Chemical Engineering Science 59 (2004) 1009 – 1026

Chemical Engineering Science

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Synthesis of mass exchange network for batch processes—Part I: Utility targeting

C.Y. Foo[a], Z.A. Manan[b,*], R.M. Yunus[b], R.A. Aziz[a]

[a] *Chemical Engineering Pilot Plant, Universiti Teknologi Malaysia, Skudai, Johor 81310, Malaysia*
[b] *Chemical Engineering Department, Universiti Teknologi Malaysia, Skudai, Johor 81310, Malaysia*

Received 16 July 2001; received in revised form 13 September 2002; accepted 14 September 2003

Abstract

Synthesis of optimal mass exchange network (MEN) for continuous processes based on Pinch Analysis has been rather well established. In contrast, very little work has been done on mass exchange network synthesis (MENS) for batch process systems. The batch process systems referred to in this work can be defined as processes which operate discontinuously and deliver the products in discrete amounts, with frequent starts and stops. There is a clear need to develop a MENS procedure for batch process systems which are industrially very common as well as important. Techniques developed in this paper for the batch MENS involved the first key steps in the synthesis task, i.e. setting the utility targets ahead of batch MEN design. The utility-targeting approach employs the vertical and horizontal cascading approaches in a newly developed tool, i.e. time-dependent composition interval table that has been adapted from heat exchange network synthesis for batch processes. Prior to MEN design, the targeting procedure establishes the minimum utility (solvent) and mass storage targets for a maximum mass recovery network. These targets are essential for network design and batch process rescheduling.

Keywords: Mass exchange networks; Pinch analysis; Batch processing; Utility targeting; Vertical cascading; Horizontal cascading

1. Introduction

1.1. *Energy integration for continuous and batch processes*

Systematic approaches in addressing energy integration schemes in a process plant began during the global energy crisis in the late 1970s. Since then, pinch technology has been accepted globally as an effective tool in designing a cost-optimal heat exchange network (HEN).

The heat exchange network synthesis (HENS) task can be stated as follows (El-Halwagi, 1997):

Given a number N_H of hot process streams (to be cooled) and a number N_C of cold streams (to be heated), it is desired to synthesise a cost-effective network of heat exchangers which can transfer heat from the hot streams to the cold streams. Also given are the heat capacity flowrate, FCP, supply temperature, T^s, and target temperature, T^t, of each stream. Available for service are heating and cooling utilities whose costs, supply temperature and target temperatures are also given.

Towards the late 1980s, the work on HEN design has become rather well established. A few good reviews of the well-established HEN techniques can be found in the literature (Nishida et al., 1981; Linnhoff, 1993; Gundersen and Naess, 1988; Shenoy, 1995). However, most of the research on HENS have focused on continuous process. Much less work has been carried out for the batch HENS problem.

The very early work addressing energy integration for batch processes was reported by Vaselenak et al. (1986). They worked on the heat recovery between vessels whose temperatures vary during operations. They presented a heuristic rule for the cocurrent heat exchange and a MILP solution for the restricted target temperature. Yet, these authors did not consider the time dependence of streams in which some streams may only exist in the plant for a certain period of time. They also investigated the opportunity for rescheduling and the generation of rescheduling superstructures in their later work (Vaselenak et al., 1987).

Besides the heuristics and numerical solutions, heat integration scheme for batch processes has also been studied by

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* Corresponding author. Tel.: +60-07-5535512; fax: +60-07-5581463.
E-mail address: zain@fkkksa.utm.my (Z.A. Manan).

0009-2509/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2003.09.043

other researchers, who used the technique of pinch analysis. Linnhoff et al. (1987, 1988) produced the first two papers based on the conventional approach of heat integration on the continuous mode (Linnhoff et al., 1982). They developed a "time slice model" to obtain the energy integration targets for the batch operation. However, their work is confined to the use of a simple scheduling diagram. No representation of which streams were thermodynamically capable of exchanging heat was obtained. In their later publication (Obeng and Ashton, 1988), they made use of the cascade analysis to calculate the energy targets for the time slice model.

The first attempt to use time-dependent heat integration was reported by Kemp and Macdonald (1987, 1988). They developed a fully time-dependent cascade analysis in contrast with the conventional technique (Linnhoff et al., 1982). Their approach allows targets to be obtained for the maximum energy recovery (MER), maximum direct heat exchange (MHX) as well as heat storage. The authors also reported a time-dependent network design and identified rescheduling opportunities in their later publications. (Kemp and Deakin, 1989a–c; Kemp, 1990).

Other efforts in developing the heat integration schemes for batch systems have also been reported by various other authors. Lee and Reklaitis (1995a,b) developed scheduling models for maximising heat recovery in cyclically operated single-product processes and across independently operated batch production line. Corominas and co-workers (Corominas et al., 1993, 1994; Grau et al., 1996) published three papers which addressed energy and waste minimisation in multiproduct batch processes. Vaklieva-Bancheva and co-workers (Vaklieva-Bancheva and Ivanov, 1993; Vaklieva-Bancheva et al., 1996) developed a MILP solution for heat exchange network design for multipurpose batch plants in which only direct heat exchange is considered. The same authors reported a case study on heat integration for an antibiotics batch-manufacturing process (Ivanov et al., 1996). Sadr-Kazemi and Polley (1996) reported that in some batch processes, heat storage might provide a more flexible alternative compared to direct integration. They suggested that external heating or cooling could lead to a higher plant throughput. Polley also examined rescheduling in his later work (Polley, 2000). Zhao et al. (1998a) presented a systematic mathematical formulation based on the cascade analysis, which involve the policy of no intermediate storage, but with heat integration. A three-step procedure is proposed for the design of HEN for batch and semi-continuous processes in their later work (Zhao et al., 1998b).

1.2. Mass exchange networks for continuous processes

El-Halwagi and Manousiouthakis (1989) introduced the concept of MENS on a continuous mode, in which the problem statement can be stated as:

Given a number N_R of waste (rich) streams and a number N_S of MSAs (lean streams), it is desired to synthesise a cost-effective network of mass exchangers that can preferentially transfer certain undesirable species from the waste streams to the MSAs. Given also are the flowrate of the each waste stream, G_i, its supply (inlet) composition y_c^s, and its target (outlet) composition y_i^t. In addition, the supply and target compositions, x_j^s and x_j^t, are given for each MSA. The flowrate of each MSA is unknown and is to be determined so as to minimise the network cost.

The candidate lean streams can be classified into N_{SP} process MSAs and N_{SE} external MSAs (where $N_{SP}+N_{SE}=N_S$). The process MSAs already existing on plant site can be used for the removal of the undesirable species at a very low cost (virtually free). The flowrate of each process MSA that can be used for the mass exchange is bounded by its availability in the plant, and may not exceed a value of L_j^c. On the other hand, the external MSAs can be purchased from the market and their flowrates are to be determined by economic considerations.

El-Halwagi and Manousiouthakis (1989) first introduced the procedure for optimal synthesis of MEN, based on the conventional heat transfer pinch analysis. They showed that by specifying the "minimum allowable composition difference, ε" (analogous to the $\Delta T_{\min}$ in HENS), a composition pinch point could be located at the mass transfer composite curves. These mass transfer composite curves provide the minimum utility targets (minimum MSA consumption) ahead of any network design. They also established that, by following the conventional approach of PDM (Linnhoff and Hindmarsh, 1983), it is possible to obtain the maximum mass recovery (MMR) network, with the minimum utility targets established.

In their later work, El-Halwagi and Manousiouthakis (1990a) presented a two-stage automated procedure for synthesising the MEN. Linear programming (LP) is used in the first stage to determine the pinch point as well as the minimum cost of MSAs, while a mixed-integer linear program (MILP) is then used to minimise the number of mass exchangers in the second stage. A limitation of this procedure is that many network designs must be completed and evaluated. The procedure is therefore computationally intensive.

Papalexandri et al. (1994) later developed a procedure based on mixed integer non-linear program (MINLP) to overcome the limitation of the sequential procedure in the linear programming. In this MINLP approach, they generate a network hyperstructure which contains many network alternatives. Optimisation is done based on this hyperstructure in order to get a minimum total annual cost (TAC). However, besides the great amount of efforts required to set up and optimise the network hyperstructure, this method does not always guarantee the generation of an optimum network (Hallale and Fraser, 1998). This is due to the fact that this hyperstructure does not take into account the thermodynamic bottleneck of the networks.

Friedler et al. (1996) introduced the P-graph theory to solve the MENS problems. Lee and Park (1996) later improved the technique by combining the P-graph theory with the non-linear programming (NLP). This two-step procedure determines the network structure as well as its operating conditions.

Garrard and Fraga (1998) introduce another numerical analysis technique based on genetic algorithms (GA) to solve the MEN synthesis task. This stochastic optimisation technique is based on the concept of natural evolution. MEN and MEN with regeneration are solved by this GA-encoding technique proposed by Garrard and Fraga (1998).

Yet another numerical analysis technique for the MENS is the state space approach introduced by Bagajewicz et al. (1998) for the design of energy-efficient distillation networks (Bagajewicz and Manousiouthakis, 1992). This state space approach is then extended for multicomponent MENS by Gupta and Manousiouthakis (1994). The drawback of this approach is that there is no guarantee of a global optimal solution. Wilson and Manousiouthakis (2000) more recently presented another conceptual framework which is called the Infinite DimEnsionAl State-space (IDEAS) approach to overcome these deficiencies.

The main drawback of the above-mentioned numerical analysis approach is the difficulties in setting up and understanding the mathematical formulation. Once the mathematical program is formulated, the engineer's insight of the design process is no longer taken into account. This is essentially not favourable as, in most circumstances, the engineer's decisions are also important for the design process.

Viewing the drawbacks of the mathematical formulation, Hallale (1998) presented MENS task by handling the capital cost target using on the pinch-based method. They firstly deal with the special case of MEN, the water minimisation problem (Hallale and Fraser, 1998), which is firstly introduced by Wang and Smith (1994). Both the utility cost and the capital cost are targeted prior to any design work. They also introduced a new graphical tool, the x–y plot to handle the capital cost targets for MENS.

A more generalised total cost targeting (utility and capital cost targeting) method for the MENS problem is later presented by the same authors (Hallale and Fraser, 2000a–d). This "supertargeting" technique is essentially the same concept as in the HENS (Linnhoff and Ahmad, 1990). Retrofit technique for MEN has also been reported by the same authors in another publication (Fraser and Hallale, 2000a,b).

The MENS concept was then extended to a much wider range of problems. These problems include the simultaneous synthesis of mass exchange and regeneration networks (El-Halwagi and Manousiouthakis, 1990b); synthesis of reactive MEN (El-Halwagi and Srinivas, 1992; Srinivas and El-Halwagi, 1994a); synthesis of combined heat and reactive MEN (Srinivas and El-Halwagi, 1994b); synthesis of waste-interception networks (El-Halwagi et al., 1996); heat-induced separation networks (Dunn et al., 1995; Dye et al., 1995; Richburg and El-Halwagi, 1995; El-Halwagi et al., 1995) as well as the special case of MEN, i.e. the water minimisation problem (Wang and Smith, 1994, 1995; Dhole et al., 1996; Olesen and Polley, 1997; Sorin and Bédard, 1999; Polley and Polley, 2000; Bagajewicz, 2000; Dunn and Wenzel, 2001a,b; Feng and Seider, 2001; Hallale, 2002; Tan et al., 2002; Foo et al., 2003; Manan and Foo, 2003; Manan et al., 2004).

1.3. *Mass exchange network synthesis for batch process systems*

Even though the technique for MENS has been rather established, yet, almost all of the MENS tasks have been carried out for the continuous processes. The only paper which briefly discussed a special case of MENS, i.e. water minimisation for batch operation, is reported by Wang and Smith (1995). By putting time as one of the main process variables, they attempt to maximise the driving force in each of the concentration interval so that water usage is minimised and water consumption can be targeted ahead of any network design. Since the work of Wang and Smith (1995) is limited to batch systems involving water, clearly, a more generalized procedure is needed for the synthesis of batch process systems involving MSA other than water.

This paper therefore aims to present the first step in the synthesis of MEN for batch process systems, i.e. minimum utility targeting. The targeting employs the newly introduced *time-dependent composition interval table* (TDCIT) that has been adapted from the time-dependent cascade analysis of HENS for batch processes. Two different approaches, i.e. the vertical and horizontal cascading methods can be employed through the TDCIT to establish the network targets prior to MEN design. These targets include the minimum utility (solvent) and mass storage targets for a MMR network.

2. Case study—the Coke Oven Gas (COG) sweetening process operated in batch mode

The COG case study from El-Halwagi and Manousiouthakis (1989) has been adapted to accommodate a batch operation mode and demonstrate the batch MENS methodology. Since, in practice, COG is usually available at discrete periods during process cycle, the coke oven operation is better modelled as a batch as opposed to a continuous mode (El-Halwagi and Manousiouthakis, 1989). The COG batch operation cycle is described in detail in the next section.

2.1. *Coke oven operation cycle*

A typical coke oven operation cycle generally involves the coking cycle and sour gas treating by a chemical solvent. The coking cycle consists of seven steps, namely (Schobert, 1987; Loison et al., 1989): (i) coal blend preparation, (ii) coal preheating, (iii) coal charging, (iv) coking cycle,

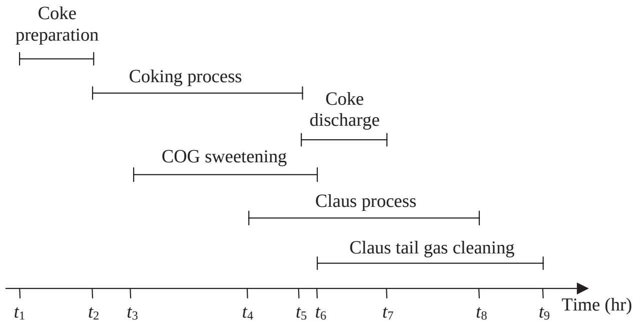

Fig. 1. Process cycle of a COG-sweetening process.

(v) coke pushing, (vi) wet coke quenching, and (vii) dry coke quenching. After the first coking cycle is completed, the coke oven is charged with another batch of coal blend to start the next cycle.

A generic representation of the batch process cycle for coke oven operation is illustrated in Fig. 1. Coke preparation takes place from time t_1 to t_2 during which a suitable coal blend is prepared, preheated and charged into the coke oven. Next, the coking process takes place from time t_2 to t_5. Coke is finally discharged from the coke oven between t_5 and t_7 and the coke oven is prepared for the next coking cycle. Note that, sour COG is released from the coke oven only shortly after the coking process commences. Hence, COG-sweetening process should be performed shortly after the onset of the coking process, i.e. from time t_3 to t_6. COG sweetening, which coincides with the coking process between times t_3 and t_5, only ends after the coking process has finished. COG sweetening removes H_2S in the COG by means of liquid absorption and Claus process (Fig. 2). The Claus unit converts the H_2S in the enriched acid gas stream coming from the stripping section of liquid absorption unit into elemental sulphur from time t_4 to t_8. The tail gas from the Claus unit undergoes further treatment from time t_6 to t_9 (Fig. 1). The tail gas from the Claus unit still contains some elemental sulphur due to the thermodynamic limitations in H_2S conversion (Astarita et al., 1983).

From the above description, it is clear that the sour COG stream exists during the early stage of the process cycle while the Claus tail gas emerges later. This indicates that both of these process-rich streams do not coexist. Note on the other hand that the process lean stream (aqueous ammonia, the MSA for absorption process) is only available after ammonia is recovered at the completion of the sour COG-sweetening process. In the interest of avoiding

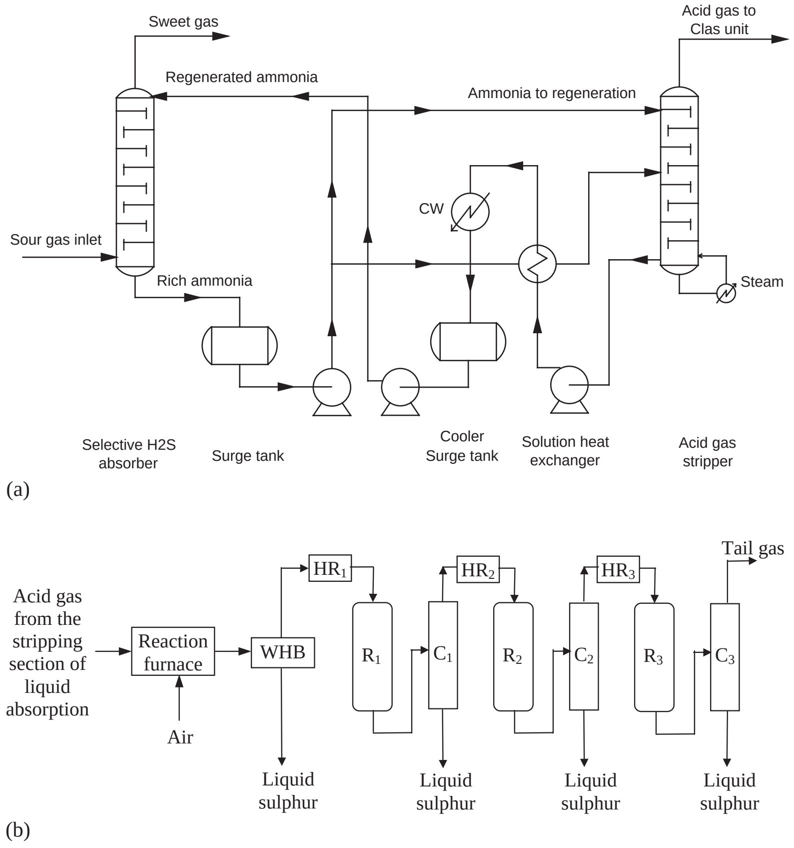

Fig. 2. (a) Sour COG sweetening using liquid absorption system; (b) a simple Claus process with a three-reactor bed (WHB = waste heat boiler; R = reactor; C = condenser; HR = heat recovery) (Maadah and Maddox, 1978).

wastage of the process and external MSAs, the MENS problem should take the discrete nature of the process into consideration.

2.2. Original solution by El-Halwagi and Manousiouthakis (1989)

El-Halwagi and Manousiouthakis (1989) proposed an integrated scheme on the combined treatment of sour COG stream (R_1) and Claus tail gas (R_2) with the use of aqueous ammonia (process MSA, S_1) and chilled methanol (external MSA to be used after S_1 has depleted, S_2) (Fig. 3). The minimum concentration difference ε is fixed at 0.0001. Stream data for this example are given in Table 1. The equilibrium solubility data for H_2S in aqueous ammonia and methanol, respectively are given by the following relations:

$$y = 1.45x_1 \tag{1}$$

and

$$y = 0.26x_2. \tag{2}$$

The minimum flowrates for process MSA and external MSA are, respectively, given by

$$L_1 = L_1^c - \frac{m_{H_2S,p}}{(x_1^t - x_1^s)} \tag{3}$$

and

$$L_2 = \frac{m_{H_2S,ext}}{(x_2^t - x_2^s)}. \tag{4}$$

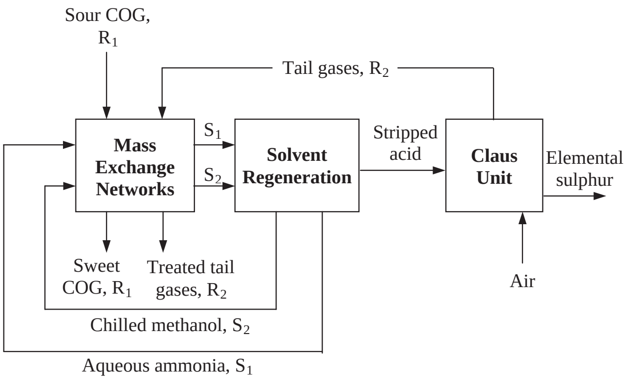

Fig. 3. Mass exchange network representation for the COG-sweetening problem.

Composition interval table (CIT) for this process is shown in Table 2. From Table 2, it can be seen that the pinch occurs at $y = 0.0010$, corresponding to zero mass cascaded in between intervals. The network design for this case study is shown in Fig. 4, where two mass exchangers are located above the pinch while another two exchangers exist below.

However, in a batch operation mode (as described in Section 2.1), the rich streams R_1 (COG stream) and R_2 (Claus tail gas) as well as the process lean stream S_1 (aqueous ammonia) do not coexist during the whole process cycle. Hence, integration between these process-rich and lean streams in batch mode cannot be achieved as suggested by El-Halwagi and Manousiouthakis (1989). The problem is

Table 1
Stream data for COG example (continuous process)

Rich streams				Lean streams			
Stream	G_i (kg/s)	y_i^s	y_i^t	Stream	L_j^c (kg/s)	x_j^s	x_j^t
R_1	0.9	0.0700	0.0003	S_1	2.3	0.0006	0.0310
R_2	0.1	0.0510	0.0001	S_2	∞	0.0002	0.0035

Table 2
Composition interval table (CIT) for COG example

Rich stream			Lean stream		Δm (kg/s)	Cumulative Δm	Modified cumulative Δm
y	R_1	R_2	x_1	S_1			
	0.9 kg/s						
0.0700	↓		0.0482			0.00000	0.00282
	↓	0.1 kg/s			0.01710		
0.0510	↓	↓	0.0351			0.01710	0.01992
	↓	↓			0.00590		
0.0451	↓	↓	0.0310	↑		0.02300	0.02582
	↓	↓		↑	−0.02582		
0.0010	↓	↓	0.0006	↑		−0.00282	0.00000
	↓	↓		2.3 kg/s	0.00070		
0.0003	↓	↓	0.0001			−0.00212	0.00070
		↓			0.00002		
0.0001		↓	0.0000			−0.00210	0.00072

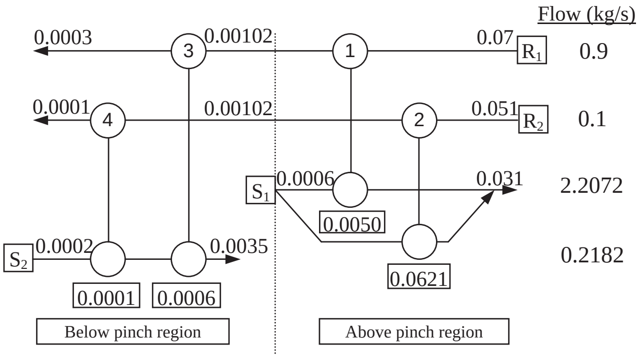

Fig. 4. Network design for COG case study (continuous operation).

resolved through the batch MENS procedure which considers time as a key design variable. The batch MENS procedure is described in detail next.

3. Synthesis of batch mass exchange network

3.1. Problem statement and basic assumptions

The basic problem statements on batch MENS shall follow the problem statement on continuous MENS by El-Halwagi and Manousiouthakis (1989) (Section 1.2). However, in addition to the continuous MENS problem statement, the batch MENS problem statement should include the following:

The process-rich and lean streams are limited by the duration where they exist in the batch process cycle. Hence, apart from the thermodynamic limitations, integration between the process-rich and lean stream is limited by the time duration whereby both streams could coexist. External MSA(s) are used when process MSA is not available.

El-Halwagi and Manousiouthakis (1989) listed a few basic assumptions for the continuous MENS problem. They are:

(1) The mass flowrate of each stream remains essentially unchanged as it passes through the network.
(2) Within the MEN, stream recycling is not allowed.
(3) In the range of composition involved, any equilibrium relation governing the distribution of a transferable component, between the ith rich stream and the jth lean stream, is linear and independent of the presence of other soluble components in the rich stream.

These assumptions on the continuous MENS are also valid for the batch MENS problem. Besides, three other key assumptions are listed as follows:

(4) The mass flowrate for each stream remains essentially unchanged as it passes through the network within its respective time duration.
(5) Mass transfer equilibrium between the rich and lean streams is independent of the time interval. This means that the mass transfer equilibrium and not the time duration will govern the distribution of the transferable components between the rich and lean streams, for the rich and lean streams coexisting in a given time interval.
(6) Mass exchange equipment considered in this work is not equipped with any mass storage devices.

The fourth assumption is reasonable when the flowrate of each stream is independent of the duration when it exists. This assumption is the extension of the first assumption made by El-Halwagi and Manousiouthakis (1989) for the continuous MENS. The fifth assumption indicates that the time function will not affect the equilibrium relationship between the rich and lean streams. It also indicates that all streams have steady-state properties. This is true for most mass exchange systems in industrial application. The final assumption indicates that any mass storage devices to be used are separate from the main mass exchange equipment.

3.2. Case study in a batch process cycle

The previous COG example is now being re-examined by the approach of batch MENS. To demonstrate the developed method, the basic data on the continuous mode have been modified to simulate a batch system with a cycle time of 10 h. This is following the basic approach of Kemp and Deakin (1989a) in the batch heat integration scheme. Rich stream R_1 exists in the process during the first 5 h, while R_2 exists between 4 and 10 h. The process MSA stream (liquid ammonia, S_1) exists from 3 to 7 h. The synthesis task now is to get the minimum requirement of the process MSA, S_1 as well as the external MSA (i.e. the chilled methanol, S_2), for the batch process. This also involves getting the timing for the MSA usage.

Data for the case study in the batch mode are shown in Table 3. The flowrate for each stream has been adjusted to take into account when the streams actually exist in the process. Note that the modified data in this hypothetical example have taken into account the batch operating scenario of the COG-sweetening process. The time duration for any individual operation in a real COG-sweetening process which varies from this case study can be easily scaled accordingly to the proposed time duration in this example.

3.3. Vertical cascading through time-dependent composition interval table

In order to achieve the target for a MMR network, the cascade analysis for batch heat integration (Kemp and Deakin, 1989a) has been modified by integrating it with the composition interval table introduced by El-Halwagi and Manousiouthakis (1989) to become a new tool called the *time-dependent composition interval table* (TDCIT),

Table 3
Stream data for COG batch process

Rich stream	$G_i \times dt$ (kg)	y_i^s	y_i^t	Start	Finish	G_i (kg/h)
				time, t^f (h)	time, t^g (h)	
R_1	3240	0.0700	0.0003	0	5	648
R_2	360	0.0510	0.0001	4	10	60
Lean stream	$L_j^c \times dt$ (kg)	x_i^s	x_i^t	t^f (h)	t^g (h)	L_j^c (kg/h)
S_1	8280	0.0006	0.0310	3	7	2070
S_2	∞	0.0002	0.0035	∞		∞

Table 4
The TDCIT for the given batch COG operation

y	x_1	Time (h)				
		0–3	3–4	4–5	5–7	7–10
		Δm	Δm	Δm	Δm	Δm
0.0700	0.0482					
		36.9360	12.3120	12.3120	0.0000	0.0000
0.0510	0.0351					
		11.4696	3.8232	4.1772	0.7080	1.0620
0.0451	0.0310					
		85.7304	−34.3512	−31.7052	−120.5640	7.9380
0.0010	0.0006					
		1.3608	0.4536	0.4956	0.0840	0.1260
0.0003	0.0001					
		0.0000	0.0000	0.0120	0.0240	0.0360
0.0001	0.0000					

shown in Table 4. As shown, the mass load in each composition versus time interval, Δm is the net mass exchange between rich and lean streams, calculated using the following mass balance equation:

$$\Delta m = [G_i(y^{in} - y^{out}) - L_j(x^{out} - x^{in})](\Delta t_{\text{int}}), \qquad (5)$$

where Δt_{int} = time duration for each time interval.

In this vertical cascading approach, the net mass exchange between the rich and lean streams within each composition interval is cascaded vertically down the composition intervals, in each respective time interval (see Table 5). Internal and external MSA requirements are then identified for each time interval. The MSA requirements over all time intervals are obtained by adding the MSA consumption for the individual time intervals. The next subsections describe the application of this *vertical cascading* technique for a single batch process with and without mass storage (Sections 3.3.1 and 3.3.2, respectively), and for a repeated batch process with storage (Section 3.3.3).

3.3.1. Target for a single batch process without mass storage

Table 5 shows an infeasible TDCIT for a single batch process. Cumulative mass load (denoted by cum. Δm) is the cumulative mass exchange from one composition interval to another, vertically from the highest to the lowest composition interval. A negative cumulative Δm signifies negative mass transfer gradient, implying that mass is transferred from the lower composition interval to a higher composition interval. Clearly, such arrangement is physically infeasible. To ensure a feasible mass cascade, the largest (absolute) negative cumulative Δm value is added at the top composition interval. This value represents the excess capacity of the process MSA required for the time interval in question, that will be cascaded down the composition interval to give positive mass cascade throughout the composition intervals, as shown in the feasible TDCIT (Table 6). The point where the mass cascade value is zero represents the mass transfer pinch point.

Note that, in the feasible mass cascade, the pinch compositions form a locus of zero cumulative Δm (numbers in bold). This case resembles the time slice model (TSM) batch for heat integration (Kemp and Deakin, 1989a). The calculations of utility targets are the same as in the case of continuous process. The largest absolute negative cumulative Δm value added at the top row in each time interval denotes the targeted excess capacity of H_2S removal by ammonia, while the bottom row in each of the time intervals denotes the minimum value of H_2S removal by external MSA, i.e. chilled methanol. Adding the targets over the whole period

Table 5
Infeasible mass cascade for individual time interval

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		0.0000		0.0000		0.0000		0.0000		0.0000
		36.9360		12.3120		12.3120		0.0000		0.0000	
0.0510	0.0351		36.9360		12.3120		12.3120		0.0000		0.0000
		11.4696		3.8232		4.1772		0.7080		1.0620	
0.0451	0.0310		48.4056		16.1352		16.4892		0.7080		1.0620
		85.7304		−34.3512		−31.7052		−120.5640		7.9380	
0.0010	0.0006		134.1360		−18.2160		−15.2160		−119.8560		9.0000
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		135.4968		−17.7624		−14.7204		−119.7720		9.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		135.4968		−17.7624		−14.7084		−119.7480		9.1620

Table 6
Feasible mass cascade for individual time interval

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		**0.0000**		18.2160		15.2160		119.8560		0.0000
		36.9360		12.3120		12.3120		0.0000		0.0000	
0.0510	0.0351		36.9360		30.5280		27.5280		119.8560		**0.0000**
		11.4696		3.8232		4.1772		0.7080		1.0620	
0.0451	0.0310		48.4056		34.3512		31.7052		120.5640		1.0620
		85.7304		−34.3512		−31.7052		−120.5640		7.9380	
0.0010	0.0006		134.1360		**0.0000**		**0.0000**		**0.0000**		9.0000
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		135.4968		0.4536		0.4956		0.0840		9.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		135.4968		0.4536		0.5076		0.1080		9.1620

of the batch will give the minimum utility requirements for the process. Thus, for the entire process, the targeted excess capacity of H_2S removal by ammonia is 153.2880 kg, while the minimum H_2S to be removed by external chilled methanol to be used is 145.7280 kg. These values serve as the utility targets for a MMR network. Using Eqs. (3) and (4), the mass of process MSA (L_1) and external MSA (L_2) can be calculated as follows:

$$L_1 = 8280 - 153.2880/(0.0310 - 0.0006) = 3237.6316 \text{ kg}$$

and

$$L_2 = 145.7280/(0.0035 - 0.0002) = 44160.0000 \text{ kg}.$$

3.3.2. Target with mass storage within a single batch

Unlike heat storage in batch heat integration, mass storage does not involve losses through mass transfer to the environment. This makes mass storage more practical to implement. Mass exchange with storage is conceptually similar to that of heat storage in batch heat integration. The mass load rejected below a local pinch point at a given time interval can be stored and supplied above the pinch at a later time interval. This is different from the conventional approach of pinch technology where mass or energy should not be transferred across the pinch point. Note that, for a batch process, these heuristic rules only hold within a given time interval. Mass (or heat, in heat integration) load rejected below a pinch in an earlier time interval could be supplied above the pinch of a later time interval, so long as there exists a positive driving force for mass or heat transfer. Fig. 5 illustrates the mass storage concept using the mass transfer grand composite curve (MTGCC). The MTGCC is adapted from the batch heat integration work by Kemp and Deakin (1989a) The MTGCC is introduced to demonstrate the usefulness of the mass storage system (Fig. 5).

When no mass storage is installed for the MEN, mass load can only be rejected to the external MSA at the region below the pinch. Hence, excess capacity of process MSA is found above the pinch in the MTGCC (Fig. 5a). This tends

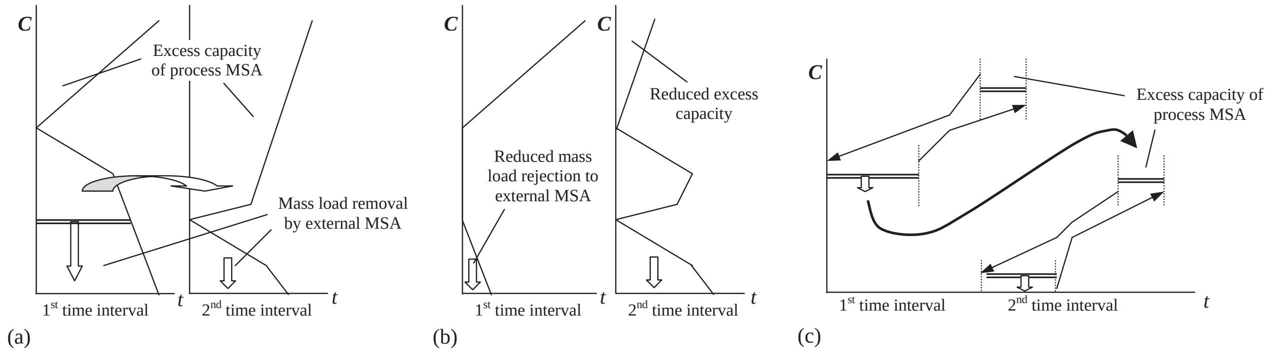

Fig. 5. (a) MTGCC for individual system where no mass storage is transferred across the time interval; (b) MTGCC with storage, where a transfer of mass load is occurring across the time interval via the mass storage system, (c) the same representation in the mass transfer composite curves.

to increase operating cost of the network since more external MSA are required while the excess capacity of the process MSA are not utilised. However, with a mass storage system, mass load rejected to the external MSA at one time interval could be stored and supplied to the above pinch region at a later time interval. This will reduce the external MSA usage and allow the excess capacity of process MSA to be utilised (Fig. 5b). The mass storage concept can also be presented on the mass transfer composite curves, shown in Fig. 5(c).

Kemp and Deakin (1989a) pointed out that it is essential to obtain the storage capacity during the targeting stage. This will help during the design of a cost-effective network in much reduced effort. Hence, the mass storage targeting technique will be carried out in the following sections for both single and repeated batch processes.

In order to obtain targets with storage, we have to work from one time interval to another and identify the mass load which can be stored and transferred across the time interval. Table 6 indicates that the local pinch compositions in the time intervals between 0–3 and 7–10 h are higher than that of the others. However, since interval 7–10 h is the final time interval, only the first time interval, 0–3 h, can be used for mass storage.

Table 6 also indicates that in the time interval between 3 and 7 h, there are negative mass loads in the composition interval between $y = 0.0010$ and 0.0451 (corresponding to $x = 0.0006$–0.0310). These are the sources of the excess capacity in the process MSA. Therefore, mass load stored during the first time interval (0–3 h) will be used in these time intervals (3–7 h) to eliminate the excess capacity of the process MSA.

However, to ensure a feasible mass transfer during the release of mass load between the storage and the process lean stream between time intervals 3 and 7 h, the mass transfer driving force is to be explored. As can be seen from Table 6, the negative mass loads in the three time intervals start at the MSA composition level of $x = 0.0006$. Hence, mass load in the first time interval (0–3 h) is to be stored between the maximum MSA composition of $x = 0.0482$ down to this composition level. Shown in Table 7, the stored mass load between these composition intervals is equivalent to 134.1360 kg. This stored mass load is then released into the system on the above pinch region between time intervals of 3 and 7 h. This has led to an elimination of excess capacity in process MSA in the second and third time intervals (3–5 h), and a reduced excess capacity in the fourth interval (5–7 h), as shown in Table 7.

One may also store the mass load at each different composition interval in the first time interval, to be transferred to the next time interval, such as that in Table 8. This option would be beneficial if there is excess capacity of the process MSA at a higher composition interval in the time interval 3–7 h. However, this also implies that additional mass storages are to be used at each different composition level. As in this example, the excess MSA capacity is only found in the third composition interval (i.e. at $y = 0.0010$–0.0451). Utilising mass storage at a different composition interval in this case study is not a favourable option, since additional storage will lead to a more complex and expensive network.

Lastly, no excess capacity of process MSA is found in the final time interval (7–10 h). Mass load rejected to the external MSA at the below pinch region could not be stored for further reuse since this is the final time interval in the single batch system. Tables 7 and 8 also show the rearrangement of the pinch locus as a result of the storage of mass load. The mass of the process MSA (L_1) and external MSA (L_2) can be calculated as follows:

$$L_1 = 8280 - 19.1520/(0.0310 - 0.0006) = 7650.0000 \text{ kg}$$

and

$$L_2 = 11.5920/(0.0035 - 0.0002) = 3512.7273 \text{ kg}.$$

3.3.3. Targets with mass storage for a repeated batch

In the industry, it is a common practice to work with repeated batches. If a repeated batch process is to be designed, the mass storage system could be useful in minimising the operational cost. In such a case, mass load from the process rich stream can be stored at the end of one process cycle to be used in the next cycle.

Table 7
TDCIT for single batch process with single mass storage

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		0.0000		0.0000		0.0000		19.1520		0.0000
		36.9360		12.3120		12.3120		0.0000		0.0000	
0.0510	0.0351		36.9360		12.3120		12.3120		19.1520		**0.0000**
		11.4696		3.8232		4.1772		0.7080		1.0620	
0.0451	0.0310		48.4056		16.1352		16.4892		19.8600		1.0620
		85.7304	$\boxed{134.1360}$ ⇒	−34.3512	$\boxed{115.9200}$ ⇒	−31.7052	$\boxed{100.7040}$ ⇒	−120.5640		7.9380	
0.0010	0.0006		**0.0000**		**0.0000**		**0.0000**		**0.0000**		9.0000
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		1.3608		0.4536		0.4956		0.0840		9.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		1.3608		0.4536		0.5076		0.1080		9.1620

Table 8
TDCIT for single batch process with mass storage at different composition level

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		0.0000		0.0000		0.0000		19.1520		0.0000
		36.9360	$\boxed{36.9360}$ ⇒	12.3120	$\boxed{36.9360}$ ⇒	12.3120	$\boxed{36.9360}$ ⇒	0.0000		0.0000	
0.0510	0.0351		0.0000		12.3120		12.3120		80.7120		**0.0000**
		11.4696	$\boxed{11.4696}$ ⇒	3.8232	$\boxed{11.4696}$ ⇒	4.1772	$\boxed{11.4696}$ ⇒	0.7080		1.0620	
0.0451	0.0310		0.0000		16.1352		16.4892		100.8900		1.0620
		85.7304	$\boxed{85.7304}$ ⇒	−34.3512	$\boxed{85.7304}$ ⇒	−31.7052	$\boxed{85.7304}$ ⇒	−120.5640		7.9380	
0.0010	0.0006		**0.0000**		**0.0000**		**0.0000**		**0.0000**		9.0000
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		1.3608		0.4536		0.4956		0.0840		9.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		1.3608		0.4536		0.5076		0.1080		9.1620

We noted from Table 7 that although the pinch composition in the final time interval is at a higher level as compared to that in the second to the fourth time interval, the excess mass load rejected at this interval cannot be used in the same process cycle since this is the last time interval in a single batch process. If this process is to be designed in a repeated mode, the mass rejected below the pinch in this time interval can now be transferred to the lean stream above the pinch in the next process cycle, if the composition permits.

The TDCIT for the repeated batch operation is shown in Table 9. As shown in this table, the excess capacity of aqueous ammonia for the removal of H_2S for this repeated mode has been reduced to 10.1520 kg (corresponding to 10.1520 kg/h or 0.00282 kg/s for the continuous mode of operation). Similarly, H_2S load to be removed by the external MSA has also been reduced to 2.5920 kg (corresponding to 2.5920 kg/h or 0.00072 kg/s in continuous mode of operation). This is due to the storage of mass load of contaminant in the final time interval to be used in the later process cycle. Hence, the consumption of the external MSA (i.e. the chilled methanol) in the final time interval has also been reduced substantially due to the use of storage system. As can be seen, the utility targets in the repeated batch mode are exactly the same as in the case of a continuous process. The same situation applies in the case of heat integration for batch processes (Kemp and Deakin, 1989a).

It should be noted that in repeated batch processes, the stored mass load at one time interval could actually be released to the time interval which exists before it, so long as there exists a positive mass transfer driving force (i.e. mass load is released above the pinch). This is the fact that in repeated batch processes, mass load is no longer constrained by the time variable. For example, mass load stored at time interval 5–7 h can be fed to the time interval 4–5 h in the same batch process. Hence, mass load flow in the reserve direction is possible for repeated batch processes. The

Table 9
TDCIT for repeated batch process with single mass storage

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		0.0000		0.0000		0.0000		10.1520		0.0000
		36.9360		12.3120		12.3120		0.0000		0.0000	
0.0510	0.0351		36.9360		12.3120		12.3120		10.1520		0.0000
		11.4696		3.8232		4.1772		0.7080		1.0620	
0.0451	0.0310		48.4056		16.1352		16.4892		10.8600		1.0620
	$\boxed{9.0000}$ $\Longrightarrow$	85.7304	$\boxed{143.1360}$ $\Longrightarrow$	−34.3512	$\boxed{124.9200}$ $\Longrightarrow$	−31.7052	$\boxed{109.7040}$ $\Longrightarrow$	−120.5640		7.9380	$\boxed{9.0000}$ $\Longrightarrow$
0.0010	0.0006		**0.0000**		**0.0000**		**0.0000**		**0.0000**		**0.0000**
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		1.3608		0.4536		0.4956		0.0840		0.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		1.3608		0.4536		0.5076		0.1080		0.1620

Table 10
GCI for horizontal cascading

y	x_1	Time (h)									
		0–3		3–4		4–5		5–7		7–10	
		Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm	Δm	Cum. Δm
0.0700	0.0482		0.0000		10.1520		0.0000		0.0000		0.0000
		36.9360		12.3120		12.3120		0.0000		0.0000	
0.0510	0.0351		36.9360		22.4640		12.3120		0.0000		0.0000
		11.4696		3.8232		4.1772		0.7080		1.0620	
0.0451	0.0310		48.4056		26.2872		16.4892		0.7080		1.0620
	$\boxed{134.1360}$ $\Longleftarrow$	85.7304		−34.3512	$\boxed{8.0640}$ $\Longleftarrow$	−31.7052	$\boxed{23.2800}$ $\Longleftarrow$	−120.5640	$\boxed{143.1360}$ $\Longleftarrow$	7.9380	$\boxed{134.1360}$ $\Longleftarrow$
0.0010	0.0006		**0.0000**		**0.0000**		**0.0000**		**0.0000**		**0.0000**
		1.3608		0.4536		0.4956		0.0840		0.1260	
0.0003	0.0001		1.3608		0.4536		0.4956		0.0840		0.1260
		0.0000		0.0000		0.0120		0.0240		0.0360	
0.0001	0.0000		1.3608		0.4536		0.5076		0.1080		0.1620

TDCIT for the reverse flow of stored mass load is shown in Table 10. However, the reverse flow of stored mass load can only determine the overall utility targets (consumption of process and external MSAs). The targeting approach cannot determine the storage target for each individual time interval, as opposed to the case of forward stored mass load flow. This is due to the fact that the mass storage capacity is determined by the cumulative mass load fed to the storage system, in which the mass load is accumulated in time during the process operation.

3.3.4. Summary of the developed vertical cascading technique

In the previous three case studies, we have made the maximum use of the available driving force within each time interval. Mass load is firstly cascaded vertically before it is cascaded to the next time interval through the mass storage. Hence, this method is called the vertical cascading technique. This vertical cascading method is able to locate the overall minimum utility targets as well as the storage target for a given case of batch operation. It should be noted that minimum utility targets for each time interval could also be located through vertical cascading, with Eqs. (3) and (4) applied in the respective time interval.

3.4. Maximising the driving force through horizontal cascading

Consider the TDCIT in Table 11 which was reproduced from Table 4. Mass load in this TDCIT is given by

$$\Delta m = [G_i(y^{in} - y^{out}) - L_j(x^{out} - x^{in})](\Delta t_{\text{int}}). \quad (5)$$

Dividing the mass load Δm over time interval Δt_{int}, Eq. (5) will become

$$\frac{\Delta m}{\Delta t_{\text{int}}} = G_i(y^{in} - y^{out}) - L_j(x^{out} - x^{in}). \quad (6)$$

Plotting the mass load over time interval graph will give a horizontal MTGCC in contrast to the horizontal GCC developed by Wang and Smith (1995) shown in Fig. 6. The positive slope of the MTGCC line indicates that there is a mass load surplus. A negative slope indicates a mass load

Table 11
The TDCIT for horizontal cascading

y	x_1	Time (h)					$\Sigma\Delta m$
		0–3	3–4	4–5	5–7	7–10	
		Δm	Δm	Δm	Δm	Δm	
0.0700	0.0482						
		36.9360	12.3120	12.3120	0.0000	0.0000	61.5600
0.0510	0.0351						
		11.4696	3.8232	4.1772	0.7080	1.0620	21.2400
0.0451	0.0310						
		85.7304	−34.3512	−31.7052	−120.5640	7.9380	−92.9520
0.0010	0.0006						
		1.3608	0.4536	0.4956	0.0840	0.1260	2.5200
0.0003	0.0001						
		0.0000	0.0000	0.0120	0.0240	0.0360	0.0720
0.0001	0.0000						

deficit in the respective time interval. The point where the horizontal MTGCC touches the horizontal axis is termed as the *time-pinch*.

The horizontal MTGCC in Fig. 6 provides some important information regarding the system. The shaded region represents the indirect mass transfer via mass storage. Mass being stored can be transferred from one time interval to the other. The vertical gap to the left of the time-pinch indicates the excess capacity of the process MSA(s) for the transfer of the mass load from the respective composition interval. The vertical gap to the right of the time-pinch, on the other hand, shows the excess mass load to be transferred by an external MSA. This targeting approach is to called the *horizontal cascading*.

3.4.1. Target for a single batch process with mass storage

Table 11 is used for the calculation for the utility targeting by horizontal cascading for a single batch process. The positive values in the time intervals show the mass load surpluses or the "excess mass load" for the respective time interval. On the other hand, the negative values refer to the "excess process MSA capacity". The final column in the TDCIT (Table 11) shows the cumulative mass load in each composition interval.

The horizontal cascading approach is illustrated in Figs. 6 and 7. The excess mass load in each time interval should be cascaded sideways to the right within a composition interval in the mass cascade table. Once the entire time interval on one composition level has been covered, mass is then cascaded to the lower rows of the table where the rich streams exist at higher composition levels. Mass load cascading leaves the MSA more contaminated. Once again, the mass cascade will proceed sideways to the right to cover the entire time interval. However, note that a rich stream which exists in a later time interval cannot be used to transfer mass to a lean stream in an earlier time interval (see Fig. 7). Therefore, we shall firstly identify the time interval when the process MSA ends. No excess mass load from the rich streams shall be cascaded upon the end of the process MSA.

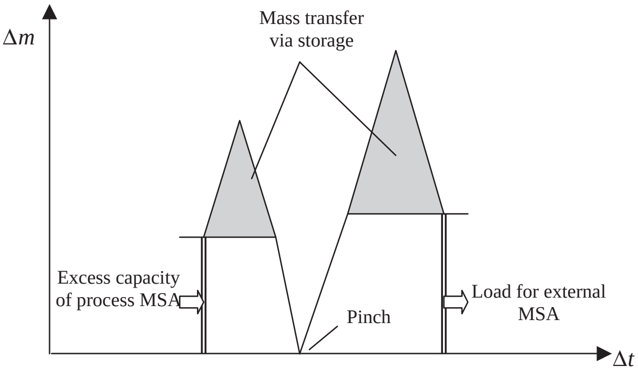

Fig. 6. GCI for horizontal cascading.

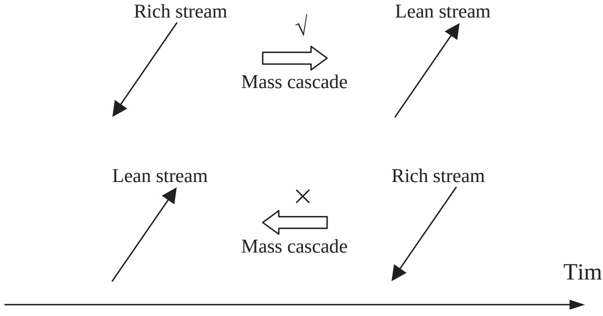

Fig. 7. Time constraints for mass cascading.

Table 11 shows that there are excess process MSA capacities from the second to the fourth time interval of the third row. This is due to the existence of the ammonia stream as the process MSA. These excess process MSA capacities that can be used by the excess mass loads that have been cascaded from the earlier time interval as well as at

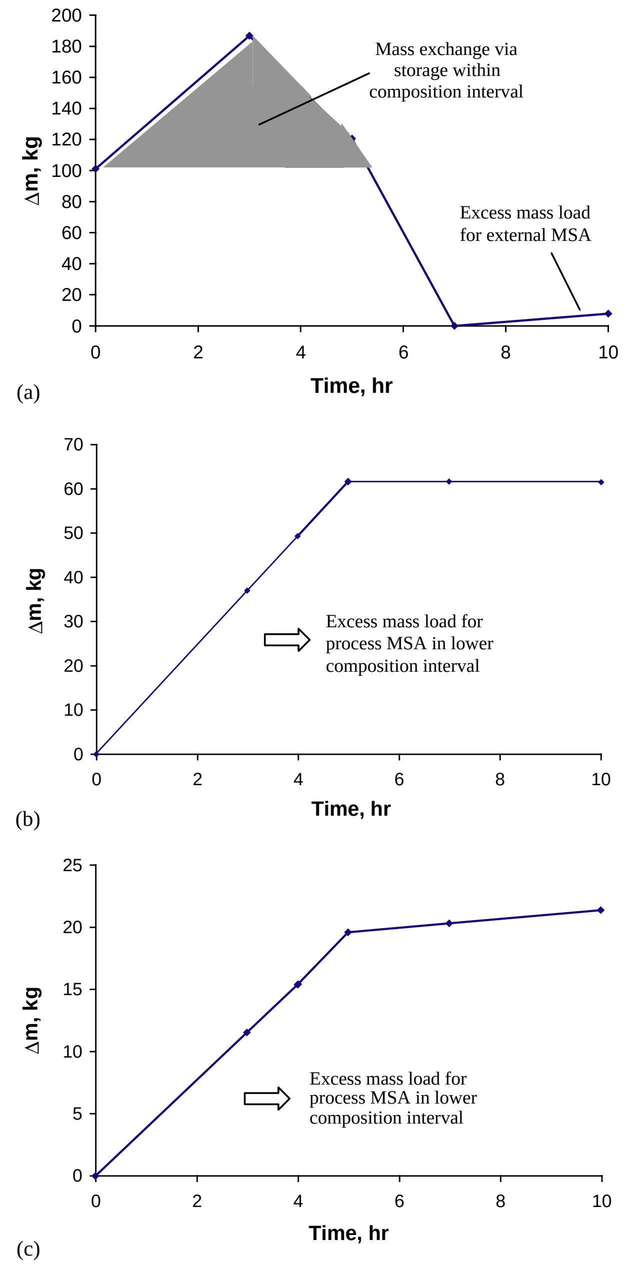

Fig. 8. MTGCC for horizontal cascading: (a) targeting in third row of Table 12, correspond to $x_1 = 0.031 \rightarrow 0.0006$; (b) targeting in first row of Table 12, correspond to $x_1 = 0.0482 \rightarrow 0.0351$, (c) targeting in second row of Table 12, correspond to $x_1 = 0.0351 \rightarrow 0.031$.

a lower composition level in the process via mass storage. Fig. 8(a) represents a MTGCC for composition interval of $y = 0.0010–0.0451$ (corresponding to $x_1 = 0.0006–0.0310$). A time-pinch occurs at 7 h, indicating that process MSA ends at this time. Shaded area of the MTGCC shows the indirect mass integration of 85.0140 kg mass load of H_2S from the first to the following three time intervals through mass storage. Excess mass load after 7 h is removed by the external MSA of chilled methanol.

Notice also that the first two rows of Table 11 consist of total surplus mass loads of 61.5600 and 21.2400 kg H_2S, respectively. Therefore, the excess capacity in the third rows of Table 11 could be used to supplement the excess mass load in the first and second rows of the table, which are at lower composition intervals. However, it should also be noted that the final column of the first and second row cannot be satisfied by the excess process MSA capacity in the third row of the table, since the process MSA exists only before the time of 7 h. Excess mass loads after 7 h have to be satisfied by external MSA. This creates a boundary (indicated by dashed line) in the TDCIT, as shown in Table 12. This boundary divides the TDCIT into two regions. The region on the up left corner indicates the mass transfer by process MSA. The region on the down right corner indicates the mass transfer region by the external MSA. MTGCC for these first two rows of Table 12 is shown in Fig. 8(b) and (c).

Let us now move down the TDCIT. Since the process MSA does not exist in the final two rows of the table, an external MSA is needed in these composition intervals. The excess mass load is cascaded from the final column of the first and second row of Table 11 and move downward to the third row of the table. The mass cascade then starts again at the first column of the fourth row and move sideways to the right within the same composition interval. After the entire time intervals of the fourth row have been covered, the mass cascade moves downwards to the final row of Table 11. The horizontal MTGCC for these composition intervals are shown in Fig. 9. The direction of mass cascade and the utility target achieved during the horizontal cascading are shown in Table 12.

The final column in Table 12 shows the mass load to be satisfied by process and external MSA. The process and the external MSA consumption, respectively, can be calculated as follows:

$$L_1 = 8280 - 19.1520/(0.0310 - 0.0006) = 7650.0000 \text{ kg}$$

and

$$L_2 = 11.5920/(0.0035 - 0.0002) = 3512.7273 \text{ kg}.$$

This technique leads to the same utility targets as were targeted by the vertical cascading technique. This is due to only one process MSA being present on the above pinch region, and possesses big mass transfer capacity. Therefore, excess mass transfer still occurs on the above pinch region, while external MSA is needed at the below pinch region.

3.4.2. *Target for repeated batch process with mass storage*

The excess mass load in the final column in the first to the third row in Table 12 can be absorbed by the process MSA if this process are to be operated in a repeated batch mode. The excess capacity in process MSA can remove a total of $19.1520 - 1.0620 - 7.9380 = 10.1520$ kg of H_2S, leaving a total of $11.5920 - 1.0620 - 7.9380 = 2.5920$ kg

Table 12
MSAs usage for horizontal cascading (single batch with storage)

y	x_1	Time (h)					$\Sigma\Delta m$
		0–3	3–4	4–5	5–7	7–10	
		Δm	Δm	Δm	Δm	Δm	
0.0700	0.0482						
		36.9360 ⇨	12.3120 ⇨	12.3120 ⇨	0.0000 ⇨	0.0000	
0.0510	0.0351					⬇	⇨
		⇨ 11.4696 ⇨	3.8232 ⇨	4.1772 ⇨	0.7080 ⇨	1.0620	−19.1520
0.0451	0.0310					⬇	
		⇨ 85.7304 ⇨	−34.3512 ⇨	−31.7052 ⇨	−120.5640	7.9380	
0.0010	0.0006						➡
		➡ 1.3608 ➡	0.4536 ➡	0.4956 ➡	0.0840 ➡	0.1260 ➡	11.5920
0.0003	0.0001						
		➡ 0.0000 ➡	0.0000 ➡	0.0120 ➡	0.0240 ➡	0.0360 ➡	
0.0001	0.0000						

⇨ Process MSA ➡ External MSA

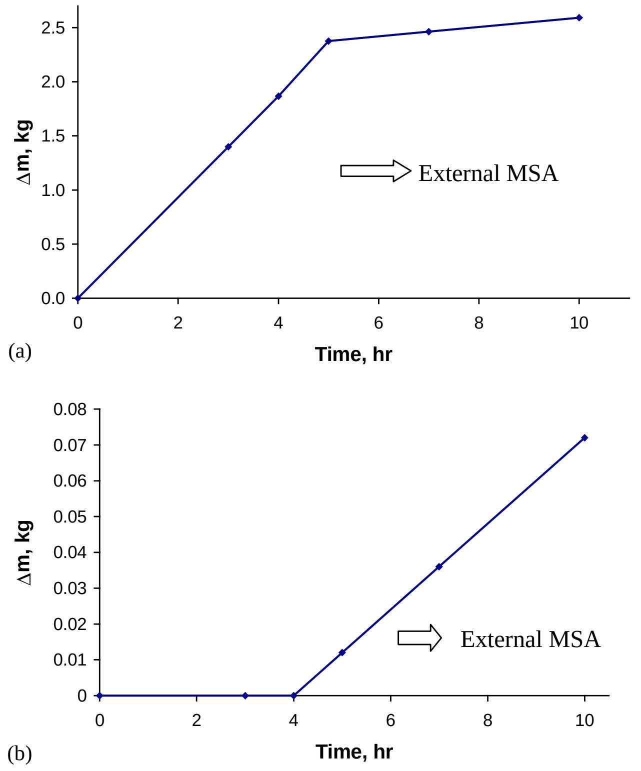

Fig. 9. (a) Horizontal MTGCC for second last row in Table 13, composition interval $x_1 = 0.0006 \rightarrow 0.0001$; (b) Horizontal MTGCC for last row in Table 13, composition interval $x_1 = 0.0001 \rightarrow 0$.

of H_2S (Table 13) to be removed by the external MSA. This contributes to the reduction of the external MSA to the minimum consumption achievable in a continuous process. Using Eqs. (3) and (4), the required capacity of both MSAs will be

$$L_1 = 8280 - 10.1520/(0.0310 - 0.0006) = 7946.0526 \text{ kg}$$

and

$$L_2 = 2.5920/(0.0035 - 0.0002) = 785.4545 \text{ kg.}$$

As in the case of repeated batch processes with vertical cascading, the horizontal mass load cascading could also be carried out in the reverse direction. Note that the time variable is no longer a constraint in this case. Utility targets obtained through the reverse mass load cascading will be the same as in the case of the forward cascading.

3.4.3. Summary of the developed horizontal cascading technique

Horizontal cascading technique has been developed as an alternative to the vertical cascading technique for the minimum utility targeting for batch MENS. This approach identifies the minimum MSA consumption for the case of single and repeated batch processes with storage system.

However, this targeting approach possesses a few limitation. Firstly, utility targets for a single batch process without storage system are failed to be located by this targeting approach. This is the fact that the nature of the cascading approach which attempts to maximise the mass transfer driving force within each composition range before the stored mass is cascaded to the higher composition range.

Secondly, horizontal cascading is only able to target the overall utility targets for the while process cycle. No utility target for individual time interval can be located as opposed to the vertical cascading approach.

Thirdly, the excess mass load to be cascaded across time intervals can only be achieved via mass storage. Table 14 shows that a mass storage system may be required for each time interval in order for mass exchange to take place across the time intervals. As the number of time intervals increases, the number of mass storage systems will also increase eventually leading to a complex system design. Thus, in this case

Table 13
MSAs usage by horizontal cascading (repeated batch)

y	x_1	Time (h)					$\Sigma\Delta m$
		0–3	3–4	4–5	5–7	7–10	
		Δm	Δm	Δm	Δm	Δm	
0.0700	0.0482						
		⇨ 36.9360	⇨ 12.3120	⇨ 12.3120	⇨ 0.0000	⇨ 0.0000 ⇨	
0.0510	0.0351						
		⇨ 11.4696	⇨ 3.8232	⇨ 4.1772	⇨ 0.7080	⇨ 1.0620 ⇨	⇨ −10.1520
0.0451	0.0310						
		⇨ 85.7304	⇨ −34.3512	⇨ −31.7052	⇨ −120.5640	⇨ 7.9380 ⇨	
0.0010	0.0006						
		➡ 1.3608	➡ 0.4536	➡ 0.4956	➡ 0.0840	➡ 0.1260 ➡	➡ 2.5920
0.0003	0.0001						
		➡ 0.0000	➡ 0.0000	➡ 0.0120	➡ 0.0240	➡ 0.0360 ➡	
0.0001	0.0000						

⇨ Process MSA ➡ External MSA

Table 14
Mass storages are required for each time interval in order for mass exchange to take place across the time interval

y	x_1	Time (h)					$\Sigma\Delta m$
		0–3	3–4	4–5	5–7	7–10	
		Δm	Δm	Δm	Δm	Δm	
0.0700	0.0482						
		⇨ 36.9360	⇨ 12.3120	⇨ 12.3120	⇨ 0.0000	⇨ 0.0000 ⇨	
0.0510	0.0351						
		⇨ 11.4696	⇨ 3.8232	⇨ 4.1772	⇨ 0.7080	⇨ 1.0620 ⇨	⇨ −10.1520
0.0451	0.0310						
		⇨ 85.7304	⇨ −34.3512	⇨ −31.7052	⇨ −120.5640	⇨ 7.9380 ⇨	
0.0010	0.0006						
		➡ 1.3608	➡ 0.4536	➡ 0.4956	➡ 0.0840	➡ 0.1260 ➡	➡ 2.5920
0.0003	0.0001						
		➡ 0.0000	➡ 0.0000	➡ 0.0120	➡ 0.0240	➡ 0.0360 ➡	
0.0001	0.0000						

Mass storage needed

it becomes essential to outline a strategy for the practical design of the MEN to achieve the utility targets.

4. Conclusion

Two utility-targeting approaches are presented for the first stage of batch mass exchange network synthesis, i.e. vertical and horizontal cascading. In the vertical cascading technique, we make use of the TDCIT to predict the minimum utility targets by maximizing the reuse of the process MSA in each individual time interval. This provides us with an insight of the maximum achievable targets for mass exchange in each of the three cases studied, i.e. the single batch process with and without mass storage as well as repeated batch processes with storage system. Besides, storage capacity targets are also identified in the later two cases.

On the other hand, the horizontal cascading method makes use of the maximum available driving force within each composition interval, before the mass load is being cascaded to the higher composition intervals. This approach maximises the use of the available driving force from the process MSA before any external MSA is used. This targeting approach locates the minimum utility targets and storage capacity for the case of single and repeated batch processes.

A summary of the utility consumption for the case studies considered in this chapter is shown in Table 15. A few conclusions can be drawn from this table. Single batch process without mass storage system consumes the most external MSA and the least process MSA compared to the other sys-

Table 15
Comparison between the modes of operation

Operation mode	Internal utility, L_1	External utility, L_2
Continuous process (kg/h)	7945.0526	785.4545
Batch process (kg)		
Vertical cascading		
Single batch (without storage)	3237.6316	44160.0000
Single batch (with storage)	7650.0000	3512.7273
Repeated batch (with storage)	7946.0526	785.4545
Horizontal cascading		
Single batch (with storage)	7650.0000	3512.7273
Repeated batch (with storage)	7946.0526	785.4545

tems. This is due to the process-rich and lean streams which only coexist in a limited period of time (3–7 h) during the process operation. Hence, direct mass integration which occurs between these process streams are limited. This leads to a batch MEN with a high operating cost, as the MEN operational cost merely depends on the external MSA consumption.

The single and repeated batch processes with mass storage system, on the other hand, consume less external MSA while the use of process MSA is maximised. The minimum utility targets obtained for these systems using both targeting approaches are the same. Repeated batch processes with storage systems is the most favourable option in this study, since it minimises the use of external MSA and maximises the process MSA. This would lead to the minimum utility cost and minimum waste generation for the network.

It should be noted that the utility consumption for a repeated batch process with storage system is the same as that for the continuous process. This again justifies that the continuous process is actually a special case of batch processes, as was claimed by Kemp and Deakin (1989a) in their early paper on batch heat integration.

Notation

C	composition level (mass fraction)
Cum. Δm	cumulative mass load
FCP	heat capacity flowrate, kW/°C
G	rich stream mass flowrate for continuous process (kg/s) or mass for batch process (kg)
L	lean stream mass flowrate for continuous process (kg/s) or mass for batch process (kg)
Δm	mass load, kg
m	mass, kg
$m_{H_2S,ext}$	mass load to be removed by external MSA
$m_{H_2S,p}$	mass load to be removed by process MSA
N	number of streams
N_H	number of hot streams
N_C	number of cold stream
N_R	number of waste (rich) streams
N_S	number of lean streams (MSA)
N_{SE}	number of external MSAs
N_{SP}	number of process MSAs
R	set of rich streams
S	set of lean streams
Δt_{int}	time duration for each time interval
t	time, h
t^f	starting time, h
t^g	ending time, h
T^s	supply temperature
T^t	target temperature
x	composition in lean stream (mass fraction)
x^s	supply composition of lean stream
x^t	target composition of lean stream
y^s	supply composition of rich stream
y^t	target composition of rich stream

Greek letters

Δ	difference
ε	minimum composition difference

Subscripts

C	cold process stream
i	rich stream number
j	lean stream number
H_2S	hydrogen sulphide removed by process or external MSA
H	hot process stream
p	process MSA
ext	external MSA

Superscripts

c	constraint value
f	starting time
g	ending time
s	supply value
t	required target value
in	inlet
out	outlet

Acknowledgements

The financial support of the Ministry of Science, Technology and Environment, Malaysia through Intensified Research Priority Area (IRPA) research grant and National Science Fellowship (NSF) scholarship is gratefully acknowledged.

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