amount of flow with quality q_{si} (such that $q_{si} > q_{p1}$) from source S_i in the lower quality region in the first zone transferred to the second zone. Now to satisfy the demands of the first zone, δ_1 of flow with quality q_{sj} (such that $q_{sj} > q_{si}$) and δ_2 of flow with quality q_{sk} (such that $q_{sk} < q_{si}$) are used in the first zone. Now it is possible to use sources at pinch or lower quality region, and external resource is not required. The flow balance is exactly same as Eq. 7, and the quality load balance may be expressed as follows:

$$\delta_1 q_{sj} + \delta_2 q_{sk} = \delta q_{si} \tag{12}$$

The change in waste production, due to perturbation of the source flows to the second zone (δ increased at q_{si} and δ_1 and δ_2 reduced at q_{sj} and q_{sk}, respectively), may be calculated as follows:

$$\Delta W = \begin{cases} \delta \dfrac{q_{si} - q_{r2}}{q_{p2} - q_{r2}} - \delta_1 \dfrac{q_{sj} - q_{r2}}{q_{p2} - q_{r2}} - \delta_2 \dfrac{q_{sk} - q_{r2}}{q_{p2} - q_{r2}} & \text{when } q_{sk} < q_{si} < q_{sj} \leq q_{p2} \\ \delta \dfrac{q_{si} - q_{r2}}{q_{p2} - q_{r2}} - \delta_1 - \delta_2 \dfrac{q_{sk} - q_{r2}}{q_{p2} - q_{r2}} & \text{when } q_{sk} < q_{si} \leq q_{p2} < q_{sj} \\ \delta - \delta_1 - \delta_2 \dfrac{q_{sk} - q_{r2}}{q_{p2} - q_{r2}} & \text{when } q_{sk} \leq q_{p2} < q_{si} < q_{sj} \\ \delta - \delta_1 - \delta_2 & \text{when } q_{p2} < q_{sk} < q_{si} < q_{sj} \end{cases} \tag{13}$$

Using expressions for δ_1 and δ_2, the change in waste flow may be simplified as follows:

$$\Delta W = \begin{cases} 0 & \text{when } q_{sk} < q_{si} < q_{sj} \leq q_{p2} \\ \delta \dfrac{(q_{sj} - q_{p2})(q_{si} - q_{sk})}{(q_{sj} - q_{sk})(q_{p2} - q_{r2})} & \text{when } q_{sk} < q_{si} \leq q_{p2} < q_{sj} \\ \delta \dfrac{(q_{sj} - q_{si})(q_{p2} - q_{sk})}{(q_{sj} - q_{sk})(q_{p2} - q_{r2})} & \text{when } q_{sk} \leq q_{p2} < q_{si} < q_{sj} \\ 0 & \text{when } q_{p2} < q_{sk} < q_{si} < q_{sj} \end{cases} \tag{14}$$

Similar to the previous case, it may be shown that ΔW is always nonnegative. Hence, by transferring excess flows from a source with quality index higher than the pinch quality of the first zone, the overall objective function cannot be improved.

Combining the results of both the cases, it may be concluded that the proposed algorithm produces a local optimal solution. As this is also a linear programming problem, a local optimum solution is the global optimum solution. This completes the proof of the following theorem:

Theorem. *The minimum value of the total resource requirement (R) subject to constraints 3–5 is identical to the one produced by the decomposition algorithm.*

It may be noted that the proof of the proposed decomposition algorithm is developed based on the analytical techniques of source composite curve.[22] However, the algorithm and the proof are independent of the method. It may be possible to prove the validity of the decomposition algorithm using other targeting techniques.[7,9] Applications of the proposed algorithm are illustrated through following examples. In these examples, different targeting techniques are used to demonstrate that the decomposition algorithm is independent of the targeting technique. Each of the case studies presented also includes a brief description of the specific targeting technique used therein. However, due to space constraints, the reader is referred to the appropriate sources for the full details of these targeting techniques.

Illustrative Examples

Carbon-constrained energy sector planning through source composite curve

The data for this example are given in Table 1.[20] For this example, energy demand and supply in TJ is considered as

Table 1. Flow and Quality Data for Example 1

	Quality (CO_2 emission factor in t/TJ)	Flow (energy in TJ)
Internal Sources		
Coal	105	5,000,000
Oil	75	1,000,000
Natural Gas	55	800,000
Internal Demands: Transportation Sector		
T1	30	400,000
T2	40	720,000
T3	50	720,000
Internal Demands: Industrial Sector		
I1	30	1,600,000
I2	40	480,000
I3	50	80,000
Resources		
R1	Biodiesel (low carbon) with a quality of 16.5 t CO_2/TJ applicable only to transportation sector	
R2	Biogas and hydropower (carbon-neutral) with a quality of 0 t CO_2/TJ applicable only to industrial sector	

the flow and carbon dioxide emission factor in t/TJ is considered as the quality index. Energy and carbon dioxide emission are conserved due to conservation of energy and mass, respectively and therefore, they satisfy Eqs. 1 and 2. In this example, there are three internal sources, namely, coal, oil, and natural gas. There are two types of demands (zones), i.e., transportation and industrial sectors. Each sector consists of three energy demands, based on the region.[20] A low carbon source, i.e., biodiesel, is the external resource (q_{r1} = 16.5 t/TJ) for transportation sector. On the other hand, carbon-neutral energy sources, consisting biogas and hydropower, is the external resource (q_{r2} = 0 t/TJ) for the industrial sector. It has been assumed that there is no limitation associated with the energy available from these resources. Unused energy is the waste for this example. The objective is to minimize the use of total resources for these two sectors satisfying all the region-specific emission constraints.

In this section, the segregated targeting problem is illustrated using the source composite curve, originally developed for targeting for resource conservation network.[11,12,15,22,23] The targeting procedure using the source composite curve is reviewed briefly before applying the decomposition algorithm to address the segregated targeting problem in the first example on carbon-constrained energy sector planning.[20]

Source composite curve

Steps of the algebraic procedure for targeting minimum waste generation through source composite curve are as follows. First six steps are shown in Table 2.

Step 1: Quality indices of all internal sources, demands and resource are tabulated in decreasing order in the first column.

Step 2: Net flows (i.e., algebraic sum of flows corresponding to a given quality) are tabulated in the second column. Consider flows corresponding to internal sources as positive and flows corresponding to demands as negative.

Step 3: Cumulative flows are tabulated in third column. Summation of net flows for all previous rows denotes the cumulative flows for any particular row. The last entry in this column suggests flow loss/gain (Δ) in the overall system. Negative entry suggests flow loss, and a positive entry indicates an overall flow gain in the system.

Step 4: The fourth column represents the quality load for each quality interval. The first entry in the fourth column is always 0. For all subsequent rows, the difference between the last two qualities is multiplied by the cumulative flows to calculate the quality load.

Step 5: Cumulative quality loads are calculated by summing quality loads for all previous rows and tabulated in fifth column. The fifth column (cumulative quality load) may now be plotted against the first column (quality) to obtain the source composite curve. The bottom entry in the fifth column signifies the total quality load discharged as waste (ΔQT).

Step 6: Waste generation can be estimated based on the cumulative quality load and the total quality load. Flow for waste generation is calculated using the following formula for rows such that $q_{nk} > q_{rk}$.

$$W_{nk} = \frac{\Delta Q_T - \sum_{l=1}^{nk} Q_l}{(q_{nk} - q_{rk})} \qquad \text{for } q_{nk} > q_{rk} \tag{15}$$

The largest entry in this column is the target for the minimum waste generation. Corresponding minimum resource

Table 2. Generation of Source Composite Curve

	1st column, quality	2nd column, net flows	3rd column, cumulative flows	4th column, quality load	5th column, cumulative quality load	6th column, waste flow
1st row	q_1	F_1	F_1	$Q_1 = 0$	$Q_1 = 0$	$W_1 = \frac{\Delta Q_T}{(q_1 - q_{rs})}$
2nd row	q_2	F_2	$F_1 + F_2$	$Q_2 = F_1\,(q_1 - q_2)$	$Q_1 + Q_2 = F_1(q_1 - q_2)$	$W_2 = \frac{\Delta Q_T - Q_2}{(q_2 - q_{rs})}$
……	……	……	……	……	……	……
kth row	q_k	F_k	$\sum_{l=1}^{k} F_l$	$Q_k = (q_{k-1} - q_k)\left(\sum_{l=1}^{k-1} F_l\right)$	$\sum_{l=1}^{k} Q_l = \sum_{l=1}^{k-1} F_l(q_l - q_k)$	$W_k = \frac{\Delta Q_T - \sum_{l=1}^{k} Q_l}{(q_k - q_{rs})}$
……	……	……	……	……	……	……
nth (last) row	q_n	F_n	$\sum_{l=1}^{n} F_l = \Delta$	$Q_n = (q_{n-1} - q_n)\left(\sum_{l=1}^{n-1} F_l\right)$	$\sum_{l=1}^{n} Q_l = \sum_{l=1}^{n-1} F_l(q_l - q_n) = \Delta Q_T$	–

Table 3. Determining the Minimum Biodiesel Requirement for the Transportation Sector of Example 1

Quality; CO_2 emission factor (t/TJ)	Net flows; energy (TJ)	Cumulative flows; cumulative energy (TJ)	Quality load; CO_2 emission (10^6 t)	Cumulative quality load; cumulative CO_2 emission (10^6 t)	Waste flow; unused energy (TJ)	Waste flow after first pinch; unused energy (TJ)
105	5,000,000	5,000,000	0	0	5,484,293.8	5,000,000
75	1,000,000	6,000,000	150	150	5,732,649.6	–
55	800,000	6,800,000	120	270	5,593,766.2	–
50	−720,000	6,080,000	34	304	5,413,731.3	–
40	−720,000	5,360,000	60.8	364.8	5,130,212.8	–
30	−400,000	4,960,000	53.6	418.4	4,960,000	–
16.5	0	4,960,000	66.96	485.36	–	–

requirement may be determined through overall flow balance equation. The quality that corresponds to the minimum waste generation, is the pinch quality (q_{pk}).

Step 7: After determining the first pinch quality (q_{pk}) and the corresponding quality load (Q_{pk}), waste generation at lower quality region is calculated using Equation (15) with $\Delta Q_T = Q_{pk}$ and $q_{rk} = q_{pk}$. This step is repeated until all the sources are exhausted.

Step 8: Waste or the surplus resources are determined at any particular pinch quality by subtracting waste generation at higher qualities from the waste generated at that quality.

The earlier procedure of waste calculation along with the decomposition algorithm is applied to solve Example 1 on carbon-constrained energy sector planning problem.

Illustrative example 1

As the quality index value of biodiesel is higher than that of the carbon-neutral energy sources, the minimum biodiesel requirement for the transportation sector with all internal sources is determined first. The numerical values calculated by applying the algebraic procedure of source composite curve are shown in Table 3. For this subproblem, the flow difference is 4,960,000 TJ (last entry in the third column in Table 3) which suggests that there is an overall energy surplus of 4,960,000 TJ. The last entry of the fifth column suggests that 485.36 $\times$ 10^6 t of carbon dioxide emission load cannot be used. The source composite curve for this example is shown in Figure 5. The sixth column in Table 3 represents the target for the minimum amount of total energy that cannot be used. It identifies the pinch quality as 75 t/TJ (corresponds to the emission factor for oil) where the minimum amount of used energy (5,732,649.6 TJ) is found. Based on the overall flow balance, the minimum requirement for the biodiesel is obtained as 772649.6 TJ (= 5,732,649.6–4,960,000 TJ).

After obtaining the total unused energy, distribution of unused energy at different emission factors are determined. Following the algebraic procedure of source composite curve, the distribution of the unused energy at different emission factors is tabulated in the seventh column of Table 3. In this example, unused energy sources are determined to be 5,000,000 TJ of coal and 732649.6 TJ (= 5,732,649.6–5,000,000 TJ) of oil. It may be noted that the available natural gas is completely used in the transportation sector, as the pinch quality is higher than the quality index of natural gas.

Requirement of the carbon-neutral energy resources (biogas, hydropower) are determined for the industrial sector with its own demand and the residual energy sources unused in the transportation sector. The numerical values calculated by applying the proposed algorithm are shown in Table 4. For this subproblem, flow difference is 3,572,649.6 TJ, which suggests that there is an overall energy surplus of 3,572,649.6 TJ. The last entry of the fifth column suggests that 508.7 $\times$ 10^6 t of carbon dioxide emission load cannot be used. The source composite curve for this carbon pinch example is shown in Figure 6. The sixth column in Table 4 represents the target for the minimum amount of total energy that cannot be used. It identifies the pinch quality as 105 t/TJ (corresponds to the emission factor for coal) and the minimum amount of used energy as 4,845,225.9 TJ. Based on the overall flow balance, the minimum requirement for the carbon-neutral energy resources is obtained as 1,272,576.3 TJ (= 4,845,225.9−3,572,649.6 TJ).

Based on the proposed methodology, the total minimum resource requirement is targeted as 2,045,225.9 TJ (772,649.6 TJ of biodiesel and 1,272,576.3 TJ of biogas and hydropower) and 4,845,225.9 TJ of coal remain unused. Table 5 summarizes the allocation of the energy sources to the transportation and industrial sectors. These results match with those reported by Lee et al.[20] obtained using automated targeting procedure. It may be noted that the present methodology is based on the decomposition algorithm that has been proved mathematically. The proposed methodology is insight based. On the other hand,

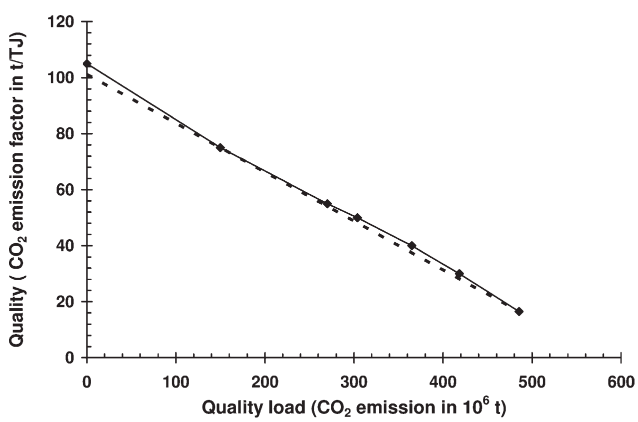

Figure 5. Source composite curve for the transportation sector incorporating entire internal sources and optimized waste line for Example 1.

Table 4. Determining the Minimum Carbon-Neutral Resource Requirement for the Industrial Sector of Example 1

Quality; CO_2 emission factor (t/TJ)	Net flows; energy (TJ)	Cumulative flows; cumulative energy (TJ)	Quality load; CO_2 emission (10^6 t)	Cumulative quality load; cumulative CO_2 emission (10^6 t)	Waste flow; unused energy (TJ)
105	5,000,000	5,000,000	0	0	4,845,225.9
75	732,649.6	5,732,649.6	150	150	4,783,316.2
55	0	5,732,649.6	114.6	264.6	4,438,104.1
50	−80,000	5,652,649.6	28.7	293.3	4,308,649.6
40	−480,000	5,172,649.6	56.5	349.8	3,972,649.6
30	−1,600,000	3,572,649.6	51.7	401.5	3,572,649.6
0	0	3,572,649.6	107.2	508.7	–

Lee et al.[20] used mathematical optimization approach to arrive at the same results.

Interplant water integration through cascade analysis technique

Water minimization using pinch analysis technique has been an active area of research since the mid 90s.[6–12,14,22–25] Recent works on water minimization has been extended into interplant integration, where further water recovery may be achieved.[26–29] In this section, a special case of interplant water integration is presented, where the individual plant water network has its own fresh water source (external resource) but may share the available water sources among the different plant networks.

In this section, the segregated targeting problem is illustrated using the cascade analysis technique that was developed for the resource conservation network[8,10,14,17,29–31] based on the decomposition algorithm. In the following sections, the targeting procedure using cascade analysis technique is first outlined, followed by the illustration in solving Example 2 on an interplant water integration problem that involves two water networks.

Targeting procedure with cascade analysis

The cascade table in Table 6 summarizes how cascade analysis technique is carried out for flow rate targeting in a resource conservation network.[8,10] Besides, Ng et al.[30] extended the cascade analysis technique to identify the waste stream(s) that emerges from a resource conservation network.

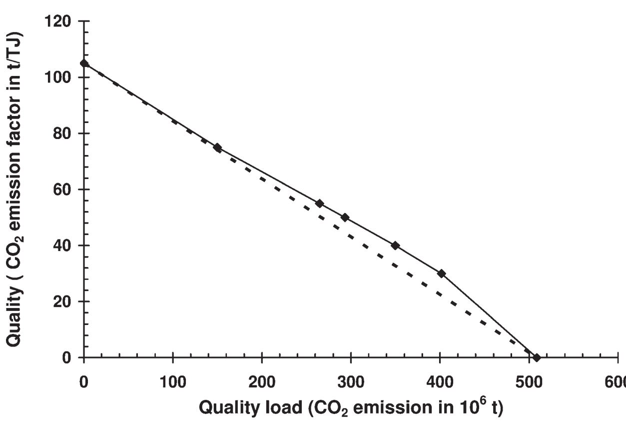

Figure 6. Source composite curve for the industrial sector incorporating residual sources and the optimized waste line for Example 1.

In this section, the major steps in carrying out the targeting technique are briefly outlined, the readers should refer to the original source for the detailed targeting procedure:[8,10,30]

Step 1: The quality levels (q_{nk}) are arranged in an ascending order ($n_k = 1, 2, \ldots, Nk$) in the first two columns of Table 6.

Step 2: Flow rates of sink (F_j) and source (F_i) are summed at their respective concentration level nk in columns 3 and 4. Column 5 represents the net flow rate, ($\Sigma_i F_i - \Sigma_j F_j$) between sources and sinks at each concentration level nk; with positive indicating surplus, negative indicating deficit.

Step 3: The net flow rate surplus/deficit is cascaded down the concentration levels to yield the cumulative surplus/deficit flow rate ($F_{C,nk}$) in column 6 with an assumed zero fresh resource flow rate ($R = 0$). This assumed flow rate is to facilitate the search for the minimum external resource flow rate and will be revised once the rigorous fresh resource target is located.

Step 4: Set up the cumulative impurity load cascade (Cum. Δm_{nk}) to fulfil the load constraints. Impurity load in column 7 (Δm_{nk}) is obtained by the product of cumulative flow rate ($F_{C,nk}$) and the difference across two quality levels ($q_{nk+1} - q_{nk}$). Cascading the impurity load down the quality levels yields the cumulative load (Cum. Δm_{nk}) in column 8. A feasible network is characterized by all positive Cum. Δm in column 8. A negative Cum. Δm_{nk} means the impurity load is transferred from lower to higher quality level, which is infeasible. In such a case, an interval external resource flow rate (R_{nk}, column 9) is calculated by dividing Cum. Δm_{nk} by the quality difference between level nk (q_{nk}) and that of the fresh resource (q_{rk}), i.e.,

$$R_{nk} = \frac{\text{Cum.}\Delta m_{nk}}{q_{nk} - q_{rk}} \tag{16}$$

Step 5: The absolute value of the largest negative R_{nk} is identified as the minimum external resource flow rate (R) for the network. The minimum flow rate will then replace the earlier assumed zero flow rate in the flow rate targeting (column 6) to obtain a new set of feasible flow rate and impurity

Table 5. Allocation of Energy Flows (in TJ) for Example 1

	Transportation sector	Industrial sector
Coal	0	154,744.1
Oil	267,350.4	732,649.6
Natural Gas	800,000	0
Biodiesel	772,649.6	0
Biogas and Hydropower	0	1,272,576.3

Table 6. Cascade Table for Targeting Minimum External Resource(s)

nk	qn_k	$\Sigma_j F_j$	$\Sigma_i F_i$	$\Sigma_i F_i - \Sigma_j F_j$	$F_{C,nk}$	Δm_{nk}	Cum. Δm_{nk}	$F_{FW,nk}$
					R			
nk	q_{nk}	$(\Sigma_j F_j)_1$	$(\Sigma_i F_i)_1$	$(\Sigma_i F_i - \Sigma_j F_j)_1$				
					$F_{C,nk}$	Δm_{nk}		
$nk+1$	q_{nk+1}	$(\Sigma_j F_j)_{nk+1}$	$(\Sigma_i F_i)_{nk+1}$	$(\Sigma_i F_i - \Sigma_j F_j)_{nk+1}$			Cum. Δm_{nk+1}	$F_{FW,nk+1}$
					$F_{C,nk+1}$	Δm_{nk+1}		
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$Nk-2$	q_{Nk-2}	$(\Sigma_j F_j)_{Nk-2}$	$(\Sigma_i F_i)_{Nk-2}$	$(\Sigma_i F_i - \Sigma_j F_j)_{Nk-2}$				
					$F_{C,Nk-2}$	Δm_{Nk-2}		
$Nk-1$	q_{Nk-1}	$(\Sigma_j F_j)_{Nk-1}$	$(\Sigma_i F_i)_{Nk-1}$	$(\Sigma_i F_i - \Sigma_j F_j)_{Nk-1}$			Cum. Δm_{Nk-1}	$F_{FW,Nk-1}$
					$F_{C,Nk-1} = \boldsymbol{W_k}$	Δm_{Nk-1}		
Nk	q_{Nk}						Cum. Δm_{Nk}	$F_{FW,Nk}$

load cascades (positive values for all Cum. Δm and zero Cum. Δm at the pinch). The final row in column 6 represents the waste flow rate (W) generated from the network.

Step 6: After identifying the minimum external resource flow rates and the pinch location, the sources and sinks are then segregated into the lower and higher quality regions. This includes the allocated flow rates of the pinch-causing source that is identified from the cascade analysis technique, i.e., quality intervals just above and below the pinch in the F_C column.[8,10]

Step 7: Cascade analysis is conducted for the lower quality region to locate the minimum pinch flow rate, $F_{P,\ nk}$, Eq. 16 is modified as Eq. 17 for this purpose:

$$F_{P,nk} = \frac{\text{Cum.}\Delta \text{m}_{nk}}{q_{nk} - q_{pk}} \tag{17}$$

where q_{pk} is the pinch quality. The allocated flow rate of the pinch-causing source is omitted in the pinch flow rate targeting in this lower quality region. The pinch flow rate target is the minimum flow rate requirement (supplied at the pinch quality) to satisfy all sinks in the lower quality region. The difference between the minimum pinch flow rate and the allocated flow rate of the pinch-causing source to the lower quality region determines the waste stream generated at the pinch quality. Besides, the unused source in this region will be discharged as waste.

Example 2 will next be used to illustrate the decomposition algorithm using the cascade analysis technique.

Illustrative example 2

Table 7 shows the limiting water data for Example 2, where interplant water integration is carried out between two water networks. Data for Network 1 are adopted from Wang and Smith[24] and that of Network 2 are adopted from Polley and Polley.[25] Network 1 is served by pure fresh water source of 0 ppm, whereas Network 2 has an impure fresh water source of 10 ppm. Because interplant water integration is carried out between the two networks, the internal water sources are shared between them. Targeting is to be carried out to identify the minimum fresh water flow rates needed for each network. In this case, impurity concentration is taken as the quality of the resource conservation problem.

Following the decomposition algorithm, flow rate targeting for Network 2 is first carried out, becasue it has a lower quality fresh water source. All available water sources of the two networks will be included during targeting. Table 8 shows the cascade table where fresh water flow rate (R) for Network 2 is targeted as 72.22 ton/h (infeasible cascade is omitted), with a pinch concentration identified at 100 ppm.

Next, cascade analysis is again carried out for the lower quality region (with impurity concentration higher than the pinch). The allocated flow rate of the pinch-causing source (112.22 ton/h between 100 and 150 ppm in Table 8) has been excluded in this targeting stage. As shown in Table 9, no pinch flow rate (F_P) is needed for the lower quality region. In other words, the source flow rates in this region is sufficient for supplying the all sinks that exist in this region, without having to use the allocated flow rate from the pinch-

Table 7. Flow and Quality Data for Example 2

Sink; SK_j	Flowrate; F_j (t/h)	Concentration; C_j (ppm)	Sources; SR_i	Flow rate; F_i (t/h)	Concentration; C_i (ppm)
Network 1 (Wang and Smith, 1994)					
1	20	0	1	20	100
2	100	50	2	100	100
3	40	50	3	40	800
4	10	400	4	10	800
$\Sigma_j F_j$	170		$\Sigma_i F_i$	170	
Network 2 (Polley and Polley, 2000)					
1	50	20	1	50	50
2	100	50	2	100	100
3	80	100	3	70	150
4	70	200	4	60	250
$\Sigma_j F_j$	300		$\Sigma_i F_i$	280	

Table 8. Flow Rate Targeting for Network 2 of Example 2

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					$R = 72.22$		
1	10			0			
					72.22	0.72	
2	20	50		−50			0.72
					22.22	0.67	
3	50	100	50	−50			1.39
					−27.78	−1.39	
4	100	80	220	140			0.00
					112.22	5.61	(PINCH)
5	150		70	70			5.61
					182.22	9.11	
6	200	70		−70			14.72
					112.22	5.61	
7	250		60	60			20.33
					172.22	25.83	
8	400			0			46.17
					172.22	68.89	
9	800		50	50			115.06
					$W = 222.22$	222044.44	
10	1,000,000						222159.50

causing source. The allocated flow rate of the pinch-causing source hence emerges as a wastewater stream at 100 ppm (112.22 ton/h). From Table 9, it may be observed that the 70 ton/h source at 150 ppm is cascaded down to sink at 200 ppm. The unused sources at 250 ppm (60 ton/h) and 800 ppm (50 ton/h) hence leave as wastewater streams. Note that the summation of the three wastewater streams yield a total of 222.22 ton/h (= 112.22 + 60 + 50 ton/h), matching the wastewater flow rate (W) as identified in Table 8.

Next, targeting is carried out using a similar procedure for Network 1, where pure fresh water source is available for service. The unused wastewater streams from Network 2 will now be used as sources in Network 1. The result of the flow rate targeting is shown in Table 10, with a fresh water (R) and wastewater (W) flow rates of 90 and 142.22 ton/h, respectively. The final allocation of the water flows between the two networks for this example is given in Table 11.

Emergy-based fuel allocation through source and demand composite curves

This example describes a scenario in which fossil and biomass-based fuel resources are allocated across different zones under emergy limit constraints. The concept of emergy was popularized as an index of environmental performance by Odum.[32] It is based on the notion of ''energy memory'', which reflects the cumulative inputs of solar energy flows throughout the life cycle of a given resource, product or commodity. Thus, emergy is said to be embedded in a product. Furthermore, physical and chemical processes are characterized by the efficiency of transforming energy inputs into the corresponding outputs; in the terminology of emergy literature, the conversion factor of a process is known as its transformity. The latter concept is useful as it allows different forms of energy to be compared by tracing inputs to a common source (usually solar energy) to allow fair comparison. For example, the solar transformity of crude oil is estimated to be 5.4×10^4 sej/J.[32] This figure simply means that every J of chemical energy in crude oil requires an indirect, cumulative input of 5.4×10^4 J of solar energy through various photosynthetic and geochemical processes that occur in the natural formation of fossil fuel resources. The unit ''sej'' stands for solar emjoules, which provides a common basis for measuring different energy sources that are ultimately traceable in origin to solar radiation. The transformity values for different fuel resources are analogous to the quality

Table 9. Wastewater Streams Identification for Network 2 of Example 2

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					$F_P = 0$		
1	100			0			
					0	0	
2	150		70	70			0
					70	3.5	
3	200	70		−70			3.5
					0	0	
4	250		60	60			3.5
					60	9	
5	400			0			12.5
					60	24	
6	800		50	50			36.5
					110	109,912	
7	1,000,000						109948.5

Table 10. Flow Rate Targeting for Network 1 of Example 2

k	C_k (ppm)	$\Sigma_j F_j$ (ton/h)	$\Sigma_i F_i$ (ton/h)	$\Sigma_i F_i - \Sigma_j F_j$ (ton/h)	$F_{C,\,k}$ (ton/h)	Δm_k (kg/h)	Cum. Δm_k (kg/h)
					$R = 90.00$		
1	0	20		−20			
					70.00	1.40	
2	20			0			1.40
					70.00	2.10	
3	50	140		−140			3.50
					−70.00	−3.50	
4	100		112.22	112.22			0.00 (PINCH)
					42.22	2.11	
5	150			0			2.11
					42.22	2.11	
6	200			0			4.22
					42.22	2.11	
7	250		60	60			6.33
					102.22	15.33	
8	400	10		−10			21.67
					92.22	36.89	
9	800		50	50			58.56
					$W = 142.22$	142108.44	
10	1000,000						142167.00

indices described in previous sections, because they serve to indicate the relative environmental cost of depleting natural resources. The most important work done to date on the use of emergy in the context of pinch analysis can be found in the works of Zhelev and Ridolfi[33] and Crilly and Zhelev.[34]

In this section, the decomposition algorithm is illustrated using the graphical-based targeting approach of source and demand composite curves. The targeting tool is based on the material recovery pinch diagram, originally developed separately by El-Halwagi et al.[7] and Prakash and Shenoy[9] to locate the minimum external resource in a resource conservation network. The targeting tool was then extended to locate waste streams and their minimum treatment flow rates in a resource conservation network,[30,31] as well as the minimum low/zero carbon footprint resource for energy sector planning.[18,20,21] The main steps of the technique are described below, but the reader may refer to the original works for further details and mathematical proof.[7,9]

Targeting procedure with source demand composite curves

In this procedure, the source and demand composite curves are generated separately following the same general approach. The steps are as follows:

Step 1: The sources (or demands) are first arranged in order of increasing quality index.

Step 2: Each source (or demand) is plotted such that the horizontal axis corresponds to the cumulative flows and the vertical axis corresponds to the cumulative quality load. The quality loads, in turn, are simply the products of flows and their corresponding quality indices. As a result, the slope of each segment of the composite curve corresponds to the quality index of that source (or demand). The segments are plotted end to end, following the sequence established in the previous step; as a result of the progressively increasing value of the quality (or slope), the composite curve curls upwards.

Step 3: Once both the source and demand composite curves have been generated, they are superimposed on the same graph such that they both begin at the origin of the coordinate axes. A feasible solution is indicated when the source composite curve always lies below or tangent to the demand composite curve.

Step 4: If the initial solution is infeasible, it is necessary to shift the source composite curve to the right, until it lies completely below the demand composite curve. The required extent of the shift corresponds to the external resource requirement. Note that in the context of the minimization objective, it is desirable to shift the composite curve as little as possible to get a feasible solution. This optimal shift will always result in at least one pinch point, at which the two composite curves are tangent to each other.

Step 5: The exact direction of the shift of the composite curve depends on the quality level of the external resource. If the quality level is 0, the source composite curve is shifted horizontally. Otherwise, it is shifted diagonally along a locus whose slope corresponds to the quality index of the resource.[7,20]

Step 6: The shifted positions of the composite curves indicate the key features of the solution. The length of the overhang on the left hand region, where the demand composite curve is present but the source is not, indicates the minimum external resource requirement. The length of the central portion, where the demand curve overlies the source curve, indicates the extent of internal reuse/recycle within the system through source-sink matching. An overhang may also exist on the right hand region, where the source composite curve is present but without any corresponding demand above it, which indicates the amount of surplus streams from the

Table 11. Allocation of Water Flows (in t/h) for Example 2

	Network 1	Network 2
Internal source (50 ppm)	0	50.00
Internal source (100 ppm)	70	107.78
Internal source (150 ppm)	0	70.00
Internal source (250 ppm)	10	0
Internal source (800 ppm)	0	0
Fresh water 1 (0 ppm)	90	0
Fresh water 2 (10 ppm)	0	72.22

Table 12. Flow and Quality Data for Example 3

Source	Available quantity (EJ)	Transformity (sej/J)	Demand	Energy required (EJ)	Transformity limit (sej/J)
Peat (for Zone 1 only)	To be determined	19,000	Zone 1	1.2	30,000
Wood (for Zone 2 only)	To be determined	7,000	Zone 2, Sector A	0.8	30,000
Oil	0.8	54,000	Zone 2, Sector B	0.3	60,000
Natural Gas	0.4	48,000			
Coal	1.2	40,000			

internal sources. The pinch point also exists within the central region, and has the same implications as the pinch points found in equivalent techniques.[7,9,18]

Illustrative example 3

In this case it is assumed that there are two geographic regions that share a common pool of fossil fuel (crude oil, natural gas, and coal) sources. Zone 1 has an access to additional peat resources for its own internal use, whereas Zone 2, which consists of two subsectors, similarly has ample resources to cultivate fuel wood in energy plantations to meet part of its energy demand. The objective is to minimize the combined use of peat and wood resources in the zones given the available resources of oil, natural gas, and coal, and given specified emergy limits set by the zones. Table 12 shows the data for the case studies. Note that 1 EJ = 10^{18} J. The transformity values for the different energy sources are taken from Odum,[32] whereas those of the demands are hypothetical.

To apply the decomposition algorithm, a graphical targeting procedure is first applied to Zone 1, because its external resource, i.e. peat, has the highest transformity value (and hence lower quality) between the two available external resources in the system. In this case, the source and demand composite curves are used. Cumulative energy flows are plotted on the horizontal axis; the slope of each segment of the composite curve corresponds to the transformity, which serves as the quality index for the different energy sources. The total emergy of each segment, which is the product of energy quantity and the corresponding transformity value is plotted cumulatively on the vertical axis. Details of the construction of such composite curves were described in the previous section. Applying this procedure to Zone 1 gives the pinch diagram shown in Figure 7 (for better illustration, only the coal segment is shown for the source composite curve). It can be seen that the peat requirement is 0.57 EJ, and the rest of the energy demand of the zone can be met using 0.63 EJ of coal. A leftover of 0.57 EJ of coal is observed. It can be seen that no oil or natural gas is required in this zone to meet the energy requirement. Note also that, because the demand composite curve is a straight line, the pinch point occurs at the terminal end of the demand composite. The total emergy limit of the demand is calculated as 36×10^{21} sej (1.2 EJ $\times$ 30,000 sej/J). Of this total, 30% (10.8×10^{21} sej) is contributed by peat and the remainder (25.2×10^{21} sej) comes from the coal usage.

After determining the target for Zone 1, it is now possible to proceed with a similar pinch targeting approach for Zone 2, which uses fuel wood as an external resource. It will be noted that the part of the common internal coal source has

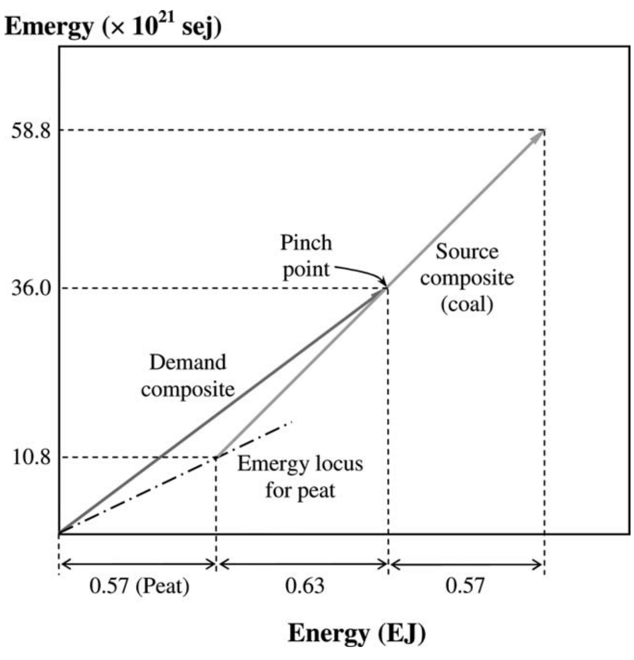

Figure 7. Targeting for Zone 1 of Example 3.

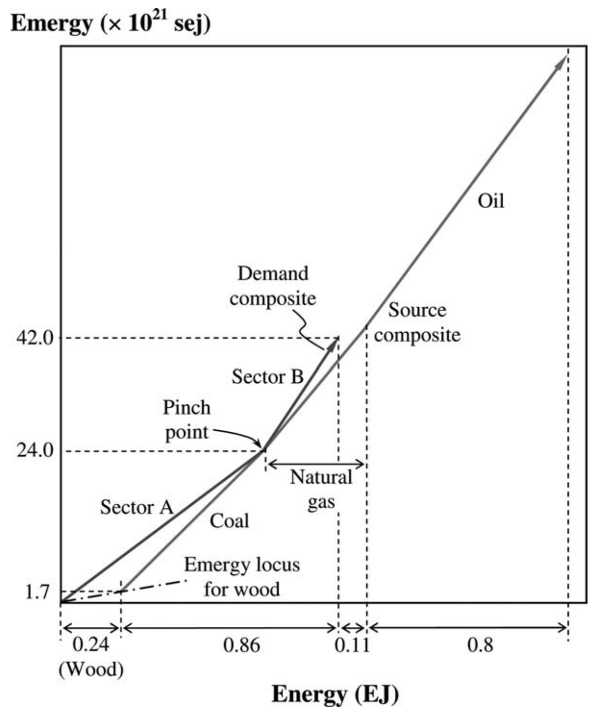

Figure 8. Targeting for Zone 2 of Example 3.

already been partially consumed in Zone 1, so that in subsequent targeting, the amount available for Zone 2 is 0.57 EJ (Figure 7). Meanwhile, the oil and gas have not yet been allocated at all and the original quantities remain intact. The pinch diagram for Zone 2 is shown in Figure 8. From here it is possible to determine that the wood requirement to be 0.24 EJ, to be entirely allocated to Sector A, which is below the pinch point. Sector A requires an additional 0.56 EJ of coal to meet its energy demand without exceeding the emergy limit of 24 × 10^{21} sej (0.8 EJ × 30,000 sej/J). Of this total, 7% (1.7 × 10^{21} sej) is contributed by the wood resource and 93% (22.3 × 10^{21} sej) comes from coal. Note that no flexibility exists in energy source allocation in this lower quality region.

Sector B of Zone 2, on the other hand, is in the lower quality region, above the pinch point, so there is some flexibility in the allocation of the remaining energy sources (coal, oil, and natural gas) without affecting the minimum wood resource already determined during targeting. One of the possible option is to use the remaining 0.01 EJ of coal (not shown) and 0.29 EJ of natural gas (0.3–0.01 EJ) to meet the requirement of the Sector B. This allocation leaves a 0.11 EJ (0.4–0.29 EJ) of natural gas and all original oil unused (Figure 8). Note that this energy mix does not fully saturate the emergy limit of Sector B of 18 × 10^{21} sej (0.3 EJ × 60,000 sej/J), because the energy usage combines for just 16.2 × 10^{21} sej of emergy. Table 13 shows the allocation of the fuels to the two zones. Of the latter figure, 4% is contributed by coal and 96% by natural gas. Because Sector B is not saturated, a second pinch point does not form at the end of the demand composite curve.

Another energy mix option is to fully substitute the natural gas with oil in Sector B, with the pinch diagram shown in Figure 9. In this case, this substitution is possible since the slopes of the segments of the source composite curve are lower than the slope of the segment of the demand curve corresponding to Sector B. Note that this result further implies complete flexibility in changing the proportions of natural gas and oil usage in this sector, depending on other considerations such as cost. Hence, Sector B will use a small amount of coal (0.1 EJ), whereas the remainder of the demand (2.9 EJ) can be met by using any combination of the other two fuels.

Conclusions

Resource conservation networks can be represented schematically as bipartite superstructure networks. The optimal requirement of a resource is equivalent to a network flow optimization problem which is of great importance in engineering and management applications. A linear network flow optimization problem can be solved using the simplex algorithm of linear programming. However, due to structured nature of a network flow optimization, simpler algorithms are proposed to solve these problems. There are several graphical and algebraic algorithms are proposed to solve different resource conservation networks. In this article, a special type of network flow optimization problem, called segregated targeting of resource network, is proposed and solved. A decomposition algorithm for generalized segregated targeting problems in multizone, multiresource, single-quality index source-sink problems has been developed. The technique is compatible for use in conjunction with previously developed algebraic or graphical targeting techniques; these methods can be embedded within the general algorithm. A rigorous mathematical proof of the decomposition algorithm has been shown. Furthermore, three case studies on carbon-constrained energy planning, interplant water integration and emergy-based allocation of fuel resources have been solved to illustrate the use of the procedure in conjunction with different pinch targeting methods.

Table 13. Allocation of Energy Flows (in EJ) for Example 3

	Zone 1	Zone 2
Oil	0	0
Natural Gas	0	0.29
Coal	0.63	0.57
Peat	0.57	0
Wood	0	0.24

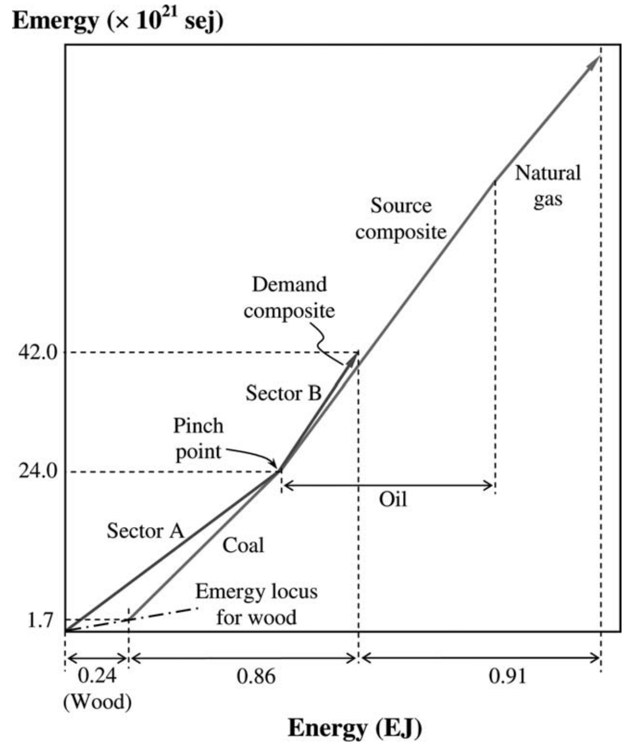

Figure 9. Revised targeting for Zone 2 of Example 3.

Notation

Cum = cumulative
f_{ijk} = flow transferred from source i to demand j of zone k
f_{rjk} = flow transferred from the specified resource of kth zone to jth demand of kth zone
f_{iw} = flow transferred from source i to the waste
F_{si} = flow of ith internal source
F_{djk} = flow of jth demand of kth zone
N_s = number of internal sources
N_{dk} = number of internal demands of kth zone
S = source
Se = solar energy
Sej = solar emjoules

q_{si} = quality of ith source
q_{djk} = quality of jth demand of kth zone
q_{rk} = quality resource allowed to kth zone
Q = quality load
R = total resource
ΔW = change in waste water
W = waste water

Subscripts

C = cumulative
d = demand
i = source index
j = demand index
k = zone index
l,n = index
P = pinch
r = resource index
s = source
T = total
w = waste
1,2,… = index number

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