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Source composite curve for waste reduction

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Abstract

Waste reduction through source reduction and on-site recycling is an important aspect of pollution prevention. Techniques of process integration may be used for pollution prevention. In this paper an algorithmic procedure is presented to reduce waste generation through maximizing on-site reuse/recycling. The proposed methodology is based on the pinch principles and establishes a minimum waste generation target prior to the detailed network design. A new graphical representation called source composite curve, is utilized to understand the targeting philosophy. Minimum waste targeting algorithm is applied to address different problems such as water management, hydrogen management, as well as material reuse and recycling. Appropriate changes in a process or process modification can further reduce the waste generation. In this paper a methodology is presented to reduce waste generation through process modifications and it is demonstrated through an example.

Keywords: Waste reduction; Targeting; Pinch analysis; Water management; Hydrogen management; Process integration; Source composite curve

1. Introduction

Pollution prevention consists of reduction of sources of pollution and recycling. Source reduction implies any activity that reduces or eliminates the generation of waste at the source, usually within a process. Waste generation that cannot be prevented should be recycled in an environmentally safe manner. Waste that cannot be feasibly recycled should be treated in accordance with environmental standards and regulations and disposed off safely. Source reduction or reduction of waste generation is the first step in a hierarchy of options for reducing pollution. Process integration techniques may be used for pollution prevention by reducing generation of waste.

Techniques of process integration are primarily used for process design (both grassroots and retrofits) with special emphasis on efficient utilization of resources and reducing environmental pollution. Process integration is a system oriented and integrated approach to industrial process design with an objective of sustainable development. Pinch analysis has established itself as a structural tool for analyzing and developing efficient processes through process integration. In this paper a new pinch analysis tool, called source composite curve, has been introduced to reduce waste through an integrated design approach.

Pinch analysis, which began as a thermodynamic-based approach to energy conservation [1], has evolved over the years to become a powerful tool for process integration and resource optimization [2–4]. Pinch analysis has been fruitfully used in analyzing heat exchanger networks [3], utility systems [5,6], mass exchanger networks [7–10], water networks [11], distillation column [12–16], production planning [17,18], etc. Pinch analysis recognizes the importance of setting targets before design. This allows different process design objectives to be screened prior to the detailed design of the process. Pinch analysis provides graphical representation tools and full control to the process designer over decision making processes.

For every application of pinch analysis different graphical representation tools have been proposed. For example, composite curves and grand composite curve have been proposed for targeting heat exchanger networks [3]; optimal load distribution diagram has been proposed for utility system [6]; concentration–contaminant load diagram [11], concentration–flow rate diagram [19], water surplus diagram [20] and source and sink composite curves [21,22] have been proposed for freshwater targeting; invariant rectifying and stripping curves have been proposed for distillation column [12]; mass exchange grand composite curve has been proposed for mass exchanger networks [23,24], etc. Associated with different representations, different algorithmic procedures, graphical and/or algebraic, have also been proposed. Primary objective of this paper is to propose a single graphical representation and a uniform

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Nomenclature

f	flow
F	total flow
N	cardinality of a set
q	quality
Q	quality load
R	total resource requirement
RVP	Reid vapor pressure
W	total waste generation
y	purity of hydrogen
Δ	overall flow loss/gain in the system

Subscript

comp	compressor
d	demand
gen	generated
makeup	make up
pyro	pyrolysis
rs	resource
s	source
T	total
w	waste

algebraic procedure to address problems such as water management, hydrogen management, material reuse and recycling, etc.

Recently, Bandyopadhyay et al. [25] has introduced a source composite curve-based approach for simultaneously targeting distributed effluent treatment system and minimum freshwater requirement. In this paper the concept of source composite curve has been generalized to reduce waste production for a variety of applications. The proposed unified and algorithmic procedure has been applied to water management, hydrogen management and material reuse/recycle in a metal degreasing process. The proposed algorithmic procedure is complemented with a generalized visualization tool, called source composite curve.

Appropriate changes to a process have been accepted as an effective measure to reduce waste generation and pollution prevention. Issues related to process modification are discussed in this paper. Different modifications and their effect on waste generation are explained through an example.

2. Problem statement and mathematical formulation

The general problem of waste reduction using source composite curve may be mathematically stated as follows. In a process, a set of N_s internal sources (streams) is given. Each source produces a flow $F_{\mathrm{s}i}$ with a given quality $q_{\mathrm{s}i}$. A set of N_d internal demands (units) is also given. Each demand accepts a flow $F_{\mathrm{d}j}$ with a quality that has to be less than a predetermined maximum limit $q_{\mathrm{d}j}$. There is an external source, called resource, with a quality q_rs and there is an external demand, called waste, without any maximum quality limit. There is no flow limitation associated with the resource and the waste. Flows are denoted by a positive real number. Quality is defined as a positive real number such that higher numerical value indicates its inferiority. In other words, a source with higher numerical value of quality is inferior to another source with lower numerical value. Typically, resource has the best quality with lowest numerical value. The objective of this work is to develop an algorithmic technique with graphical representation that will identify an optimum strategy for integrating sources and demands to minimize waste production. A network representing the above problem is shown in Fig. 1.

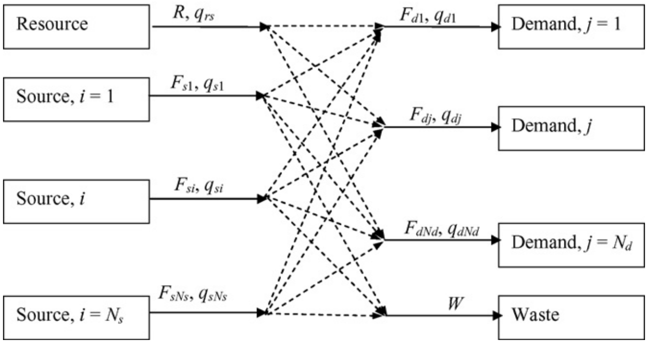


Fig. 1. A network representing a generalized waste reduction problem.

Conservation equations for flows and qualities are defined before developing appropriate mathematical formulation for the above problem. Whenever two streams with flows F_1 and F_2 and qualities q_1 and q_2, respectively, are mixed, it produces a mixed stream with flow, F_3 and quality, q_3. Flows and qualities are said to obey the following relationships.

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

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

The product of quality with flow is defined as quality load (Q). Above equations represent conservation of flow and quality load.

Let f_{ij} denotes the flow transferred from source i to demand j. Due to flow conservation (1), flow balance for every internal source and for every internal demand may be written as follows.

$$\sum_{j=1}^{N_\mathrm{d}} f_{ij} + f_{i\mathrm{w}} = F_{\mathrm{s}i}, \qquad \text{for every internal source } i \tag{3}$$

$$f_{\mathrm{rs}j} + \sum_{i=1}^{N_\mathrm{s}} f_{ij} = F_{\mathrm{d}j}, \qquad \text{for every internal demand } j \tag{4}$$

Total waste generation from the process can be expressed as

$$W = \sum_{i=1}^{N_\mathrm{s}} f_{i\mathrm{w}} \tag{5}$$

Similarly, the total resource requirement may be calculated to be

$$R = \sum_{j=1}^{N_\mathrm{d}} f_{\mathrm{rs}j} \tag{6}$$

Table 1
Tabular representation of minimum waste targeting algorithm

	First column	Second column	Third column	Fourth column	Fifth column	Sixth column
	Quality	Net flows	Cumulative flows	Quality load	Cumulative quality load	Waste flow
First row	q_1	F_1	F_1	$Q_1 = 0$	$Q_1 = 0$	$W_1 = \dfrac{\Delta Q_T}{q_1 - q_{rs}}$
Second row	q_2	F_2	$F_1 + F_2$	$Q_2 = F_1\ (q_1 - q_2)$	$Q_1 + Q_2 = F_1\ (q_1 - q_2)$	$W_2 = \dfrac{\Delta Q_T - Q_2}{q_2 - q_{rs}}$
...	...	...	...	...	...	...
*k*th row	q_k	F_k	$\sum_{l=1}^{k} F_l$	$Q_k = (q_{k-1} - q_k)\left(\sum_{l=1}^{k-1} F_l\right)$	$\sum_{l=1}^{k} Q_l = \sum_{l=1}^{k-1} F_l(q_l - q_k)$	$W_k = \dfrac{\Delta Q_T - \sum_{l=1}^{k} Q_l}{q_k - q_{rs}}$
...	...	...	...	...	...	...
*n*th (last) row	q_n	F_n	$\sum_{l=1}^{n} F_l = \Delta$	$Q_n = (q_{n-1} - q_n)\left(\sum_{l=1}^{n-1} F_l\right)$	$\sum_{l=1}^{n} Q_l = \sum_{l=1}^{n-1} F_l(q_l - q_n) = \Delta Q_T$	–

Taking summation over all internal sources and demands on Eqs. (3) and (4), the overall flow balance across the process can be established.

$$\sum_{j=1}^{N_d} f_{rsj} + \sum_{i=1}^{N_s} F_{si} = \sum_{j=1}^{N_d} F_{dj} + \sum_{i=1}^{N_s} f_{iw} \tag{7}$$

Using Eqs. (5) and (6), overall flow balance across the process (7) can be simplified as

$$R = \sum_{j=1}^{N_d} f_{rsj} = W - \Delta \tag{8}$$

where $\Delta = \sum_{i=1}^{N_s} F_{si} - \sum_{j=1}^{N_d} F_{dj}$, a constant for a given process. Δ signifies overall flow loss/gain in the system. Positive Δ signifies that there is flow gain in the system and a negative Δ implies overall flow loss.

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

$$f_{rsj}q_{rs} + \sum_{i=1}^{N_s} f_{ij}q_{si} \le F_{dj}q_{dj}, \quad \text{for every internal demand } j \tag{9}$$

The objective is to minimize W subject to the constraints given by Eqs. (3), (4) and (9). As all constraints and the objective function are linear, this is a linear programming problem. There are $(N_s + N_d + N_sN_d)$ flow variables with $(N_s + N_d)$ equality constraints and N_d inequality constraints. Therefore, the degree of freedom for the linear programming problem is (N_sN_d).

It may be noted that waste generation (W) and resource requirement (R) and not independent. Eq. (8) implies that R and W are related by a constant, Δ. Therefore, minimization of W implies minimization of R as well. In other words, minimization of waste generation is equivalent to the minimization of resource requirement.

The above linear programming problem is solved through an algorithmic procedure. The proposed algorithmic procedure is associated with a graphical representation, called source composite curve.

3. Minimum waste targeting algorithm

Algebraic procedure for targeting minimum waste generation for a given problem is discussed in this section. Applications of this mathematical technique are demonstrated in the subsequent sections. Steps of the proposed algorithm are as follows. Formulae for each step are tabulated in Table 1.

Step 1: Qualities of all internal sources, demands and resource are tabulated in decreasing order in the first column. If value of a particular quality occurs more than once, the same need not be repeated. Without loss of generality, it can be said that the quality for *k*th row is denoted as q_k such that

$$q_1 > q_2 > \cdots > q_k > \cdots > q_n \tag{10}$$

Step 2: Net flows (i.e., algebraic sum of flows corresponding to a quality) are tabulated in second column. Consider flows corresponding to internal sources as positive and flows corresponding to demands as negative. For *k*th row, net flow is denoted as F_k (Table 1). It may be noted that the flows concerned are the point flows at each quality.

Step 3: Cumulative flows are tabulated in third column. Summation of net flows for all previous rows ($\sum_{l=1}^{k} F_l$) denotes the cumulative flows for *k*th row. Last entry in this column gives Δ, as defined in Eq. (8).

Step 4: Fourth column represents the quality load (Q_k) for each quality interval. First entry in fourth column is kept 0. For all subsequent columns, the difference between the last two qualities is multiplied by the cumulative flows to calculate the quality load and tabulated in fourth column. Mathematically, quality load (Q_k) for each quality interval can be calculated using the following formula.

$$Q_k = \begin{cases} 0, & \text{for } k = 1 \\ (q_{k-1} - q_k)\left(\sum_{l=1}^{k-1} F_l\right), & \text{for } k > 1 \end{cases} \tag{11}$$

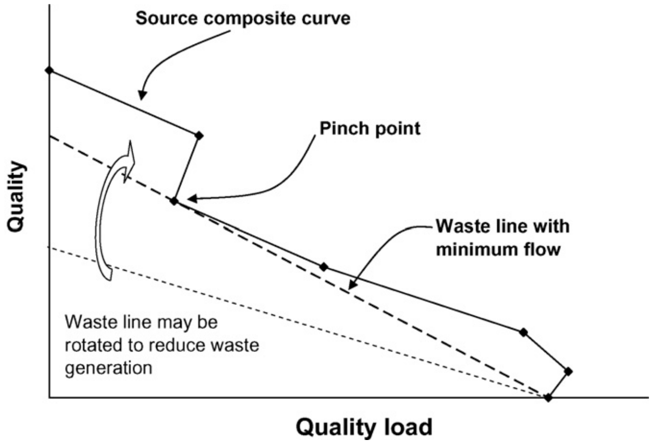


Fig. 2. Representation of source composite curve and targeting minimum waste flow.

Step 5: Cumulative quality loads are calculated by summing quality loads for all previous rows ($\sum_{l\le k} Q_l$) and tabulated in fifth column. Using Eq. (11), cumulative quality load for kth row may be expressed as

$$\sum_{l=1}^{k} Q_l = \begin{cases} 0, & \text{for } k=1 \\ \sum_{l=1}^{k-1} F_l(q_l - q_k), & \text{for } k>1 \end{cases} \tag{12}$$

Now fifth column (cumulative quality load) may be plotted against the first column (quality) to obtain the source composite curve. A schematic source composite curve is shown in Fig. 2. Bottom entry in the fifth column signifies the total quality load (ΔQ_{T}) thrown to the waste.

$$\Delta Q_{\mathrm{T}} = \sum_{l=1}^{n} Q_l = \sum_{l=1}^{n-1} F_l(q_l - q_n) \tag{13}$$

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 $q_k > q_{\mathrm{rs}}$.

$$W_k = \frac{\Delta Q_{\mathrm{T}} - \sum_{l=1}^{k} Q_l}{q_k - q_{\mathrm{rs}}}, \quad \text{for } q_k > q_{\mathrm{rs}} \tag{14}$$

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

In most cases, resource quality has the least numerical value ($q_n = q_{\mathrm{rs}}$). Then, Eq. (14) can be further simplified using Eqs. (12) and (13).

$$W_k = \frac{\Delta Q_{\mathrm{T}} - \sum_{l=1}^{k} Q_l}{q_k - q_n} = \sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n} \right) \tag{15}$$

Any line with a negative slope on this quality (q) versus quality load (ΔQ) diagram, passing through the point (ΔQ_{T}, q_{rs}), represents a waste line. Equation for the waste line may be expressed as

$$\Delta Q = \Delta Q_{\mathrm{T}} - W(q - q_{\mathrm{rs}}) \tag{16}$$

Note that the waste line has a negative slope (Eq. (16)) and the slope is inversely proportional to the waste flow. Eq. (14) can be derived from Eq. (16) if the waste line passes through (ΔQ_{T}, q_{rs}) and ($\sum_{l\le k} Q_l$, q_k) on the quality (q) versus quality load (ΔQ) diagram.

To minimize the waste generation, the waste line should be rotated upwards with (ΔQ_{T}, q_{rs}) as the pivot point (Fig. 2). It should be noted that at any quality, the waste line cannot pickup more quality load than what is available (as given by the source composite curve or the cumulative quality load available at any given quality). Therefore, the minimum waste can be targeted by rotating the waste line with (ΔQ_{T}, q_{rs}) as the pivot point such that it just touches the source composite curve (Fig. 2). Maximum entry in the sixth column represents the minimum waste flow such that it just touches the source composite curve. Quality that corresponds to the minimum waste flow is called the pinch quality and the point at with the waste line touches the source composite curve is known as the pinch point.

In the following sections, applications of source composite curve are illustrated with various examples.

4. Water management

El-Halwagi and Manousiouthakis [7] proposed systematic composite representations to identify targets for mass exchange network. Wang and Smith [11] proposed a systematic graphical method for freshwater targeting. These methods are applicable for units, which can be modeled as mass transfer units (e.g., washing, scrubbing, etc.) with water being used as a mass-separating agent and cannot be applied for processes like cooling tower, boiler, etc., as these units cannot be modeled as mass transfer operations [19]. Sorin and Bedard [26] and Polley and Polley [27] proposed a set of rules for solving water allocation problems. Hallale [20] developed a new graphical approach, water surplus diagram, for freshwater targeting. A rigorous graphical technique has been developed recently to target freshwater requirement involving separate source and sink composite curves [21,22]. Bandyopadhyay et al. [25] introduced a source composite curve-based approach for simultaneously targeting distributed effluent treatment system and minimum freshwater requirement.

Application of source composite curve for water management is illustrated through an example. Process data for water management example is given in Table 2 [27]. For this example, actual water flow rate in t/h has been considered as flows and contaminant concentration in ppm is considered as quality. Conservation of mass for water and contaminant satisfies Eqs. (1) and (2). Freshwater is the resource ($q_{\mathrm{rs}} = 0$) and wastewater is the waste for this problem. The objective is to reduce wastewater generation. Numerical values calculated by applying the proposed algorithm are shown in Table 3.

For this problem $\Delta = -20$ t/h (last entry in the third column). It suggests that there is an overall water loss of 20 t/h.

Table 2
Process data for water management example

	Quality (contaminant concentration in ppm)	Flow (water flow rate in t/h)
Sources		
S1	50	50
S2	100	100
S3	150	70
S4	250	60
Resource (freshwater)	0	–
Demands		
D1	20	50
D2	50	100
D3	100	80
D4	200	70
Waste (wastewater)	–	–

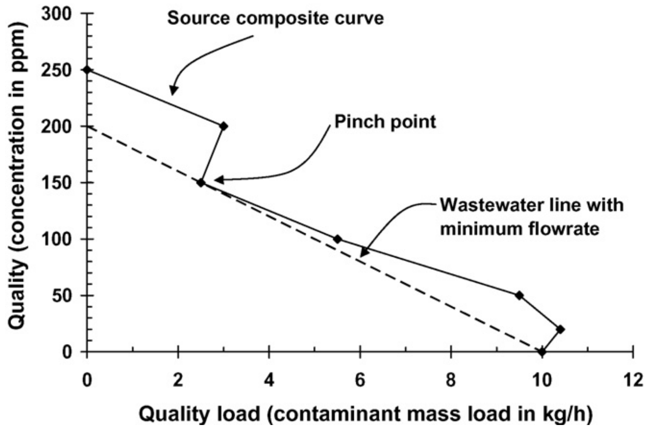
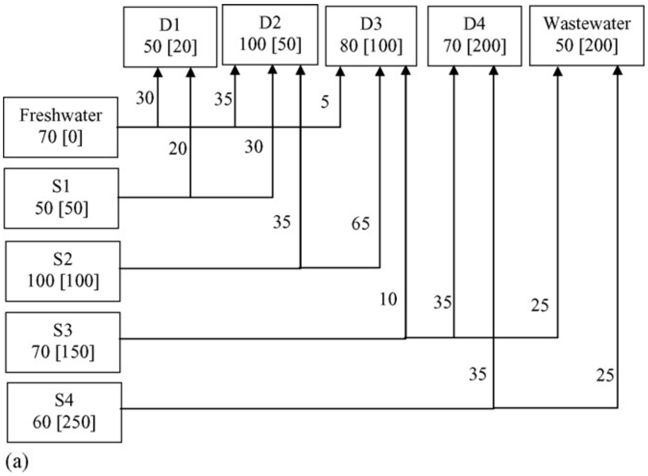


Fig. 3. Source composite curve and wastewater line for water management example.

Last entry of the fifth column suggests that 10 kg/h of contaminant load is thrown to the wastewater ($\Delta Q_T = 10$ kg/h). The source composite curve and wastewater line for the water management example are shown in Fig. 3. The maximum slope of the wastewater line corresponds to the minimum wastewater flow rate, since they have an inverse relationship (Eq. (16)). The minimum wastewater flow rate target is 50 t/h and the corresponding pinch concentration is 150 ppm. Since there is a water loss of 20 t/h, the minimum freshwater target comes out to be 70 t/h. This matches with the result reported by Polley and Polley [27]. Polley and Polley [27] obtained the answer applying a set of rules proposed by them. However, the methodology proposed by Polley and Polley [27] is applicable for problems with only a few sources and demands.



(b)

	D1 50 [20]	D2 100 [50]	D3 80 [100]	D4 70 [200]	Wastewater 50 [200]
Freshwater 70 [0]	30	35	5		
S1 50 [50]	20	30			
S2 100 [100]		35	65		
S3 70 [150]			10	35	25
S4 60 [250]				35	25

Fig. 4. (a) One possible network satisfying minimum wastewater generation for the water management example and (b) corresponding water allocation table (level shows flow rate in t/h).

Possible networks satisfying minimum wastewater target for water management example may be obtained using nearest neighbor algorithm [22]. One such network and associated water allocation table are shown in Fig. 4. It may be noted that the proposed network is different from the one published by Polley and Polley [27].

5. Hydrogen management

Hydrogen is an important utility in petroleum refineries. Hydrogen is required in many operations for hydrogenation of aromatics and olefins, reduction of sulfur content in fuels, upgrading larger hydrocarbons, etc. To illustrate the waste reduc-

Table 3
Generation of source composite curve and targeting wastewater for water management example

Quality Contaminant concentration (ppm)	Net flows Net flow rate (t/h)	Cumulative flows Cumulative flow rate (t/h)	Quality load Mass load (kg/h)	Cumulative quality load Cumulative mass load (kg/h)	Waste flows Wastewater flow rate (t/h)
250	60	60	0	0	40
200	−70	−10	3	3	35
150	70	60	−0.5	2.5	**50**
100	20	80	3	5.5	45
50	−50	30	4	9.5	10
20	−50	−20	0.9	10.4	−20
0	0	**−20**	−0.4	**10**	–

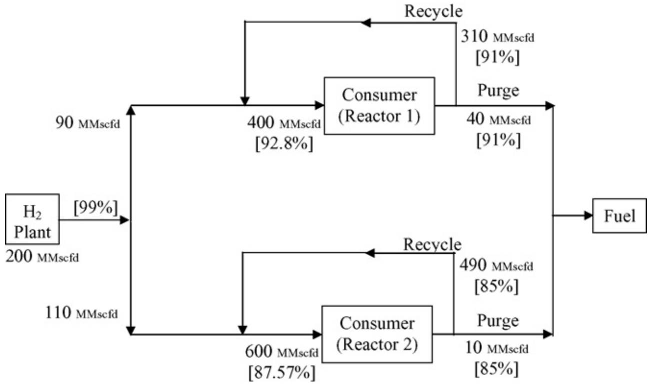


Fig. 5. Existing process flow diagram showing hydrogen consumers for hydrogen management example.

tion methodology developed in the previous section, an example of hydrogen management problem is considered [28–30]. The existing system comprises of two hydrogen consumers or demands (Reactor 1 and Reactor 2) as shown in Fig. 5. Each consumer has a makeup, recycle and purge. Makeup hydrogen is produced from a hydrogen plant or it may be imported. The purge streams are often sent to the fuel system where they are fired for their heating value or flared. The hydrogen demands (consumers) consist of the makeup and recycle, whereas the hydrogen sources comprise the purge and recycle taken together.

For this example, volumetric hydrogen flow rate in million standard cubic feet per day (MMscfd) has been considered as flows. Considering ideal gas, volumetric flow balance satisfies Eq. (1). In Fig. 5, purity of hydrogen (y) is reported in percentage. In this problem impurity concentration is defined as $q = 1 - y$ and is considered as quality. Volume conservation for hydrogen may be written as

$$F_1 y_1 + F_2 y_2 = F_3 y_3 \tag{17}$$

Subtracting Eq. (17) from Eq. (1), Eq. (2) may be obtained. It implies that the above defined quality is conserved as defined in Eq. (2). Hydrogen from the hydrogen plant is the resource ($q_{rs} = 0.01$) and fuel is the waste for this problem. The objective is to reduce fuel production. Table 4 shows the data extracted from the existing hydrogen flowsheet (Fig. 5).

The source composite curve and fuel line for the hydrogen management example are shown in Fig. 6. The minimum fuel flow rate target comes out to be 32.86 MMscfd and the corresponding pinch quality is 0.15 (corresponding to 85% purity). There is a net loss of 150 MMscfd of flow as it can be read from the last entry of third column in Table 5. Thus, the minimum hydrogen requirement target comes out to be 182.86 MMscfd, which agrees with the result obtained by Alves [28] and Hallale and Liu [29] using the surplus diagram. It may be noted that the methodology based on surplus diagram is graphical and iterative in nature. One possible hydrogen allocation network and corresponding process plow diagram are shown in Fig. 7. It may be noted that the waste can be reduced by 34.3% and the fresh hydrogen requirement can be reduced by 8.6%.

Table 4
Process data for hydrogen management example

	Purity (%)	Quality	Flow (MMscfd)
Sources			
S1	91	0.09	350
S2	85	0.15	500
Resource (makeup hydrogen)	99	0.01	–
Demands			
D1	92.8	0.072	400
D2	87.5667	0.124333	600
Waste (fuel)	–	–	–

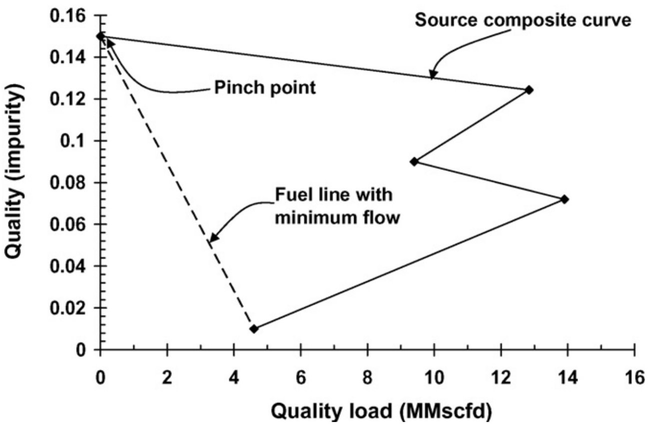


Fig. 6. Source composite curve and fuel line for hydrogen management example.

6. Material reuse network

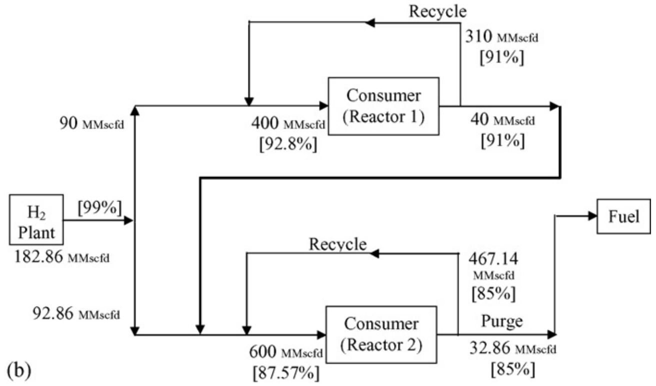
Other than concentration or purity, other properties such as pH, density, viscosity, reflectivity, solubility, etc., are also important for synthesizing process flow diagram of a chemical process industry. El-Halwagi and co-workers have developed visualization tools to synthesize and analyze material reuse networks [31–35]. Proposed algorithm can be also applied to such material reuse problems. To illustrate the applicability of the proposed waste reduction technique, an example of metal degreasing process is considered. Process flow diagram of a metal degreasing

Table 5
Generation of source composite curve and targeting minimum waste for hydrogen management example

Quality	Net flows (MMscfd)	Cumulative flows (MMscfd)	Quality load (MMscfd)	Cumulative quality load (MMscfd)	Waste flows (MMscfd)
0.15	500	500	0	0	**32.86**
0.124333	−600	−100	12.8335	12.8	−72.01
0.09	350	250	−3.4333	9.4	−60
0.072	−400	−150	4.5	13.9	−150
0.01	0	**−150**	−9.3	4.6	–

	D1 400 [92.8]	D2 600 [87.57]	Fuel 32.86 [85]
Makeup hydrogen 182.86 [99]	90	92.86	
S1 350 [91]	310	40	
S2 500 [85]		467.14	32.86

(a)



(b)

Fig. 7. (a) Hydrogen allocation network and (b) corresponding process flow diagram for hydrogen management example with minimum fuel generation.

process is shown in Fig. 8 [34]. A fresh organic solvent is used in the degreaser of a reactive thermal degreasing process to remove grease from metal. Solvent is regenerated and reused in the degreaser. Fresh solvent is also used in an absorber column to arrest light gases from the offgas produced in the regeneration section before sending it to the flare. Condensates produced in two condensers are sent to a waste disposal unit (Fig. 8).

For this example, mass flow rate in kg/s has been considered as flows. Flow balance satisfies Eq. (1) due to conservation of mass. Primary property of the solvent that is considered for reuse and recycle, is the Reid vapor pressure (RVP), an important property in characterizing volatility of the solvent [34]. It may be interesting to note that RVP, as a property, is not conserved. However, it follows the following blending rule [34].

$$F_1(\mathrm{RVP})_1^{1.44} + F_2(\mathrm{RVP})_2^{1.44} = F_3(\mathrm{RVP})_3^{1.44} \quad (18)$$

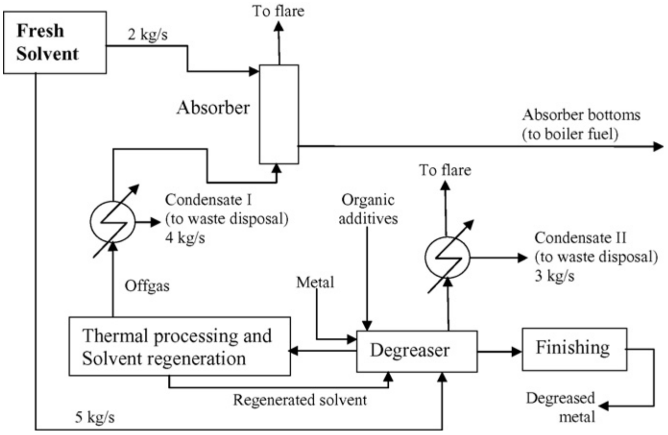


Fig. 8. Process flow diagram of a metal degreasing example.

Table 6
Process data for metal degreasing process

	RVP (atm)	Quality ($\mathrm{atm}^{1.44}$)	Flow (kg/s)
Sources			
Condensate I	6	13.199	4
Condensate II	2.5	3.741	3
Resource (fresh solvent)	2	2.713	–
Demands			
Degreaser	3	4.865	5
Absorber	4	7.362	2
Waste	–	–	–

In this problem, quality is defined as $q = \mathrm{RVP}^{1.44}$ and Eq. (18) implies that the quality obeys the summability criteria as defined in Eq. (2). Fresh organic solvent is the resource ($q_{\mathrm{rs}} = 2.713\ \mathrm{atm}^{1.44}$) and total condensate discharged to the waste disposal unit is the waste. The objective is to reduce waste production. Table 6 shows the data for this metal degreasing process.

The source composite curve and waste line for this example are shown in Fig. 9. The minimum waste generation is calculated (Table 7) to be 2.38 kg/s and the corresponding pinch quality is 13.199 $\mathrm{atm}^{1.44}$ (corresponding to a RVP of 6 atm). There is no solvent loss in this problem ($\Delta = 0$). Therefore, the minimum fresh solvent requirement target is also 2.38 kg/s, which agrees with the result obtained graphically by Kazantzi and El-Halwagi [34] using the source and sink composite curves, proposed independently by El-Halwagi et al. [21] and Prakash and Shenoy [22]. One material reuse network and corresponding process plow diagram are shown in Fig. 10. It may be noted that the waste generation and the fresh solvent requirement both are reduced by 52.4%.

7. Process modification

By modifying certain process parameters overall waste generation can be reduced significantly. Two primary ways process may be modified to reduce waste generation are by changing quality and/or flow of internal demands and sources. These options are discussed in details.

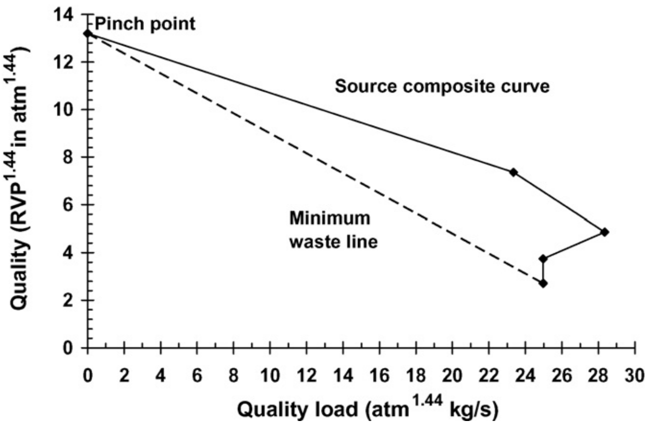


Fig. 9. Source composite curve and fuel line for hydrogen management example.

Table 7
Generation of source composite curve and targeting minimum waste for metal degreasing process

Quality ($\text{atm}^{1.44}$)	Net flows (kg/s)	Cumulative flows (kg/s)	Quality load ($\text{atm}^{1.44}$ kg/s)	Cumulative quality load ($\text{atm}^{1.44}$ kg/s)	Waste flows (kg/s)
13.199	4	4	0	0	**2.381**
7.362	−2	2	23.348	23.348	0.349
4.865	−5	−3	4.994	28.342	−1.567
3.741	3	0	−3.372	24.97	0
2.713	0	**0**	0	24.97	–

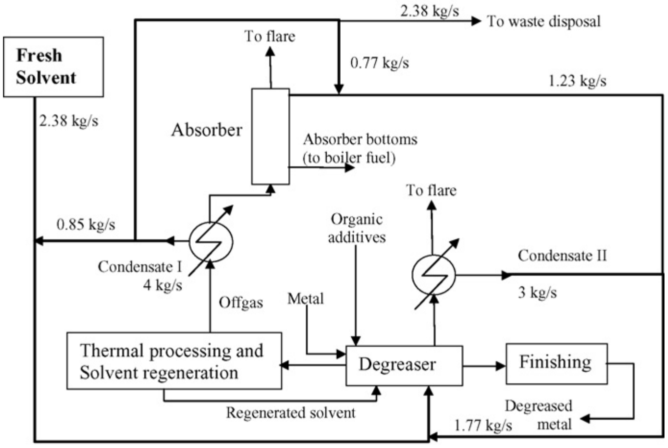
7.1. Quality modification

Numerical value of quality of an internal demand may be increased from q_a to q_b and because of greater acceptance of quality load, waste generation may reduce. Similarly, numerical value of quality of an internal source may be decreased to enhance its usability in the process. Algebraically both these options are equivalent. Mathematically, this may be formulated as reduction of flow (F') at higher quality (q_b) and introduction of the same flow at lower quality (q_a). Due to change in quality, waste generation flow is expected to change according to Eq. (16). Modified waste generation flow (for each row in sixth column of Table 1) can be expressed as follows.

$$W'_k = \begin{cases} \displaystyle\sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n}\right) - F' + F', & q_b > q_a \geq q_k \\ \displaystyle\sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n}\right) - F' + F'\left(\frac{q_a - q_n}{q_k - q_n}\right), & q_b \geq q_k > q_a \\ \displaystyle\sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n}\right) - F'\left(\frac{q_b - q_n}{q_k - q_n}\right) + F'\left(\frac{q_a - q_n}{q_k - q_n}\right), & q_k > q_b > q_a \end{cases} \tag{19}$$

(a)

	Degreaser 5 [3]	Absorber 2 [4]	Waste 2.38 [6]
Fresh solvent 2.38 [2]	2.38		
Condensate I 4 [6]	0.85	0.77	2.38
Condensate II 3 [2.5]	1.77	1.23	



(b)

Fig. 10. (a) Material reuse network and (b) modified process flow diagram of a metal degreasing example for minimum waste generation.

Since the minimum waste production is controlled by the pinch point, physical significance of Eq. (19) may be appreciated against the pinch point. Quality modification above pinch ($q_b > q_a \geq q_k$) is not going to reduce the waste generation (19). Quality modification below pinch ($q_k > q_b \geq q_a$) reduces waste generation. Reduction in waste generation is proportional to the difference in the quality load flow, $F'(q_b - q_a)$. On the other hand, quality modification across the pinch has the potential for maximum reduction in waste production, as it is proportional to $F'(q_k - q_a)$. It may be interesting to note that the waste reduction for quality modification across the pinch is independent of the higher quality (q_b). It may be noted that by changing quality of an internal demand or an internal source, overall flow gain/loss in the system (Δ) does not change. Therefore, reduction in waste generation also reduces requirement of the resource by same amount.

For illustration, let us consider the example of water management. Let the quality (i.e., contaminant concentration) of demand D4 be increased from 200 to 210 ppm. Since the pinch quality for this problem is 150 ppm, modification of the D4 quality is actually an above pinch modification. According to Eq. (19), above pinch quality modification does not lead to a reduction in waste generation. The same may be confirmed by applying the minimum waste targeting algorithm. The source composite curve and wastewater line for the modified example are shown in Fig. 11a. The wastewater line for the modified example is parallel to that of the original example. It may be noted that though the wastewater flow rate remains 50 t/h, the outlet concentration of the wastewater reduces from 200 to 186 ppm.

To illustrate below pinch quality modification, let the concentration of demand D2 be increased from 50 to 60 ppm. Since the pinch quality for this problem is 150 ppm, modification of the D2 quality is actually a below pinch modification. According to

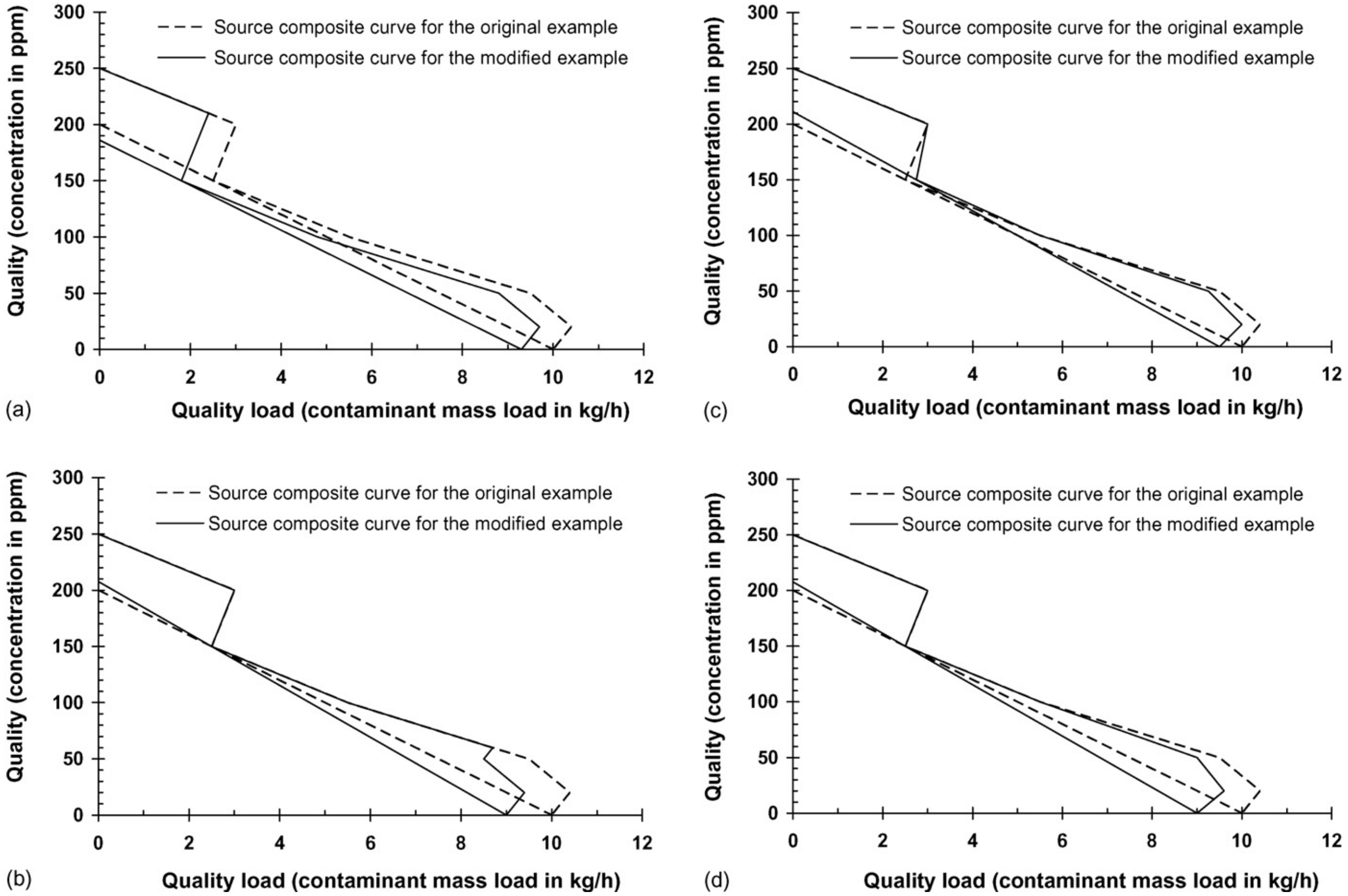


Fig. 11. Source composite curve and wastewater line for the modified water management example: (a) above pinch quality modification, (b) below pinch quality modification, (c) above pinch flow modification and (d) below pinch flow modification.

Eq. (19), below pinch quality modification lead to a reduction of 6.67 t/h in waste generation as well a reduction of resource requirement. The same may be confirmed by applying the minimum waste targeting algorithm. The source composite curve and wastewater line for the modified example are shown in Fig. 11b. Slope of the minimum wastewater line for the modified example is more than that of the original example. It may be noted that the outlet concentration of the wastewater increases from 200 to 207.7 ppm.

7.2. Flow modification

Similar to the quality modification, demand flow may be increased or source flow may be decreased to reduce waste generation. Mathematically, this may be formulated as reduction of flow (F'') at some quality (q_c). Eq. (16) may be modified to calculate waste generation flow for flow modification.

$$W''_k = \begin{cases} \displaystyle\sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n}\right) - F'', & q_c \geq q_k \\ \displaystyle\sum_{l=1}^{k} F_l + \sum_{l=k+1}^{n-1} F_l \left(\frac{q_l - q_n}{q_k - q_n}\right) - F'' \left(\frac{q_c - q_n}{q_k - q_n}\right), & q_k > q_c \end{cases} \tag{20}$$

Eq. (20) suggests that flow modification at or above the pinch has maximum possible effect in reducing waste generation. However, flow modification below the pinch also reduces waste generation but not to the extent as the other case. It may be noted that by reducing flow of an internal demand or an internal source, overall flow gain/loss in the system (Δ) also reduces by the same amount. Therefore, for above pinch flow modification, waste generation is reduced while resource requirement remains same. On the other hand, for below pinch flow modification, waste generation is reduced slightly and the resource requirement increases.

For illustration, let us again consider the example of water management. Let the flow of demand D4 be increased from 70 to 75 t/h. According to Eq. (20), above pinch flow modification leads to a reduction of 5 t/h of waste generation and the resource requirement remains 70 t/h. The source composite curve and wastewater line for the modified example are shown in Fig. 11c. The wastewater line for the modified example is parallel to that

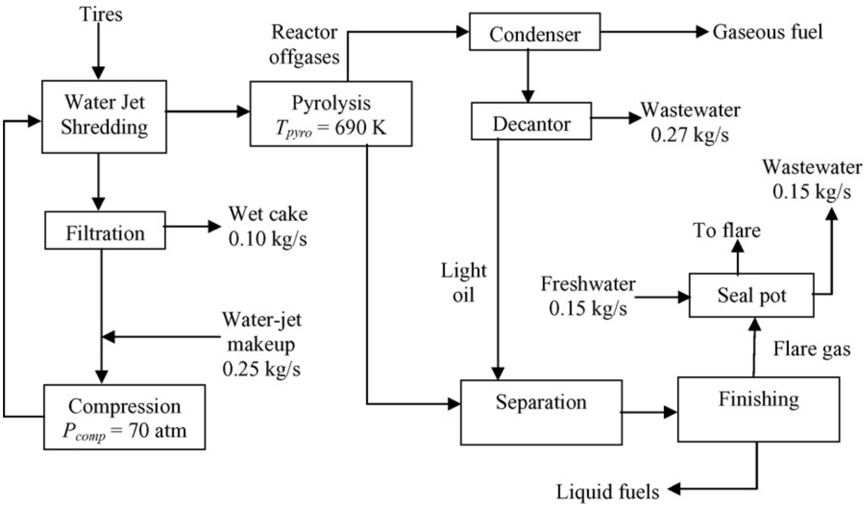


Fig. 12. Simplified block diagram of a tire-to-fuel plant.

of the original example. On the other hand, flow of source S2 may be reduced from 100 to 90 t/h to study the effect of below pinch flow modification. According to Eq. (20), below pinch flow modification leads to a reduction of 6.7 t/h of waste generation and the resource requirement increases to 73.3 t/h. The source composite curve and wastewater line for the modified example are shown in Fig. 11d.

Appropriate process modifications (quality modification or flow modification or both) may reduce the waste generation significantly. Preceding discussions may help a process designer to address scope of sequence of process modifications qualitatively. To determine the exact quantitative waste reduction, the minimum waste targeting algorithm should be repeated. Since pinch point may be changed, Eq. (19) or (20) may not give exact solution if they are applied only at the pinch point. The concept of process modifications are discussed with an example.

8. Tire-to-fuel plant

To demonstrate the scope of process modifications for waste reduction, an example of tire-to-fuel plant is considered [36]. A simplified block diagram of the process is shown in Fig. 12. Discarded tires are shredded using high pressure water jets and shredded tires are fed to a high temperature pyrolysis reactor to breakdown hydrocarbon of the tires into oils and gaseous fuels. Pyrolysis reactor offgas is cooled in a condenser and wastewater is decanted form the decanter. Organic layer from the decanter is mixed with the liquid product of the reactor. Oils are further separated and processed to produce transportation fuels. A gaseous waste leaves the finishing unit and is flared. A seal pot with some freshwater stream is provided to prevent back propagation of fire from flare. In this example, there are two internal water demands, namely, makeup water for water jets and water required in the seal pot. There are three internal wastewater sources: wastewater form the seal pot, wastewater from the decanter and the wet cake produced in the filtration system. Phenol is the primary contaminant for this example. Wastewater associated with the wet cake, is treated in the waste disposal unit and it is not allowed to recycle back in the process. Other two wastewater streams are sent for off-site treatment. Objective is to reduce the wastewater production.

Makeup water for water jets and water for seal pot can accept a phenol concentration up to 50 and 200 ppm, respectively. The process data for this example is given in Table 8. Applying the proposed algorithm, minimum wastewater generation is targeted to be 0.245 kg/s and the corresponding pinch concentration of 500 ppm. The source composite curve and waste line for this example are shown in Fig. 13. Production of wastewater can be further reduced by making appropriate process modifications.

8.1. Below pinch quality modification

Flare gas form the finishing unit may be utilized as a mass separating agent to strip off phenol from the water provided to the seal pot. The seal pot may be modified to a stripping column to purify wastewater, while wastewater stream continues to act as a buffer to prevent back propagation of fire. Due to available flow rate of the flare gas and required driving force for adequate mass transfer operation, the inlet concentration of the inlet water to the seal pot can be increased up to 500 ppm. However, the outlet concentration of the wastewater from the seal pot remains at 200 ppm. According to Eq. (19), this should results in reducing the wastewater flows by 0.09 kg/s (=0.15 × (500 − 200)/500).

Table 8
Process data for tire-to-fuel example

	Quality (phenol concentration in ppm)	Flow (water flow rate in kg/s)
Sources		
Decanter	500	0.27
Seal pot in	200	0.15
Resource (freshwater)	0	–
Demands		
Water jet	50	0.25
Seal pot out	200	0.15
Waste (wastewater)	–	–

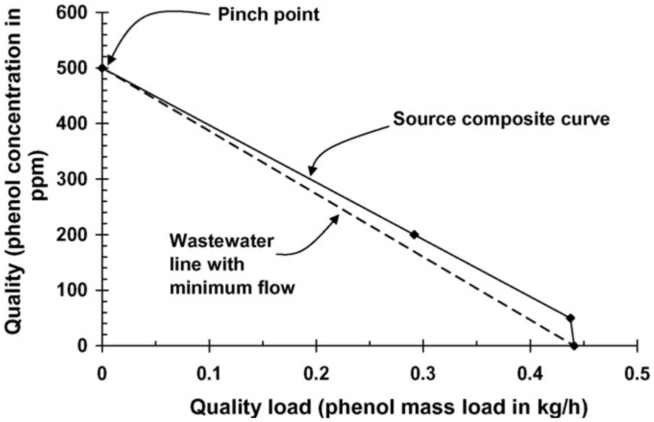


Fig. 13. Source composite curve and fuel line for the example of tire-to-fuel plant.

However, wastewater flow rate reduces only to 0.208 kg/s as the pinch point jumps to 200 ppm. A reduction of 0.037 kg/s can only be achieved due to relocation of pinch point. Increasing the concentration up to 325 ppm is sufficient to achieve the required wastewater reduction.

8.2. Flow modification

Forty percent of the makeup water flows with the wet cake obtained from the filtration unit. Remaining 60% of the water is decanted in the decanter. Reactor produces some water during pyrolysis process and the same water is also decanted in the decanter. According to Eq. (20), wastewater with maximal concentration should be reduced first. Therefore, the decanted water flow rate can be reduced by reducing makeup water flow rate (F_{makeup}) and water generation during pyrolysis process. The flow rate of the makeup water depends on the outlet pressure (P_{comp}) of the compressor by the following expression:

$$F_{\mathrm{makeup}} = 0.47\ \exp(-0.009 P_{\mathrm{comp}}) \qquad (21)$$

where F_{makeup} is in kg/s and P_{comp} is in atm. In order to achieve proper shredding compressor outlet pressure must be within the range 70–95 atm. At present the compressor outlet pressure is 70 atm and the makeup water requirement is 0.25 kg/s. Increasing the compressor outlet pressure to 95 atm, reduces the makeup water requirement to 0.20 kg/s. This results in a reduced flow rate of wet cake to 0.08 kg/s and reduced decanted water flow rate to 0.24 kg/s. Modification of the compressor outlet pressure reduces the demand by 0.05 kg/s and also reduces the decanted wastewater by 0.03 kg/s. Therefore, using Eq. (20), reduction in wastewater flow rate can be estimated to be 0.018 (=0.03 − (0.05 × 50)/200) kg/s. Since there is not pinch jump, the total wastewater also reduces by the same amount, to 0.19 kg/s.

8.3. Above pinch flow modification

Decanted water can be further reduced by changing reactor temperature. The amount of water generated (F_{gen}) during the pyrolysis process is related to the pyrolysis temperature (T_{pyro}) by the following relationship:

$$F_{\mathrm{gen}} = 0.152 + (5.37 - 7.84 \times 10^{-3} T_{\mathrm{pyro}}) \exp(27.4 - 0.04 T_{\mathrm{pyro}}) \qquad (22)$$

where F_{gen} is in kg/s and T_{pyro} is in K. in order to maintain the acceptable product quality, the pyrolysis temperature has to be in between 690 and 740 K. At present the pyrolysis temperature is 690 K and the reactor generates 0.12 kg/s of water. The same water is decanted in the decanter. Eq. (22) suggests that the minimum water of 0.08 kg/s is generated in the pyrolysis reactor when the reactor temperature is 710 K. A reduction of 0.04 kg/s in water generation in the pyrolysis reactor reduces the wastewater generation to 0.15 kg/s.

Water requirement in the seal pot may be increased further. However, this affects the wastewater flow rate by the same amount. Therefore, this modification is equivalent to changing quality. As the pinch point is at 200 ppm, increase in water flow rate through seal pot is equivalent to quality modification above pinch. Eq. (19) suggests that such modifications have no effect

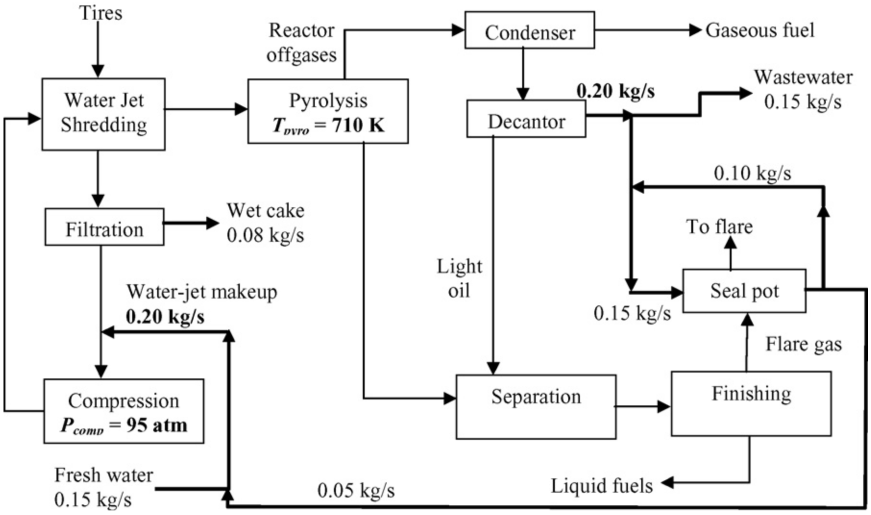


Fig. 14. Modified block diagram of a tire-to-fuel plant with minimum wastewater production.

in reducing wastewater flow rate. The final flow sheet of the process is shown in Fig. 14 to produce minimum wastewater of 0.15 kg/s. It may be noted that the waste production may be further reduced by incorporating wastewater treatment and recycling. However, this is beyond the scope of this paper.

9. Conclusions

Waste reduction and waste minimization have broader meaning than source reduction [37]. Waste reduction generally incorporates both source reduction and on-site recycling. These are the first two steps of the waste management hierarchy. The proposed method reduces waste generation by incorporating appropriate on-site recycling and simultaneously reduces resource requirement.

A unified targeting methodology has been presented for targeting waste generation in process industries. The proposed algorithm solves a particular type of linear programming problem through algebraic procedures. The proposed minimum waste targeting algorithm has been applied to different waste reduction problems such as waster management, hydrogen management and material reuse networks.

A methodology has also been presented to reduce waste generation through process modifications. Different possible modifications and their effect on waste generation and resource requirement have been identified. The methodology has been demonstrated through an example.

References

[1] B. Linnhoff, D.W. Townsend, D. Boland, G.F. Hewitt, B.E.A. Thomas, A.R. Guy, R.H. Marsland, User Guide on Process Integration for the Efficient Use of Energy, The Institution of Chemical Engineers, Rugby, UK, 1982.

[2] B. Linnhoff, Pinch analysis: a state-of-the-art overview, Trans. IChemE: Chem. Eng. Res. Des. 71 (1993) 503–522.

[3] U.V. Shenoy, Heat Exchanger Network Synthesis: Processes Optimization by Energy and Resource Analysis, Gulf Publishing Company, Houston, 1995.

[4] R. Smith, Chemical Process Design, McGraw-Hill, New York, 1995.

[5] S.G. Hall, S.J. Parker, B. Linnhoff, Process integration of utility systems, in: IEA Workshop on Process Integration, Gothenburg, Sweden, 1992.

[6] U.V. Shenoy, A. Sinha, S. Bandyopadhyay, Multiple utilities targeting for heat exchanger networks, Trans. IChemE: Chem. Eng. Res. Des. Part A 76 (1998) 259–272.

[7] M.M. El-Halwagi, V. Manousiouthakis, Synthesis of mass exchange networks, AIChE J. 8 (1989) 1233–1244.

[8] N. Hallale, D.M. Fraser, Capital cost targets for mass exchange networks a special case: water minimization, Chem. Eng. Sci. 53 (2) (1998) 293–313.

[9] N. Hallale, D.M. Fraser, Capital and total cost targets for mass exchange networks part 1: Simple capital cost models, Comput. Chem. Eng. 23 (11–12) (2000) 1661–1679.

[10] N. Hallale, D.M. Fraser, Supertargeting for mass exchange networks. Part I. Targeting and design techniques, Chem. Eng. Res. Des. 78 (2) (2000) 202–207.

[11] Y.P. Wang, R. Smith, Wastewater minimization, Chem. Eng. Sci. 49 (7) (1994) 981–1006.

[12] S. Bandyopadhyay, R.K. Malik, U.V. Shenoy, Invariant rectifying–stripping curves for targeting minimum energy and feed location in distillation, Comput. Chem. Eng. 23 (8) (1999) 1109–1124.

[13] S. Bandyopadhyay, R.K. Malik, U.V. Shenoy, Feed preconditioning targets for distillation through invariant rectifying–stripping curves, Ind. Eng. Chem. Res. 42 (26) (2003) 6851–6861.

[14] S. Bandyopadhyay, M. Mishra, U.V. Shenoy, Energy-based targets for multiple-feed distillation columns, AIChE J. 50 (8) (2004) 1837–1853.

[15] S. Bandyopadhyay, Effect of feed on optimal thermodynamic performance of a distillation column, Chem. Eng. J. 88 (1–3) (2002) 175–186.

[16] B.F. Deshmukh, R.K. Malik, S. Bandyopadhyay, Efficient feed preheat targeting for distillation by feed splitting, in: Proceedings of European Symposium on Computer Aided Process Engineering – 15 (ESCAPE-15), Barcelona, May 29–June 1, 2005, pp. 751–756.

[17] A. Singhvi, U.V. Shenoy, Aggregate planning in supply chains by pinch analysis, Trans. IChemE: Chem. Eng. Res. Des. 80 (6) (2002) 597–605.

[18] A. Singhvi, K.P. Madhavan, U.V. Shenoy, Pinch analysis for aggregate production planning in supply chains, Comput. Chem. Eng. 28 (6–7) (2004) 993–999.

[19] V.R. Dhole, N. Ramchandani, R.A. Tanish, M. Wasilewski, Make your process water pay for itself, Chem. Eng. 103 (1996) 100–103.

[20] N. Hallale, A new graphical targeting method for water minimisation, Adv. Env. Res. 6 (3) (2002) 377–390.

[21] M.M. El-Halwagi, F. Gabriel, D. Harell, Rigorous graphical targeting for resource conservation via material recycle/reuse networks, Ind. Eng. Chem. Res. 42 (19) (2003) 4019–4328.

[22] R. Prakash, U.V. Shenoy, Targeting and design of water networks for fixed flow rate and fixed contaminant load operations, Chem. Eng. Sci. 60 (1) (2005) 255–268.

[23] D.M. Fraser, N. Hallale, Retrofit of mass exchange networks using pinch technology, AIChE J. 46 (10) (2000) 2112–2117.

[24] D.M. Fraser, M. Howe, A. Hugo, U.V. Shenoy, Determination of mass separating agent flows using the mass exchange grand composite curve, Trans. IChemE: Chem. Eng. Res. Des. 83 (12) (2005) 1381–1390.

[25] S. Bandyopadhyay, M.D. Ghanekar, H.K. Pillai, Process water management, Ind. Eng. Chem. Res. 45 (15) (2006) 5287–5297.

[26] M. Sorin, S. Bedard, The global pinch point in water reuse network, Trans. IChemE 77B (1999) 305–308.

[27] G.T. Polley, H.L. Polley, Design better water networks, Chem. Eng. Prog. 96 (2) (2000) 47–82.

[28] J. Alves, Analysis and design of refinery hydrogen systems, Ph.D. Thesis, University of Manchester Institute of Science and Technology (UMIST), Manchester, UK, 1999.

[29] N. Hallale, F. Liu, Refinery hydrogen management for clean fuels production, Adv. Env. Res. 6 (2001) 81–98.

[30] N. Hallale, I. Moore, D. Vauk, Hydrogen: liability or asset? Chem. Eng. Prog. (September 2002) 66–75.

[31] M.D. Shelley, M.M. El-Halwagi, Componentless design of recovery and allocation systems: a functionanity-based clustering approach, Comp. Chem. Eng. 24 (2000) 2081–2091.

[32] M.M. El-Halwagi, I.M. Glasgow, M.R. Eden, X. Qin, Property integration: componentless design techniques and visualization tools, AIChE J. 50 (8) (2004) 1854–1869.

[33] X. Qin, F. Gabriel, D. Harell, M.M. El-Halwagi, Algebraic techniques for property integration via componentless design, Ind. Eng. Chem. Res. 43 (2005) 3792–3798.

[34] V. Kazantzi, M.M. El-Halwagi, Targeting material use via property integration, Chem. Eng. Prog. 101 (8) (2005) 28–37.

[35] D.C.Y. Foo, V. Kazantzi, M.M. El-Halwagi, Z. Abdul Manan, Surplus diagram and cascade analysis technique for targeting property-based material reuse network, Chem. Eng. Sci. 61 (8) (2006) 2626–2642.

[36] M.B. Noureldin, M.M. El-Halwagi, Interval-based targeting for pollution prevention via mass integration, Comput. Chem. Eng. 23 (1999) 1527–1543.

[37] D.T. Allen, K.S. Rosselot, Pollution Prevention for Chemical Processes, John Wiley, New York, 1997.