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Synthesis of mass exchange network for batch processes—Part II: Minimum units target and batch network design

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Abstract

The first part of this series of papers (Chem. Eng. Sci. 59(5) (2004) 1009) presented a methodology for identifying the minimum utility targets for a mass exchange network (MEN) for a batch process. This paper describes the methodology for setting the minimum number of mass exchange units target and a procedure for designing a maximum mass recovery network that features the minimum utility targets. The time-grid diagram and the overall time-grid diagram that include the time dimension in network design have been introduced to provide a better representation of the mass exchange network for a batch process. The systematic network design procedure also includes a technique to simplify and evolve the preliminary batch MEN to reduce the number of mass exchangers to the minimum.

Keywords: Mass exchange network design; Maximum mass recovery; Pinch analysis; Minimum units; Batch process systems; Time-grid diagram.

1. Introduction

The majority of research on mass exchange network synthesis (MENS) have focused on continuous processes (El-Halwagi, 1997; El-Halwagi and Spriggs, 1998; Dunn and El-Halwagi, 2003). The only work on mass exchange network (MEN) design for batch process based on Pinch analysis is reported by Wang and Smith (1995) for the special case of water minimisation. Clearly, more work is needed to be done in this area, particularly for the general case of MENS for batch process systems involving mass separating agent (MSA) other than water.

The batch MEN research described in this paper is based on the same framework that was developed for heat exchange network synthesis (HENS) for batch processes developed by Kemp and Macdonald (1988). Kemp and Macdonald (1988) first represented the batch heat exchange network (HEN) using the conventional grid diagram that was developed for continuous processes. To achieve maximum energy recovery, they carried out the HEN design separately for each time interval. Established pinch design rules for HEN design were used to obtain a complete network (Kemp and Macdonald, 1988).

Kemp and Deakin (1989b) later formulated a procedure for network design with heat storage. The heat storage system may function either as a hot stream (heat source) or a cold stream (heat sink), depending on which stream the storage system is finally integrated with. The storage system may act as a heat source if it is to be matched with a colder stream. Similarly, the storage system may act as a heat sink if it is to be matched with a hotter stream.

Kemp and Macdonald (1988) also pointed out that network design using the conventional grid diagram could not completely represent a batch recovery network. The main drawback of this representation is the absence of the time variable to indicate how the various processes are interlinked. Hence, a better representation is needed.

Techniques for setting the minimum units target are well established for continuous HEN and MEN problems, but

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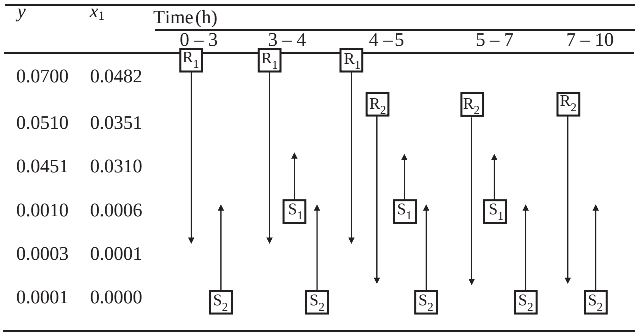
have yet to be developed for batch process systems. The minimum units target is crucial to establish the lower bound in terms of the number of units before a network is further "relaxed" (Linnhoff et al., 1982; El-Halwagi, 1997). Hence, it is necessary that the minimum units target be established before the batch network is designed and further simplified. Zhao et al. (1998) proposed a three-step procedure to design and optimise a batch HEN. A rematching technique was proposed during the second step to reuse the common exchangers and ultimately reduce the total capital cost of a network. The network was further optimised in the final stage. The disadvantage of the approach, however, is that the minimum number of heat exchangers is not targeted ahead of network design.

El-Halwagi (1997) pointed out that, for a MEN problem, the minimum utility target for a MEN is not always compatible with the minimum number of units target. Evolution techniques are needed to reduce the complexity of a preliminary MEN. Network evolution techniques have been well developed for the HEN and MEN problems for continuous processes (Linnhoff et al., 1982; El-Halwagi, 1997). Kemp and Deakin (1989b) explored the use of the established network evolution techniques to trade-off the fixed costs and the operating costs of a batch HEN. Heat load loops and paths were identified in each time interval to help a designer reduce the number of heat exchangers, ultimately leading to a simplified batch network.

The HEN relaxation technique developed for continuous processes (Linnhoff et al., 1982) provides a good basis for network evolution and simplification for a batch process. However, no attempt has been made to address the case when the same heat exchanger exists in different time intervals. Note that it is possible to use only one heat exchanger in the different time intervals of a batch process cycle. However, if one were to use the loop-breaking technique that was developed for continuous systems, there is the risk of a designer attempting to break a loop and eliminate an exchanger in a batch network that may involve the same heat exchanger appearing across time intervals. The network evolution technique for a batch network should therefore be performed across all time intervals.

In this paper, we will first present the targeting approach to locate the minimum number of mass exchange units needed for a batch MEN. Next, a detailed procedure for designing a maximum mass recovery (MMR) network is presented by introducing two new graphical tools, i.e., the time-grid diagram (TGD) and overall time-grid diagram (OTGD). These grid diagrams include time as another dimension in network design to enable designers to have a better understanding of the batch system during the design stage. This is followed by the development of evolution techniques to reduce the complexity of a preliminary batch MEN through mass load loops and paths analysis. All the above methodologies are illustrated using the same case study presented in the first part of this series of papers (Foo et al. (2004)).

Table 1
TDCIT showing the number of rich and lean streams in each time interval



2. Minimum number of units target

El-Halwagi (1997) demonstrated the technique for targeting the minimum number of mass exchange units for a continuous MEN. As in the case of heat integration, fewer mass exchange units contribute to the reduction of network complexity. Besides, fewer mass exchange units also lead to reduced pipework, foundation, maintenance and instrumentation. The minimum number of units is related to the total number of streams in a MMR network, according to the expression,

$$U = N_R + N_S - N_{\mathrm{SN}}, \tag{1}$$

where N_R is the number of rich streams in the system, N_S the number of lean streams, and N_{SN} the number of independent sub-networks into which the original network can be subdivided. Due to the existence of the pinch composition which divides the problem into two different sub-networks, Eq. (1) should be applied separately in the region above and below pinch to yield the minimum number of mass exchange units in these regions.

The targeting methodology for a continuous process is now extended to a batch MEN problem. Due to the existence of the different time intervals, process rich or lean streams may exist in more than one time interval. In order to reduce the number of mass exchange units, the mass exchangers connecting the same pair of rich and lean streams are normally reused in each time interval. In other words, if possible, one would like to make use of a "common exchanger" in every time interval. Hence, the targeting approach should consider the opportunities to reuse these exchangers. Let us now apply the targeting technique on the batch coke oven gas (COG) process described in Part 1 of this series of papers. The rich and lean streams for this process which exist in the different time intervals are shown in the time-dependant composition interval table (TDCIT) in Table 1.

Applying Eq. (1) to target the minimum number of units required for the time interval k,

$$U_k = N_{R,k} + N_{S,k} - N_{\mathrm{SN},k}. \tag{2}$$

Table 2
Minimum units targeting using Eq. (2)

Time interval, k	Rich streams, R_i	Lean streams, S_j	U_k
1	R_1	S_2	1
2	R_1	S_1, S_2	2
3	R_1, R_2	S_1, S_2	3
4	R_2	S_1, S_2	2
5	R_2	S_2	1
		$\sum_k U_k$	9

Table 3
Calculation of additional exchangers

Stream matches	$U_{AE,l}$
R_1–S_1	1
R_1–S_2	2
R_2–S_1	1
R_2–S_2	2
$\sum_l U_{AE,l}$	6

Table 4
The pinch locus divides the network in each time interval into regions above and below the pinch

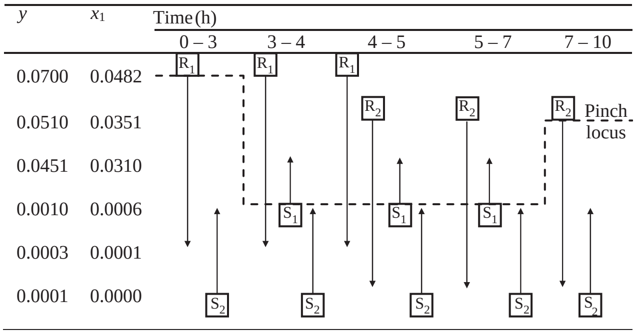


Table 5
Rich and lean streams in the regions above and below the pinch

Above pinch

Time interval, k	Rich streams, R_i	Lean streams, S_j	$U_{k,\text{above}}$
1	—	—	0
2	R_1	S_1	1
3	R_1, R_2	S_1	2
4	R_2	S_1	1
5	—	—	0
		$\sum_k U_{k,\text{above}}$	4

Below pinch

Time interval, k	Rich streams, R_i	Lean streams, S_j	$U_{k,\text{below}}$
1	R_1	S_2	1
2	R_1	S_2	1
3	R_1, R_2	S_2	2
4	R_2	S_2	1
5	R_2	S_2	1
		$\sum_k U_{k,\text{below}}$	6

By applying Eq. (2), the minimum number of mass exchangers is found to be 9 for this process (Table 2). However, if we further examine the streams in their respective time intervals, one may realise that some of the streams actually exist in a few time intervals. For instance, both streams R_1 and S_2 exist from the first to third time intervals (Table 1). The common exchanger which exchanges mass between these two streams is considered three times in these time intervals, by applying Eq. (2). In fact, only one mass exchange unit is necessary for these two streams. Hence, it could be concluded that if the same pair of streams exist in more than one time interval, the numbers of “additional exchangers”, U_{AE} are given as

$$U_{AE} = N_{TI} - 1, \tag{3}$$

where N_{TI} is the number of time intervals where both streams co-exist.

Hence, the minimum units of exchanger in a batch MEN with l additional exchangers are given by

$$U = \sum_k U_k - \sum_l U_{AE,l}. \tag{4}$$

Applying Eq. (3) to the COG problem without considering the pinch composition, one will find out that the additional exchangers that exist in the process are 6 (Table 3). Hence, the minimum units needed for this batch network is actually $9 - 6 = 3$ (Eq. (4)). However, due to the existence of pinch composition that divides the problem into two different sub-networks, i.e., regions above and below the pinch (Table 4), Eq. (4) can be applied separately in these sub-networks. Hence Eq. (4) becomes

$$U_{\text{min,MMR}} = U_{\text{above}} + U_{\text{below}}, \tag{5a}$$

where,

$$U_{\text{above}} = \sum_k U_{k,\text{above}} - \sum_l U_{AE,l,\text{above}} \tag{5b}$$

and

$$U_{\text{below}} = \sum_k U_{k,\text{below}} - \sum_l U_{AE,l,\text{below}}. \tag{5c}$$

Table 5 further locates the streams in the COG case study that exist in their respective time intervals in two separate regions, i.e., the regions above and below the pinch.

Table 6
Calculation of the additional exchangers for the regions above and below pinch

Above pinch		Below pinch	
Stream matches	$U_{CE,l,\mathrm{above}}$	Stream matches	$U_{CE,l,\mathrm{below}}$
R_1–S_1	1	R_1–S_2	2
R_2–S_1	1	R_2–S_2	2
$\sum_l U_{AE,l,\mathrm{above}}$	2	$\sum_l U_{AE,l,\mathrm{below}}$	4

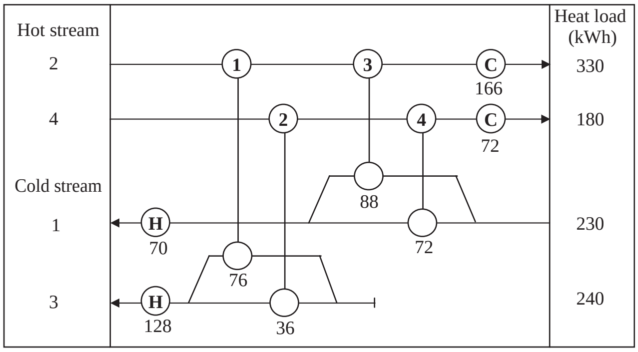


Fig. 1. A batch heat exchange network shown on conventional grid diagram (Kemp and Deakin, 1989b) do not yield a satisfactory representation, as no indication is shown as to where which heat exchanger is operated in which time interval.

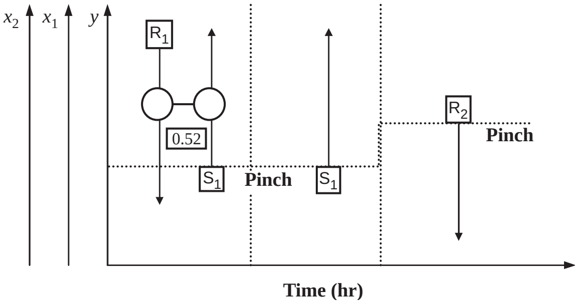


Fig. 2. The new TGD shows the driving force of the system and the actual period of time when the streams exist in the system.

Applying Eq. (2) in these separate regions yields the minimum number of units target to be 4 + 6 = 10 (Table 5).

The number of additional exchangers is next calculated in Table 6. Two additional exchangers are found in the region above the pinch, while four exchangers are found in the region below the pinch. Hence, the total minimum numbers of exchangers are calculated by applying Eq. (5), i.e., $4+6-2-4=4$. Note that this target is achieved by considering the regions above and below the pinch as two separate networks. There is a possibility to reduce $U_{\mathrm{min,MMR}}$ below the minimum by assessing the regions above and below the pinch as one entire network. The same situation is also observed in the continuous HENS (Linnhoff et al., 1982) as well as continuous MENS (El-Halwagi and Manousiouthakis, 1989) problems. By assessing the network as a whole, the network can be further simplified to eliminate the extraneous exchangers using the loop and path network “relaxation” technique. This technique will be demonstrated in the later section of this paper.

3. Batch mass exchange network (MEN) design

Generally, the overall development of HEN design for heat integration for batch processes has received far less attention as compared to the development on utility targeting. The conventional grid diagram (Linnhoff et al., 1982) is used in most of the work related to batch heat integration (Kemp and Macdonald, 1988; Kemp and Deakin, 1989b; Zhao et al., 1998). The greatest drawback of this approach is that the designer hardly visualises the actual existence of the heat exchanger in each time interval. Examples of batch network representation on the conventional grid diagram are shown in Fig. 1. These conventional grid diagrams do not represent heat recovery network in batch processes satisfactorily. No time indications were found where the designer could visualise the allocation of heat exchangers in each time interval. This drawback will be resolved with the graphical tools presented in this paper.

The approach developed for the design of batch MEN in this work is based on the work of Kempand Macdonald (1988) as well as that of El-Halwagi and Manousiouthakis (1989). As in the case of batch HEN, the desired mass transfer in batch MEN cannot be achieved by mass exchange alone. They are limited by the instantaneous mass flow of each stream and by the periods when both streams actually exist.

In designing a MEN for a batch system, it would be advantageous to represent the composition change in the grid diagram during the time interval of interest. In order to achieve this, we have introduced the TGD. The TGD is a modification of the conventional grid diagram for HENS (Linnhoff et al., 1982) as well as for MENS (El-Halwagi and Manousiouthakis, 1989). Consideration of the composition and time intervals will allow us to clearly represent the network in terms of the streams’ driving forces as well as the duration in which they exist.

Fig. 2 shows that the TGD comprises of two axes. The vertical axis represents the composition driving force for the rich and lean streams. The horizontal axis represents the period when the streams exist in the process. A rich stream is drawn from the top to the bottom of the composition interval, while a lean stream is drawn in the opposite direction. The streams are shown in the time slice in which they exist. A mass exchanger is represented by a pair of linked circles. The amount of mass being transferred is shown in a box. The pinch compositions are indicated by the dashed line which divides the network into the regions above and below the pinch.

In order to achieve the minimum utility targets established, the network design is conducted independently for each time interval (Kemp and Macdonald, 1988). Two feasibility criteria for stream matching at the pinch, similar to the ones used for the continuous MENS problem, are to be followed (El-Halwagi and Manousiouthakis, 1989). These are:

1. *Stream population*: Immediately above the pinch, all rich streams are to be matched with the lean streams in order to bring down the rich streams to the pinch composition. Therefore, the number of rich streams (N_R) should be less than the number of lean streams (N_S) above the pinch, i.e.:

$$N_{R,\text{above}} \leqslant N_{S,\text{above}}. \tag{6}$$

Below the pinch, lean streams are to be brought to the pinch composition through mass exchange with the rich streams. Thus, below the pinch, the number of lean streams should be less than the number of rich streams, i.e.:

$$N_{R,\text{below}} \geqslant N_{S,\text{below}}. \tag{7}$$

In order for these rules to be observed, stream splitting may be required at the pinch.

2. *Operating versus equilibrium line*: This criteria is analogous to that of the FCP (heat capacity flowrate) inequality in HENS problem. However, in this case, the mass transfer equilibrium has to be incorporated. A feasible match above the pinch shall have a minimum driving force of ε at the pinch side. Thus, the slope of the operating line should be greater than that of the equilibrium line, i.e.,

$$(L_j/m_j)_{\text{above pinch}} \geqslant G_{i,\text{above pinch}}. \tag{8}$$

Immediately below the pinch, the opposite holds true:

$$(L_j/m_j)_{\text{below pinch}} \leqslant G_{i,\text{below pinch}}. \tag{9}$$

In order for these criteria to be met, stream splitting may be required.

Even though the TGD in Fig. 2 is essential in indicating the streams' timing and their composition levels, it may not provide a clear picture of the entire MEN for the batch system. A non-expert user might have difficulties in linking the network design in one time interval to another time interval.

There may be tendencies to regard the streams which exist in one time interval as independent from the streams in another time interval. It is important to note from Fig. 2 that streams with the same name (for example, stream S_1) are in fact the same stream, even though these streams may appear as independent streams which exist in the different time intervals.

In order to overcome this potential confusion, we introduce another grid diagram, called the OTGD. The OTGD is a cumulative representation of the MEN during the entire process duration. Each stream is represented in their respective time intervals. Here, the composition is not considered.

Fig. 3 shows the OTGD. Both rich and lean streams are drawn from left to the right, indicating that they proceed in time. Both streams exist in their respective time intervals. A counter-current mass exchanger is represented by a pair of linked circles, with the amount of mass being transferred shown in a box. Composition is not shown in this diagram, but could be easily traced from the TGD in Fig. 2. Both the TGD and OTGD will be used to design the MEN for a single-batch system with and without storage, as well as for a repeated-batch system with storage, utilising the COG example in the first part of this series of papers (Foo et al., 2004).

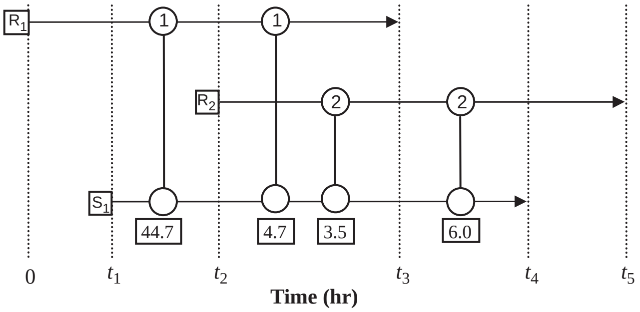


Fig. 3. The OTGD shows the cumulative representation of the entire network throughout the process duration.

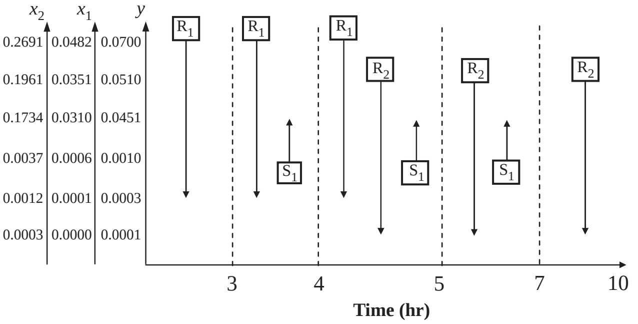


Fig. 4. A TGD showing the process streams for a single-batch COG operation.

3.1. Network design for a single-batch system without mass storage

In order to design a MMR network that achieves the utility targets set in the first part of this series of paper, the previously mentioned two feasibility criteria for stream matching, i.e., the stream population, and operating line versus equilibrium line are followed. These criteria are applicable to the individual time interval of the TGD which have different pinch compositions.

Fig. 4 shows the process streams of a single-batch COG operation in the TGD, with a 10-h cycle time. R_1 is a process-rich stream which exists during the first three time intervals (between 0–5 h), while R_2 is another process-rich stream which exists in the last three time intervals (between 4–10 h). The only process-lean stream, S_1, exists during the second to fourth time interval (between 3–7 h).

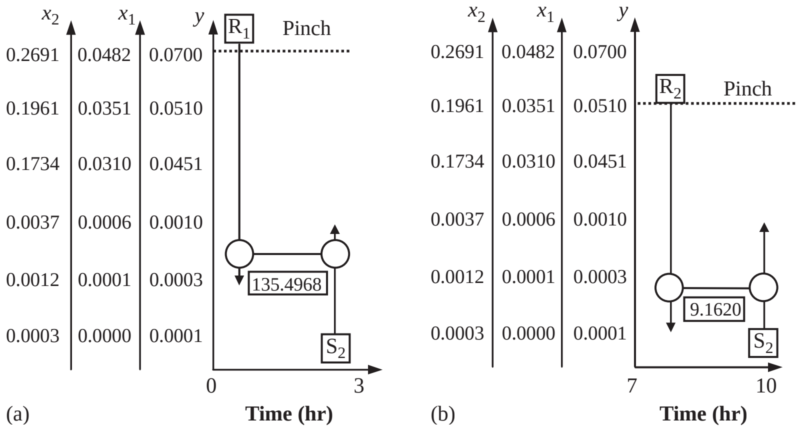


Fig. 5. MEN designs for (a) the first and (b) the final time intervals.

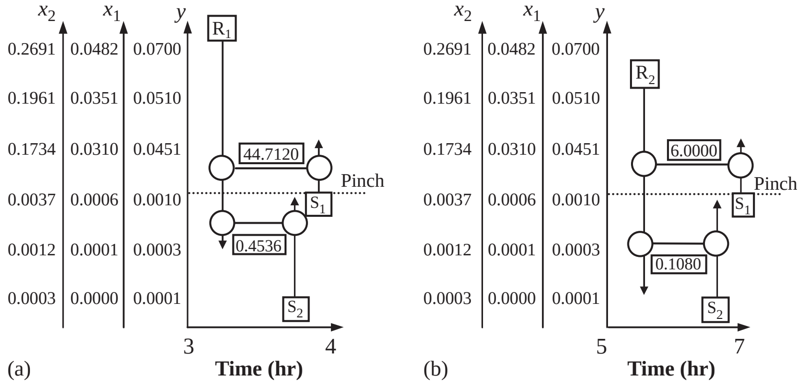


Fig. 6. MEN designs for the (a) second and (b) fourth time intervals.

Fig. 5 shows the MEN design for the first and final time intervals of the system. Both process-rich streams R_1 and R_2 exist below the pinch region in their respective time intervals. Since process MSA is not available in these time intervals, and mass storage system is not employed in this case, external MSA is used to absorb the mass load from the rich streams.

During the second and the fourth time intervals, process MSA S_1 is present in the process in the region above the pinch. Hence, the MEN in this region is designed to match the rich process stream with the process MSA. The external MSA is used in the region below the pinch, since no process MSA is available there (Fig. 6).

In the third time interval, two rich process streams exist in the region above the pinch while only one process MSA is found. Thus, in order to have a feasible stream-matching criteria, stream splitting is done for the process MSA. Below the pinch, no process MSA is found. Thus, the rich process streams are again matched to the external MSA (S_2). There are two feasible matches as shown in Fig. 7. In Fig. 7(a), rich streams exchange mass load with the external MSA in a series configuration. In Fig. 7(b), the external MSA is split to match with the rich streams in a parallel configuration. Note that the minimum composition difference is satisfied in both designs.

The network design for the entire process cycle is represented in Fig. 8, taking the series configuration at the lean end of the network in the third interval (Fig. 7a). Note that the mass exchangers are numbered after the network designs in the individual time intervals are combined into a complete network representation (Fig. 8). It should also be noted that the mass exchanger matching the same pair of streams is given the same number to avoid confusion. Four mass exchangers are needed here, as has been predicted in the minimum units targeting section (Section 2) of this paper. An overall representation of the MEN in the OTGD is shown in Fig. 9.

3.2. Network design for a single-batch system with mass storage

So far, only the network with direct mass exchange within a time interval have been considered. *Indirect mass exchange*, which refers to mass being stored for use at a later time, is also a possibility. The concept introduced by Kemp and Deakin (1989b) for the network design of batch

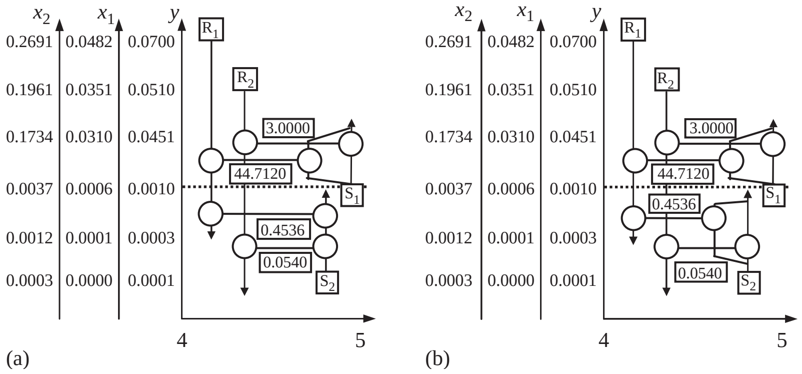


Fig. 7. Two MEN designs for the third time interval: (a) series configuration; (b) parallel configuration.

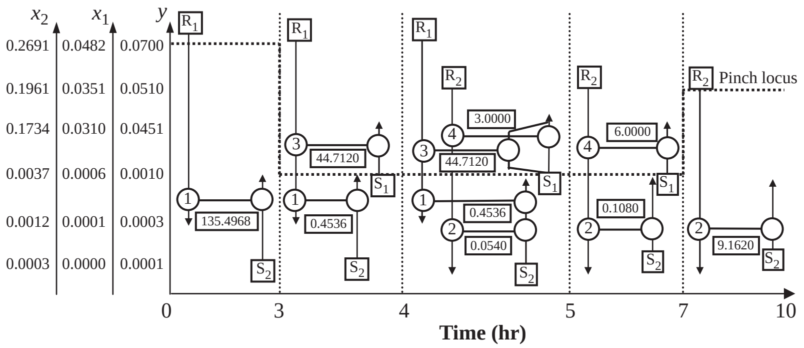


Fig. 8. Network design for a single-batch process operation (without mass storage) by TGD.

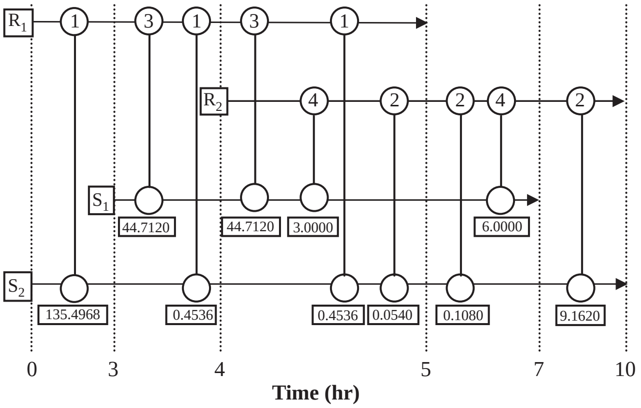


Fig. 9. The OTGD representing the entire network (single-batch process without storage).

HEN with heat storage will be extended to the MEN design here.

The mass kept in storage system may function either as a lean or a rich stream, depending on which stream the storage system is finally integrated with. Mass stored at any time interval will function as a lean stream if it is matched with a richer stream. On the other hand, the mass stored will function as a rich stream if it is integrated with a leaner stream.

Fig. 10 shows the network design in a TGD for the case study which operates in a single-batch mode with mass storage. Note that the mass load from rich stream R_1 in the first time interval in the region above the pinch, that is initially supposed to be transferred into the external MSA, can now be transferred to the mass storage system (see Fig. 8 for MEN without storage system).

By absorbing the rich stream from the first time interval, the storage system acts as a “lean stream”. Between the second and fourth time intervals, the storage system acts as a “rich stream” by releasing its mass load to leaner streams which exist in these intervals. This mass storage minimises the consumption of the external MSA for the overall process.

The use of storage system has also enabled the excess capacity of process MSA to be exploited in the second to the fourth time intervals. Finally, it is important to note that the use of storage has resulted in a new locus of pinch compositions. Recall that no changes can be made in the final time interval in the case of MEN without storage, since the excess capacity of the process MSA cannot be used in an earlier time interval.

A representation of the network in an OTGD is shown in Fig. 11. A rectangular box represents the storage system. Mass load transferred to and from the storage system is indicated by dotted arrows. The amount of mass load transferred to and from the storage system is shown in a box below the

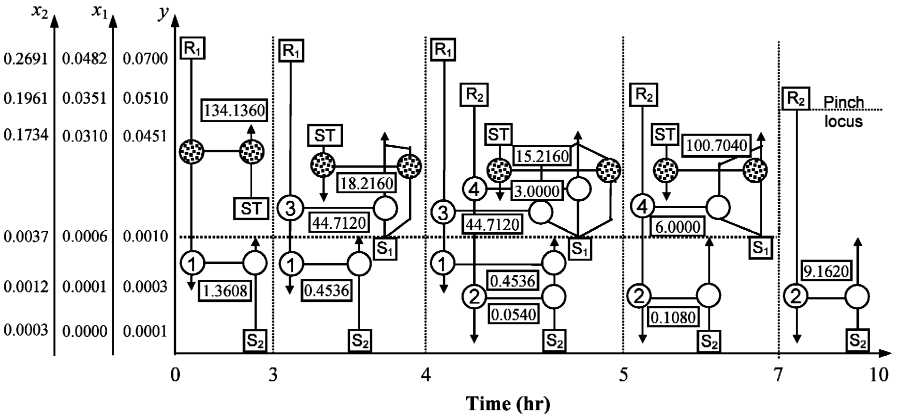


Fig. 10. Network design for single-batch MENS with mass storage.

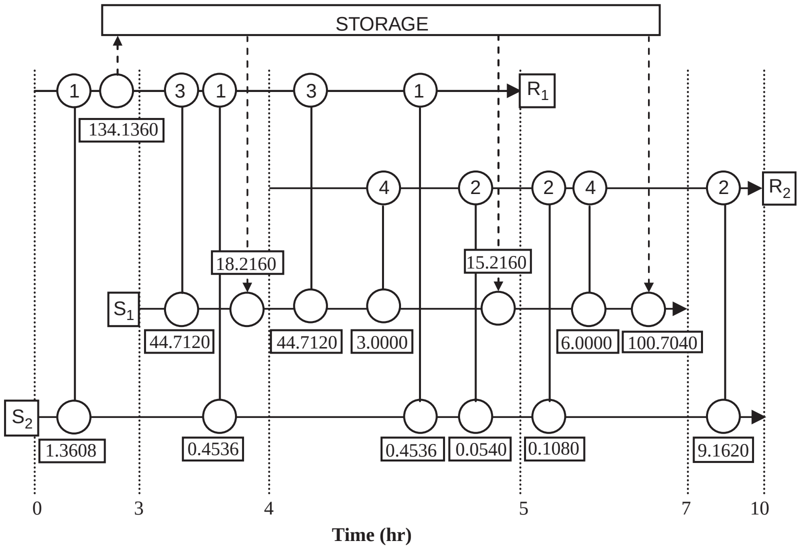


Fig. 11. OTGD for a single-batch process with storage.

process-storage mass exchanger. The process-storage mass exchanger is represented by a circle linked by a dotted arrow to and from the storage.

3.3. Network design for repeated-batch processes with mass storage

When a batch process is operated repeatedly, the capacity in the mass storage in one process cycle can be used in a later process cycle. Kemp and Deakin (1989a,b) reported that the repeated-batch system for HENS results in the same utility consumption as for the continuous system. We will demonstrate that the same concept applies for batch MEN as well.

Consider the network design for batch MENS with mass storage in Fig. 10. Recall from the previous section, that, if we could also store the excess capacity of the process MSA available during the final time interval, we would have been able to further minimise the consumption of the external MSA.

Fig. 12 shows the network design in OTGD for the repeated batch process. Mass storage is used between time intervals of 7 and 10 h to absorb the excess process MSA capacity. This eventually leads to the reduction of external MSA consumption and the excess capacity of process MSA in this time interval. The absorbed mass load will then be transferred to the lean stream in the later process cycle.

As shown in the time interval between 5–7 h in Fig. 12, mass load in the process-storage mass exchanger has increased with the same amount of mass load stored from the final time interval. This again has reduced the excess process MSA capacity in the fourth time interval (5–7 h).

3.4. Conceptual design of mass storage system

Mass storage plays an important role in reducing the pollutant mass load from process streams in utilising the excess capacity of process MSA for pollution prevention purpose. In this section, the concept of mass storage system is briefly discussed. The detailed design of a mass storage system is

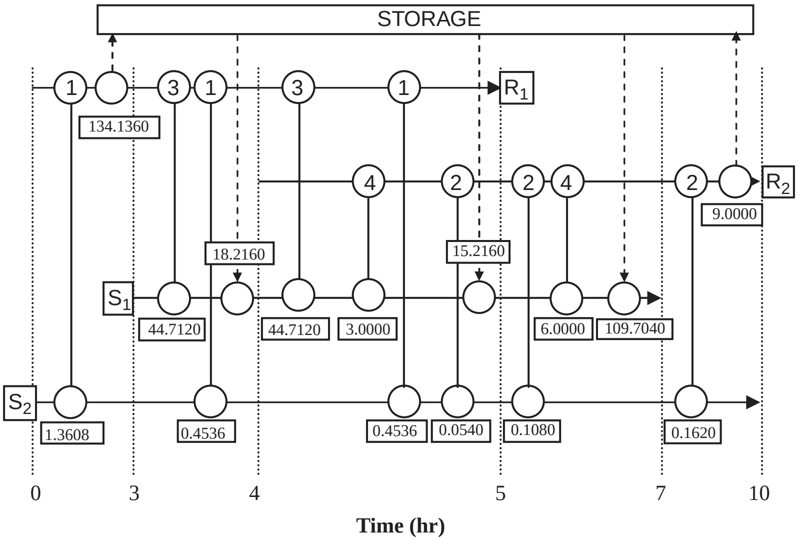


Fig. 12. OTGD for repeated-batch processes with storage.

beyond the scope of the paper, and thus will not be covered here.

Sections 3.2 and 3.3 describe that a mass storage can function either as lean or rich stream, depending on which stream the stored mass is finally integrated with. The mass storage is a type of mass transfer equipment employing a regenerated MSA. The MSA is used to extract pollutant mass load from a rich stream at one time interval. The MSA from mass storage system can be regenerated by employing a process MSA with excess capacity to absorb its mass load.

The COG case study is utilised as an example to demonstrate the proposed design of a mass storage system. Fig. 12 shows a mass storage system extracting mass load from the rich streams R_1 and R_2 in the first and final time intervals, respectively. The stored mass load is transferred back to the process MSA (S_1) in time interval between 3–7 h. The rich streams R_1 and R_2 exist in the gas phase (sour gas stream), while the lean stream of S_1 exists in the liquid phase (aqueous ammonia). It is possible to utilise a solid adsorbent as the mass storage system media. The adsorbent will first extract the pollutant mass load (in this case, hydrogen sulphide) from the sour gas streams R_1 and R_2, which exist in the respective first and final time intervals via an adsorption process. The stored mass load will be retained in the adsorbent until aqueous ammonia as the process MSA S_1 is available between the second and fourth time intervals. In these time intervals, aqueous ammonia will be used to “leach” hydrogen sulphide from the storage MSA. This will “regenerate” the storage MSA for further reuse. Hydrogen sulphide is then “recovered” by sending the aqueous ammonia stream to the Claus unit for sulphur recovery. Regeneration of storage MSA reduces the excess process MSA capacity and ultimately minimises the process waste.

If the process MSA used in the COG case study is in solid form (e.g. a solid adsorbent), it may be more effective to utilise a liquid solvent as a mass storage media. In this case, the storage media will first absorb pollutant mass load from the rich streams R_1 and R_2 via an absorption process. At a later time, the solvent can be regenerated by the process MSA via an adsorption process.

Table 7
Mass storage system media selection

Rich phase	Lean phase	Mass transfer operation involved	Proposed MSA media
Gas	Liquid	Adsorption/leaching	Solid adsorbent
Gas	Solid	Absorption/adsorption	Liquid solvent
Liquid	Liquid	Adsorption/leaching	Solid adsorbent
Liquid	Solid	Extraction/adsorption	Liquid solvent
Liquid	Gas	Extraction/stripping	Liquid solvent
Solid	Liquid	Leaching/extraction	Liquid solvent

The selection of other mass storage MSA media is shown in Table 7. In the case of a liquid waste stream, three different kinds of mass storage systems could be used. If the process MSA is a liquid solvent, one may utilise a solid adsorbent as the MSA for mass storage. The mass load from the rich stream is firstly adsorbed by the solid adsorbent. Regeneration will occur by contacting the solid adsorbent with the process MSA at a later time to leach the stored mass load. On the other hand, when the process MSA is a solid adsorbent or a gaseous stream, a liquid solvent can be used as a mass storage media. For the case of solid adsorbent as a process MSA, through solvent extraction and adsorption, the pollutant mass load can be transferred to the storage system at a given time and released back to the process at a later time interval. While in the case of stripping gas as a process MSA, regeneration is carried out through solvent extraction and stripping processes.

The final example involves a solid waste stream that utilises a liquid-phase process MSA for leaching its contaminant mass load. One may utilise a liquid solvent to leach the contaminant mass load at a given time and this storage media is later regenerated by solvent extraction. From the above examples, we have seen that the selection of mass transfer operation for mass storage system is dependant upon the phase of the rich streams as well as the process MSA(s). Table 7 summarises some typical kinds of mass transfer operations associated with mass storage system for the different combinations of waste streams and process MSA.

4. Network evolution through mass load loop and path

Owing to the existence of pinch composition, the MEN is decomposed into two sub-networks, i.e., the network above and below the pinch. Hence, the minimum mass exchanger units for a MMR network, $U_{\min,\mathrm{MMR}}$ is obtained by applying Eq. (5). However, as mentioned in the previous section, a MMR network will normally possess more exchangers compared to that for which the pinch is ignored, i.e.,

$$U \leqslant U_{\min,\mathrm{MMR}}. \tag{10}$$

Note, however, that ignoring the pinch would incur extra utilities and additional operating cost. We will examine how the conventional network evolution techniques can be utilised to reduce the complexity of a preliminary network. It should be noted that since this network evolution technique is used to reduce the complexity of the preliminary network which only consists the direct mass exchanger, only MEN without storage system will be considered for the network evolution.

As shown in the minimum units targeting (Section 2), for the case of batch COG process, four exchangers are needed for a MMR network. If the pinch composition is ignored, three exchangers are actually needed. A further examination of the batch network reveals that a cross pinch mass loop exists in the third time interval (Fig. 13). Hence, it is clear that by breaking this mass loop, one mass exchanger will be eliminated from the preliminary MMR network. However, any attempt to eliminate any mass exchanger in the third time interval will not give us much impact on the overall reduction of network complexity, since all the mass exchange units in this time interval are also used in other time intervals (refer to Fig. 8 or Fig. 9). Hence, we should handle this problem by considering the network across all time intervals.

Firstly, the overall mass load for each mass exchanger (obtained by adding the individual mass load over all the time intervals) is listed in Table 8. Mass exchanger 4 (with a mass load of 9 kg), which is a process-to-process mass exchanger which exists in the third and fourth time intervals, is observed to be the smallest unit throughout the whole network. Following the heuristic to eliminate the mass exchanger with smallest mass load (Linnhoff et al., 1982), the mass exchanger with a mass load of 9 kg is to be eliminated in both time intervals in order to reduce the network complexity.

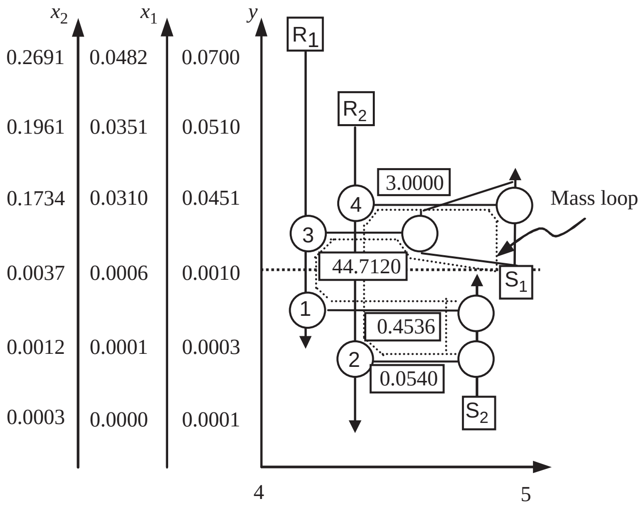


Fig. 13. A mass load loop identified in the third time interval (4–5 h).

Table 8
The overall mass load for each mass exchange unit

Mass exchange	Mass load (kg)
1	136.4040
2	9.3240
3	89.4240
4	9.0000

Next, the mass load for each mass exchanger in the third time interval is examined. Fig. 13 shows that the smallest mass exchanger found in this interval is actually exchanger 2. However, any attempt to break the loop by eliminating exchanger 2 will result in a negative driving force at the lean end of exchanger 4, and hence, an infeasible match (Fig. 14). Such infeasibility cannot be corrected since the outlet composition of R_2 (0.0001) will have to match with the inlet composition of process MSA, S_1 at $x_1 = 0.0006$. In order for R_2 to reach the composition of $y = 0.0001$, it must be exchanged with a leaner stream after leaving the exchanger 4. As a conclusion, exchange 2 must be maintained in order to have a feasible network.

The next attempt to reduce the number of mass exchanger is through a mass load path, which is a continuous connection which starts with an external MSA and concludes with a process MSA (El-Halwagi, 1997). Fig. 15(a) shows two mass load paths identified in the third time interval. Mass load path S_1–R_2–S_2 passes through exchangers 2 and 4, while mass load path S_1–R_1–S_2 passes through exchangers 1 and 3. Since the main objective now is to eliminate the fourth exchanger, the path of S_1–R_2–S_2 should firstly be analysed. One can use this path to shift a load of 3 kg from S_1 to S_2 (Fig. 15a). This load shifting will lead to the elimination of the fourth exchanger and incur a utility penalty due to the use of excess amount of external MSA (S_2).

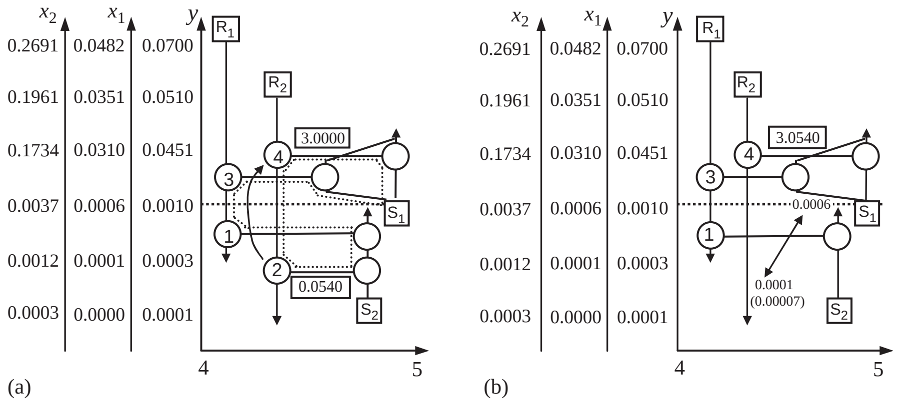


Fig. 14. Mass load loop breaking in the third time interval: (a) mass load shifted from exchanger 2 to exchanger 4; (b) ε violation occurs at the lean end of exchanger 4 (number in bracket indicates the corresponding target composition of R_2 in S_2).

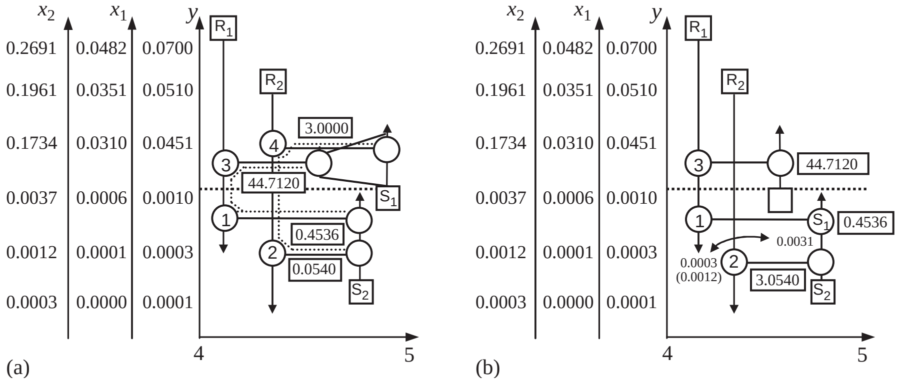


Fig. 15. (a) Two mass load paths are identified in the third time interval: S_1–R_1–S_2 and S_1–R_2–S_2; (b) infeasibility occurs on the lean end of the first mass exchanger.

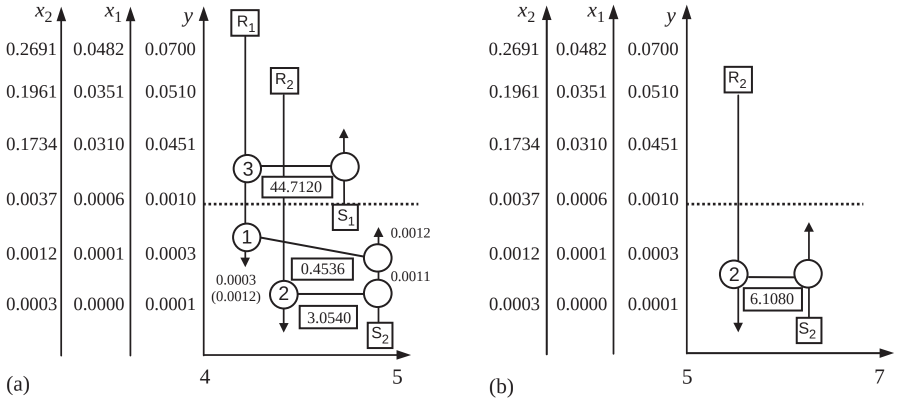


Fig. 16. Simplified network after mass load shifting through the mass load path: (a) third time interval (4–5 h); (b) fourth time interval (5–7 h).

One may calculate the new flowrate of S_2 by summing the total mass load transferred across exchangers 1 and 2. However, this will result in a thermodynamically infeasible situation. This is due to the outlet composition of R_1 ($y = 0.0003$, corresponding to the lean composition of $x = 0.0012$ for S_2) having to operate with the S_2 composition of 0.0031 at the lean end of exchanger 1 (15b). As imposed by thermodynamic constraint, the maximum feasible composition of S_2 leaving the second mass exchanger is 0.0011 (minimum composition difference at the lean end of the mass exchanger shown in Fig. 16a). Therefore, the flowrate of S_2 (calculated by Eq. (4) in Foo et al. (2004)) ought to be increased to

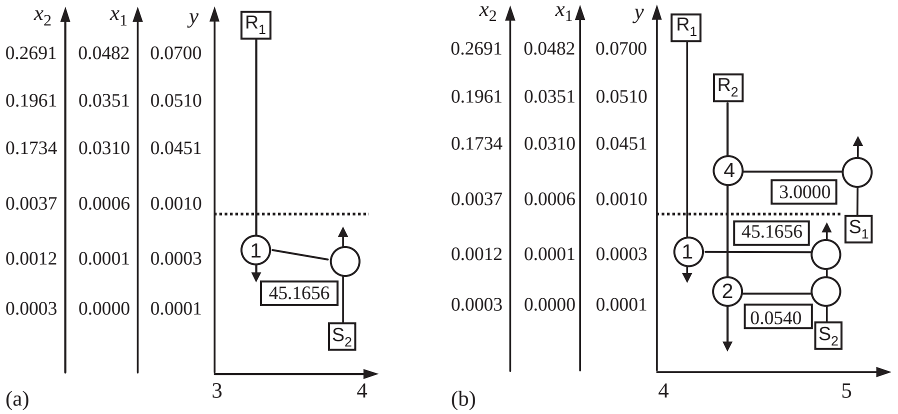


Fig. 17. Simplified network after mass load shifting through a mass load path to eliminate exchanger 3: (a) second time interval (3–4 h); (b) third time interval (4–5 h).

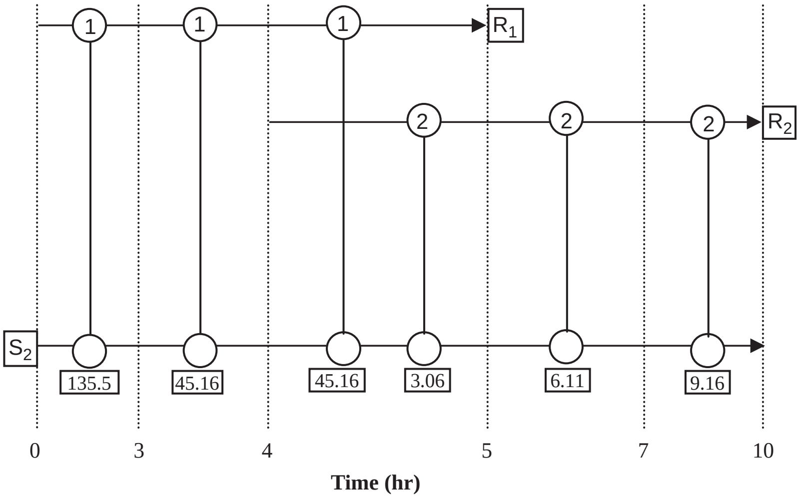


Fig. 18. Elimination of the process MSA by shifting the entire mass load of process streams to the external MSA.

become

$$L_2 = 3.0540/(0.0011 - 0.0002) = 3393.3333\,\text{kg}.$$

The same technique is also applied to the network in the fourth time interval. The mass load of 6 kg is shifted from exchanger 4 to exchanger 2, through the mass load path S_1–R_2–S_2 (Fig. 16b). This mass load path eliminates the use of the fourth exchanger and increases the flowrate of external MSA S_2 to

$$L_2 = 6.1080/(0.0035 - 0.0002) = 1850.9091\,\text{kg}.$$

In other words, the total mass load shifting of 9.0000 kg from S_1 to S_2 has eliminated the fourth exchanger, with an expense of increasing flowrate of external MSA, S_2 by 5057.6969 kg (the original S_2 consumption in the third and fourth time intervals is calculated as 153.8182 + 32.7273 = 186.5455 kg). This situation presents a trade-off between the network complexity and the operating cost (external MSA).

On the other hand, if the fourth exchanger is justified to be maintained due to same technical considerations, one may also utilise another mass load path S_1–R_1–S_2 to eliminate exchanger 3. This exchanger is found to operate in the second and third time intervals. By shifting the mass load of 44.7120 kg from exchanger 3 to 1, this unit is eliminated in both second and third time intervals (Fig. 17). The increase in the flowrate of the external MSA in the second and third time intervals are calculated as follows:

$$L_2 = 45.1656/(0.0035 - 0.0002) = 13,686.5455\,\text{kg}$$

and

$$L_2 = 45.2196/(0.0035 - 0.0002) = 13,702.9091\,\text{kg}.$$

It should be noted that, since the third mass exchanger has a larger mass transfer load, the penalty on the external utility is also expected to be larger than the case involving the elimination of the fourth exchanger.

Table 9
Number of mass exchangers and utility consumption for each network option

Alternative network	Number of mass exchangers	L_1(kg)	L_2 (kg)
Original network	4	3237.6316	44,160.0000
After elimination of exchanger 2	3	2941.5790	49,217.6969
After elimination of exchanger 4	3	296.0526	71,258.1819
After elimination of process MSA	2	0	73,985.4545

If it is justified to shift all the mass transfer load from the process MSA so that all the waste load (244.1520 kg) is transferred to the external MSA as shown in Fig. 18, the flowrate of the external MSA will increase to

$$L_2 = 244.1520/(0.0035 - 0.0002) = 73,985.4545\,\text{kg}.$$

By comparing the simplified network (Fig. 18) and the preliminary network (Fig. 9), we notice that the application of network evolution technique has resulted in an increase of utility consumption. On the other hand, the number of mass exchange units has dropped from four to two. This provides a designer with options to reduce the network complexity and overcome constraints imposed through mass integration. The utility consumption of the process and the external MSA, as well as the number of mass exchangers needed from the COG case study, are summarised in Table 9.

5. Conclusion

The minimum number of units target provides another systematic and valuable design guideline for the design of an optimal MEN. The units target coupled with the utility target can be generated ahead of network design.

A systematic procedure for designing a batch MMR network that achieves the minimum utility targets has been developed. Two new graphical tools called the TGD and the OTGD that incorporate the time and composition axes have been introduced to provide a better representation of the problem during MEN design for the batch system. The three cases studied, i.e., the single-batch processes with and without mass storage and the repeated batch with storage system, have proved that the established targets for the direct and indirect (via mass storage) mass exchange can be achieved through a systematic network design methodology developed in this paper.

By applying the loops and paths network evolution technique, one may reduce the network complexity and overcome constraints imposed through mass integration. Elimination of the process-to-process mass exchangers results in external utility penalty. The extent of network simplification and the reduction in the number of mass exchange units directly influences the increase in the operating cost. Ultimately, it is up to the designer to decide how much increase in the operating cost (due to the unit reduction) is acceptable.

Notation

FCP	heat capacity flowrate, kW/°C
G_i	mass of rich stream i, kg
L_j	mass of lean stream j, kg
m_j	constant of equilibrium of component (contaminant) in lean stream j
N	number of streams
N_R	number of rich streams
$N_{R,\text{above}}$	number of rich streamsat the above pinch region
$N_{R,\text{below}}$	number of rich streams at the below pinch region
$N_{R,k}$	number of rich streams in time interval k
N_S	number of lean streams
$N_{S,\text{above}}$	number of lean streams at the above pinch region
$N_{S,\text{below}}$	number of lean streams at the below the pinch region
$N_{S,k}$	number of lean streams in time interval k
N_{SN}	number of independent sub-networks
$N_{\text{SN},k}$	number of independent sub-networks in time interval k
N_{TI}	number of time interval where both rich and lean streams co-exist
U	number of mass exchange units
U_{above}	number of mass exchange units at the above pinch region
U_{AE}	number of additional exchangers
$U_{AE,l}$	number of l additional exchangers
$U_{AE,l,\text{above}}$	number of l additional exchangers at the above pinch region
$U_{AE,l,\text{below}}$	number of l additional exchangers at the below pinch region
U_{below}	number of mass exchange units at the below pinch region
U_k	number of mass exchange units
$U_{k,\text{above}}$	number of mass exchange units in time interval k at the above pinch region
$U_{k,\text{below}}$	number of mass exchange units in time interval $k$at the below pinch region
$U_{\min,\text{MMR}}$	number of minimum mass exchange units for a MMR network
x	composition in lean stream (mass/mole fraction)
y	composition in rich stream (mass/mole fraction)

Greek letter

ε	minimum composition difference

Subscripts

above	at the above pinch region
AE	additional exchanger
below	at the below pinch region
i	rich stream number
j	lean stream number
k	number of time interval
l	number of additional exchanger pair
min	minimum
MMR	maximum mass recovery
R	rich stream
S	lean stream
SN	independent sub-network
TI	time interval

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