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SYNTHESIS OF MAXIMUM ENERGY RECOVERY NETWORKS IN BATCH PROCESSES

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Abstract—In the heat integration problem for batch processes, there are two differences in treatment from continuous operations. The first is the occurrence of cocurrent heat exchange, this case may happen when a process can not be transferred to another process. The second is that time must be considered as a variable. We divide the problem into two cases, namely co-current heat exchange and counter-current one, and then intend to find the rules to satisfy the requirement of each case. For the former, a matching rule and a MILP formulation had been proposed but any method did not obtain the optimal solution. The latter including the time as a variable often occurs in the practical industry. The limitation of time has been reduced by changing the schedule of processing or using the heat storages. However, the systematic rule considering the batch cycle time has not been presented for the rescheduling and heat storage is not usually practical although it is reasonable concept. Therefore this paper presents general method for optimal rescheduling to maximize heat recovery and reduce batch cycle time when heat exchanges occur as counter-current type. In the exchanges of co-current type, the heuristic, called the modified H/H which can be used to find the optimal match sequence of heat exchange between hot and cold tanks, is proposed. The proposed heuristics have the advantages of simple calculation and small computation time.

INTRODUCTION

Batch processes are widely used in the food, pharmaceutical, fine chemical plant. Systematic methods for design of these plants mainly dealt with selection of capital equipment to minimize investment cost before 1980. Energy and process integration on batch processes has difficult problems such as addition of time as a variable, reduction flexibility, and the energy costs as a small portion of batch operating costs. Early papers on energy integration mainly treated continuous processes and researches on batch processes were scarcely advanced.

However, recently energy integration on batch processes in spite of above difficulties has been studied. Vaselenak, Grossmann and Westerberg [1] proposed a heuristic on determining processing order of exchanges between hot and cold vessels during the batch cycle where both hot and cold fluids return to their original tanks after passing through the heat exchanger. They did not consider time as a variable. Linnhoff, Ashton, and Obeng [2] proposed a procedure using a Time Average Model (TAM) to analyze the energy flows for debottlenecking, and later showed how performance targets equivalent to pseudo-continuous operation can be obtained by limited rescheduling of batch operations using the Time Slice Model (TSM), but presented no quantitative rescheduling method. Kemp and Macdonald [3] presented a procedure called time-temperature cascade based on Pinch Technology. They divided the process into time intervals analogous to the temperature intervals and achieved the heat recovery target by using heat storage as well as direct heat exchange. Kemp and Deakin [4] presented detailed methods making up weak point in the previous paper for network design and process scheduling based on the Time-Temperature Cascade approach. They claimed that Maximum Energy Recovery (MER) was obtained by maximum heat exchange and heat storage. They did not consider batch cycle time and rescheduling simultaneously. Heat storage is convenient concept in order to recover heat irrelevant to time, but it is not practical except special situation.

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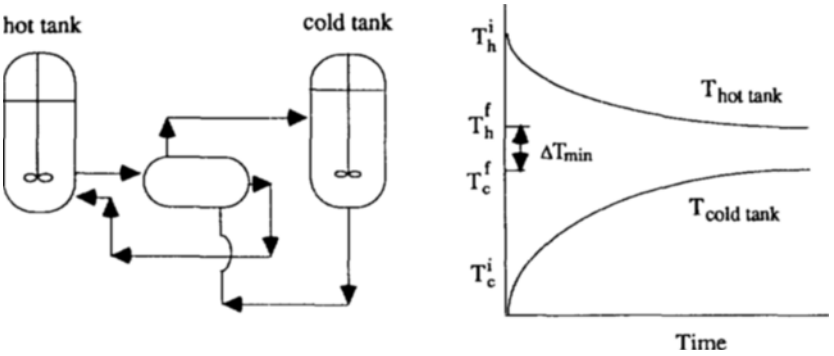


Fig. 1. Cocurrent heat exchange in batch processes.

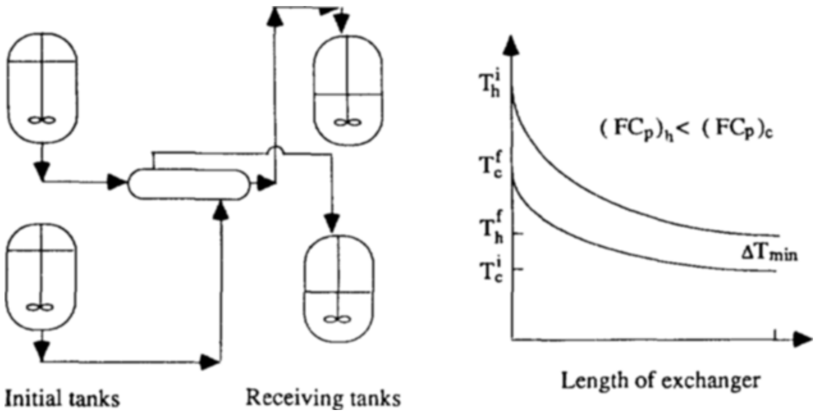


Fig. 2. Countercurrent heat exchange in batch processes.

Therefore this paper presents general method for optimal rescheduling to maximize heat recovery and reduce batch cycle time when heat exchanges occur as counter-current type. In the exchanges of co-current type, a heuristic rule so called the modified H/H, is proposed to determine the order of heat exchange.

OLD METHODS FOR DETERMINING THE PROCESSING ORDER OF EXCHANGES

Because of processing requirements, three configurations of batch vessels and receiving tanks are shown to result in three different temperature profiles for the fluids: cocurrent, countercurrent, and combined cocurrent/countercurrent.

Cocurrent Heat Exchange – Cocurrent heat exchange occurs when both the hot and cold fluids return to their original tanks after passing through the heat exchanger. In this case, the processing requirements specify that the materials must remain in their tanks while being heated or cooled as shown in Fig. 1.

Countercurrent Heat Exchange – Countercurrent heat exchange occurs when the processing requirements allow the fluids to transfer from their original tanks into receiving tanks while being heated or cooled as shown in Fig. 2.

1. Heuristic Procedure for Cocurrent Heat Exchange

Match the coldest hot tank with the warmest cold tank provided the match is feasible. This algorithm is based on Hottest/Highest heuristic in position of initial temperatures of tanks. The target temperatures of tanks are not considered when a feasible match is searched and tick-off rule is applied to hot tanks first baselessly, so the high temperature of hot tanks is not used properly. A mixed-integer linear program is presented to improve the heuristic rule in the same paper.

2. Mixed-Integer Linear Program Cocurrent Heat Exchange

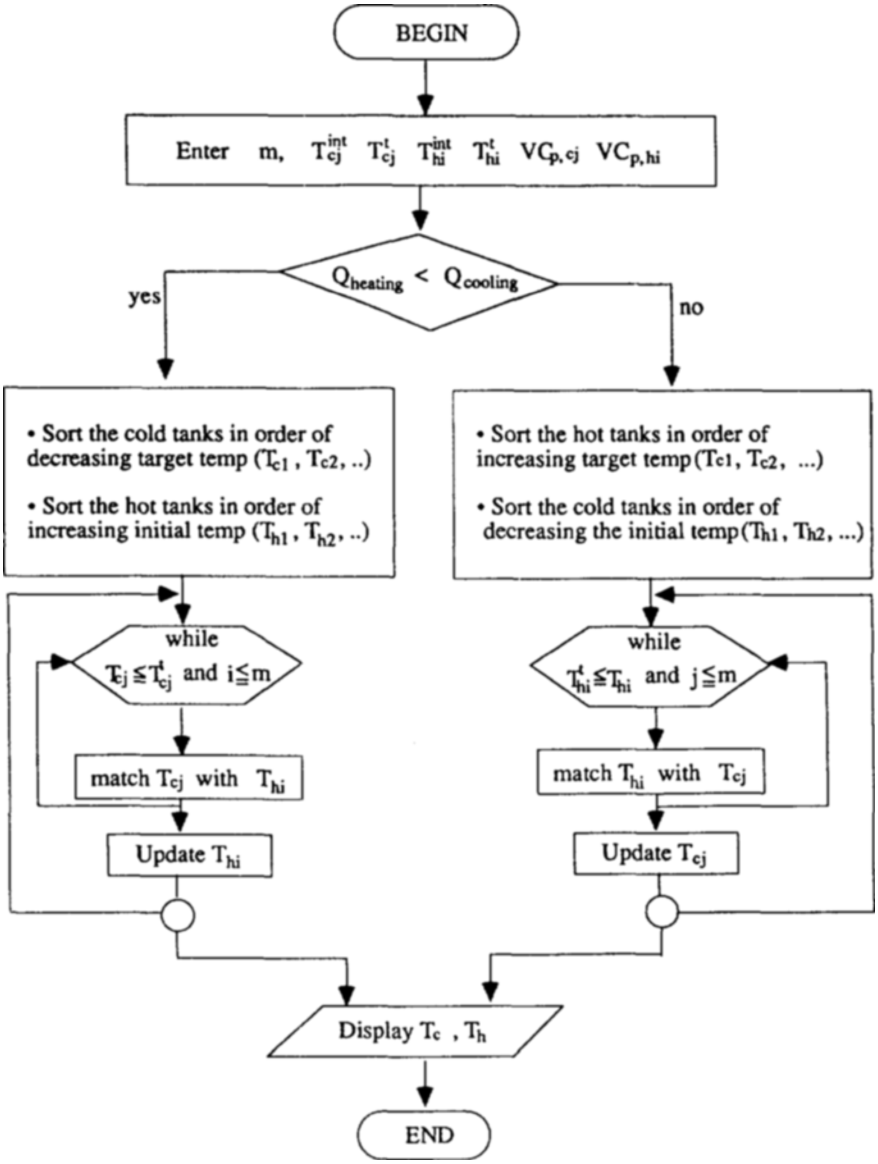


Fig. 3. Flow chart of the modified H/H.

This aim can be expressed as maximizing the heat lost by the hot tanks or as minimizing the sum of the temperatures of the hot tanks after T time periods, weighted by their respective $(VC_p)_i$'s:

$$\max \sum_{i=1}^{Nhot} (VC_p)_i(T_i^0 - T_i^T)[\text{or } \max \sum_{j=1}^{Ncold} (VC_p)_j(T_j^T - T_j^0)]$$

This MILP formulation is expected to find optimal matches to maximize heat recovery, but can not be achieved the optimal solution because of hidden errors. Therefore in this paper, new heuristic to easily find proper matches is proposed.

MODIFIED H/H

This rule is made for the cocurrent heat exchange. H/H rule for heat integration in continuous processes is known as the best heuristic method to maximize heat recovery. In the method, log mean temperature difference (LMTD), the driving force is maintained

Table 1. Stream data for problem 1

Tank	VC_p (kJ/C)	$T_{initial}$ (C)	$T_{desired}$ (C)	Q_{needed} (kJ)
A	1.0	400	150	250
B	1.4	350	125	315
C	1.3	325	175	195
				$760=Q_{cooling}$
X	2.0	100	175	150
Y	1.5	90	200	165
Z	1.6	50	275	360
				$675=Q_{heating}$

during the heat transfer. The merit is applied to the modified H/H. The flowchart is shown in Fig. 3 and detail explanations are given below.

1. Select the batches to which tick-off rule is applied by comparing the amount of heat requirement between hot batches and cold batches. min ($Q_{cooling}$ for hot tanks, $Q_{heating}$ for cold tanks)

2. If hot tanks are selected in step 1, go to the step 6.

3. If cold tanks are selected, sort them decreasing target temperature and provide each tank with an index, T_{c1}, $T_{c2},\cdots$, $T_{ci},\cdots$ Sort hot tanks in order of increasing initial temperature and provide each tank with an index, T_{h1}, $T_{h2},\cdots$, $T_{hj},\cdots$

4. Match T_{c1} with sorted hot tanks until T_{c1} is equal to T_{c1}^{t} or any feasible match is not remained. The amount of heat exchanges at each match is constrained by the law of thermodynamics. Eliminate cold tank corresponded to index c1 in finding feasible match and store T_{c1} as the temperature of corresponded cold tank after final match.

5. Update the temperatures of hot tanks and repeat steps 3-5 until there is no remained cold tank.

6. Sort the hot tanks in order of increasing target temperature and in order of decreasing the initial temperature for cold tanks.

7. Match T_{h1} with sorted cold tanks and the rest of procedures are similar to steps 3-5.

We compare the availability of three methods through the illustrative problem carried in the literature cited. The problem consists of three hot tanks and three cold tanks whose process data are shown in Table 1. Hot tanks need to be removed the heat of 760 kJ and cold tanks are required to be added the heat of 675 kJ. The achievable maximum amount of heat recovery is equal to or less than the minimum value of heat requirements of hot and cold tanks. Results are shown in Table 2. In the match sequence determined by old heuristic, hot tanks is to be tick-off in the order of increasing initial temperature, so the amount of heat exchange is far from optimal one. The match sequence by MILP is not the best too. If the MILP is formulated correctly, it might generally obtain a optimal solution. However, a MILP is not often used in practical problem because it is not only complicated but also difficult in handling the problems of large size. The difference of the modified H/H from the old one is in that the alternative of hot or cold tanks is chosen by comparing heat requirements before finding the match sequence and the tick-off is applied to the selected tanks. The match sequence which meets the goal is found by the proposed rule and it takes about 0.1 second of CPU time to solve the problem 1 on a SDT-400 computer. Until now we consider only the amount of heat recovery but in future work design problem including costs will be studied.

Table 2. Comparison of results for problem 1

Matching rule	Sequence of match	Heat recovery (kJ)
L/H	C/X, C/Y, B/Y, B/Z, A/Z	628.9
MILP	A/X, B/Z, C/Y, A/X, B/X	652.6
Modified H/H	C/Z, B/Z, A/Z, B/Y, A/Y, B/X, A/X	675.0

THE ANALYSIS METHODS INCLUDING THE TIME AS A VARIABLE

1. Time-Dependent Heat Cascades

In the method recommended by Kemp and Macdonald [3], a problem is divided into time intervals which are analogous to the temperature intervals used in the Problem Table Technique for continuous processes. They define time intervals to be between times where streams start, finish or change heat capacity flow rate. A series of heat cascades can be developed for each time interval, showing the target energy use for each time period and thus the possibilities for energy recovery by direct heat exchange. If two processes, a process need to remove heat and the other to require heat do not coexist simultaneously, direct heat exchange is not possible. Such a problem can be solved easily by heat storage. Heat storage make heat transfer from one time interval to another. A time-dependent cascade shows not only energy target for each time interval but also the amount of heat storage needed and the temperature at which it is required. However, to achieve the hot utility target using heat storage is difficult for economic reasons. Heat storage

Table 3. Stream data for problem 2, $(\Delta T)_{min} = 10°C$

Stream name	Supply temp. (℃)	Target temp. (℃)	Interval temp. Supply (℃)	Interval temp. Target (℃)	CP (kW/K)	Heat flow (kW)	Start time (hr)	Finish time (hr)	Heat load (kWhr)
C1	20	135	25	140	−10	−1150	0.5	0.7	−230
H2	170	60	165	55	4	440	0.25	1.0	330
C3	80	140	85	145	−8	−480	0.0	0.5	−240
H4	150	30	145	25	3	360	0.3	0.8	180

Table 4. Practical heat storage-with temperature penalty or single level

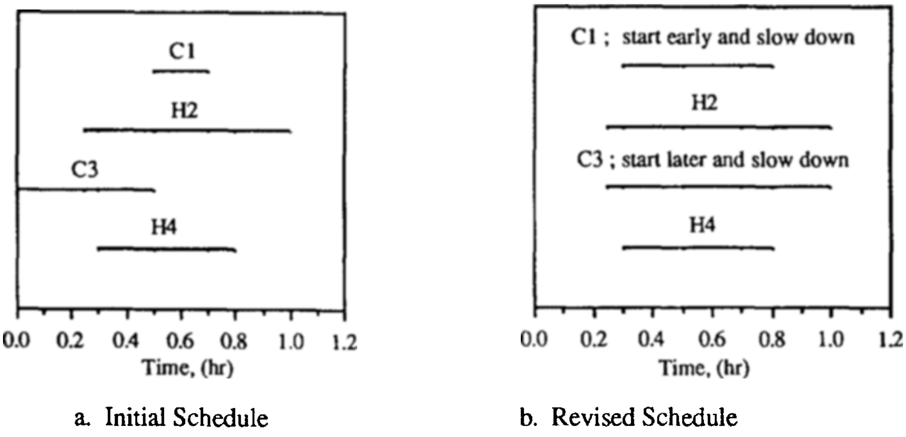
T, ℃	\t, hr	0.3-0.5		0.5-0.7	T, ℃	\t, hr	0.3-0.5		0.5-0.7
165		0		12	165		0		33
	ΔH	$\boxed{16}$		$\boxed{16}$		ΔH	$\boxed{16}$		$\boxed{16}$
145		16		28	145		16		49
	ΔH	$\boxed{-1}$		$\boxed{7}$		ΔH	$\boxed{-1}$		$\boxed{7}$
140		15		35	140		15		56
	ΔH	$\boxed{-11}$	$\xrightarrow{4}$	$\boxed{-33}$		ΔH	$\boxed{-11}$		$\boxed{-33}$
85		0		6	85		4		23
	ΔH	$\boxed{28}$	$\xrightarrow{28}$	$\boxed{-18}$		ΔH	$\boxed{33}$	$\xrightarrow{37}$ ↓	$\boxed{-18}$
65		14			61.43		0	↓	
	ΔH	$\boxed{14}$	$\xrightarrow{14}$ ↓			ΔH	$\boxed{9}$	↓	
55		0	14 ↓	16	55		9	$\boxed{\text{STO}}$	5
			↓			ΔH		↓	$\boxed{-5}$
45			↓		51.43			↓	0
	ΔH	$\boxed{18}$	$\xrightarrow{12}$ ↓ $\xrightarrow{26}$	$\boxed{-42}$		ΔH	$\boxed{18}$	↓ $\xrightarrow{37}$	$\boxed{-37}$
25		6		0	25		27		0

will impose an additional temperature drop because two exchangers are required for each match-one into and one out of the heat storage medium. Moreover, a heat storage facility will often be at a fixed temperature, so that the heat entering will be degraded to be lowest temperature of the hot stream rather than being available over the full range of temperatures of the original hot stream.

The stream data shown in Table 3 is frequently used as a example in the study of analysis of batch process. The example is defined in terms of two sources and two sinks and the time needed to pass through the whole processes, a batch cycle time (BCT), is 1 hour. The minimum allowable temperature difference is taken as 10℃. The stream data is divided into six time intervals and five temperature ones. The targeting procedure is same for continuous processes except that it should be applied to individual time interval. The each temperature-cascade occupies one column in a table. "kWhr" is used as the unit of heat loads so that it may give weighting for the length of the time intervals.

The cascade analysis which can be adopted to allow for the configuration of the practical heat storage system is proposed by Kemp and Deakin [4]. An additional temperature difference can be placed on any matches which take place across time intervals and thus involve heat storage. Table 4 illustrates the above effect for time interval between 0.3 and 0.7 hr. The hot utility required by the interval 0.5-0.7 hr is 70 kWhr for the maximum direct heat exchange situation without heat storage. If $(DT)_{min}$ is taken as 20℃ for matches involving heat storage, as against 10℃ for direct heat exchange, cascade table is changed to Table 4. For the left-hand set of cascades in the table, a countercurrent thermal regeneration device can be used as the heat storage device. A fixed-temperature storage device can be used for the right-hand one.

But such a device is not practical too. Therefore practical and realizable method is required and it is used to reschedule the process operations so that the streams fall in the same time interval. As consequences of rescheduling the processes, the amount of heat by the direct heat exchanges increase.



a. Initial Schedule b. Revised Schedule

Fig. 4. Time slice model.

2. Rescheduling

The stream data shown in Table 3 is used in the researches on rescheduling continuously.

Linnhoff, Ashton and Obeng's paper suggests a "Time Slice Model" (TSM) based on energy analysis within each time period [2]. The batch cycle is represented in terms of the time periods when heat flows occur. TSM represents the batch cycle, subject to all assumptions and constraints in the schedule. Each time slice is defined where streams begin or finish. Time slice is the same concept as time interval used in the Cascade analysis. The initial schedule is represented in Fig. 4(a). The schedule of stream C1 is changed by starting its operation early and decreasing the heat capacity flow rate and for stream C3 by starting later and increasing the duration so that cold streams and hot streams coincide. With these scheduling changes, Fig. 4(b) can be developed. For this revised schedule the energy target for hot utility becomes 20 kWhr, which is the same target for pseudo-continuous model. Table 5 shows reduction of the energy targets by rescheduling based on the TSM. But TSM does not allow for the effect of rescheduling of some streams on other linked streams by considering individual ones. This method is insufficient to guide quantitatively how to revise the original schedule to reduce the energy consumption for general batch processes.

Methods for identifying rescheduling opportunities based on the heat storage targets obtained in the cascade analysis are claimed by Kemp and Deakin [4]. The feasible overall time-dependent cascade shows where heat storage could make additional savings, giving both the storage required and the temperature range. Streams included a range of that kind can be rescheduled as an alternative to heat storage. Cascade table can identify easily which stream is to be rescheduled at the beginning, but it gives a little help to find opportunities of further rescheduling in spite of the complexity of application. To achieve nearly the TAM (Time Average Model) energy targets, schedules of some processes must be changed succeedingly. In fact this procedure occupies a major portion in rescheduling. The explanations about very this procedure is lack in the paper. Their method is similar to the trial and error method used in TSM. After the method is examined thoroughly, it can be found to have neither systematization nor clearness in developing the rescheduling. When a process is made to change, we must know which streams exist in which interval. This is the most important for designer to change batch schedule. In consequence, it is necessary to show stream and time simultaneously in order to find with ease the streams to be rescheduled. We can ignore the heat recovered via heat storage in the process

Table 5. Energy targets for problem 2

	Initial schedule		Revised schedule	
	Hot utility target (kWhr)	Cold utility target (kWhr)	Hot utility target (kWhr)	Cold utility target (kWhr)
TAM	20	60	20	60
TSM	198	238	20	60

Table 6. Finding reasonable combination for problem 2

	Match				Combination	
	C1/H2	C3/H4	C1/H4	C3/H2	(C1/H2, C3/H4)	(C1/H4, C3/H2)
Hot target		150	50		150	50
Cold target	100	190		90	290	90

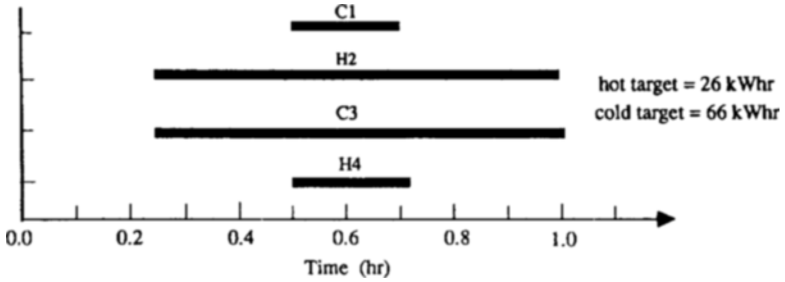


Fig. 5. Adjusted schedule 1 for problem 2.

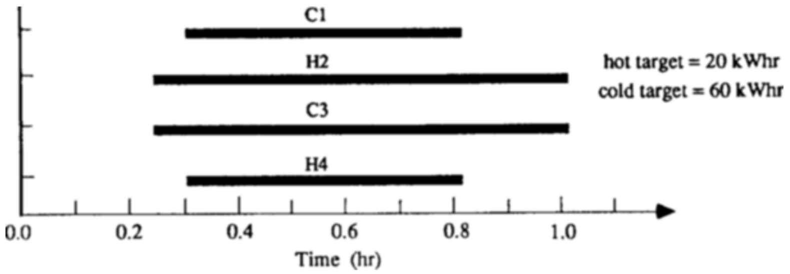


Fig. 6. Adjusted schedule 2 for problem 2.

of rescheduling and have only to consider it in final step if necessary. The reason why we can follow this thought is that generally heat storage is not only impractical but also required in only special situation.

THE MINIMIZATION OF THE UTILITY TARGETS

Streams are in large made to classify into two groups. One is the independent process and the other is the dependent process. The former is composed of streams which do not affect other streams so that it can be easily rescheduled in various ways. For example, changing the start time under the initial duration or altering the finish time by adjusting the duration, etc. The latter includes streams which are connected with other streams. Such a process often appears in the multiproduct batch plant or the repeated single product one. In this paper, the rescheduling methods for each class are proposed. The Utility-Deviation Minimization method is suggested for the independent processes and the Utility-BCT Minimization is done for the dependent processes.

1. The Utility-Deviation Minimization

The term, deviation, measures the extent of the change from initial schedule. This method can not only guide to reach nearly optimal schedule but also require just simple calculation. The followings explain it step by step.

(1) Make matches composed of a arbitrary hot stream and a arbitrary cold one ignoring time constraints and then calculate the targets for each match.

(2) Make the combinations of matches, provided that each combination must contain all streams only once.

(3) The targets of combination are equal to the sum of ones for included each match.

(4) Select the combination having the smallest targets.

(5) Make a hot and a cold stream composed of each match in the selected combination place at the same time interval, on condition that the deviation from the original schedule is made to be as small as possible

Table 7. Stream data for problem 3, $(\Delta T)_{min} = 10°C$

Stream name	Supply temp. (℃)	Target temp. (℃)	Start time (hr)	Finish time (hr)	CP (kW/K)	Heat flow (kW)	Heat flow (kWh)
Section I (two cycles, A and B, per batch)							
Primary heating 1A, C1	0	33	0.0	0.4	−4.894	−161.5	−64.6
Primary heating 2A, C2	33	85	0.4	1.0	−3.115	−162.0	−97.2
Primary cooling A, H3	105	80	1.5	1.75	7.648	191.2	47.8
Primary heating 1B, C4	0	33	7	7.4	−4.894	−161.5	−64.6
Primary heating 2B, C5	33	85	7.4	8.0	−3.115	−162	−97.2
Primary cooling B, H6	105	80	8.5	8.75	7.648	191.2	47.8
Section II (one cycle in two parts, 1 and 2, per batch)							
Feed preheating 1 C7	20	120	10.3	11	−5.36	−536.0	−375.2
Column reboil 1 C8	119	120	11	13	−536.5	−536.5	−1073.0
Column reflux 1 H9	120	119	11	13	536.5	536.5	1073.0
Product cooling 1 H10	120	100	13	13.5	7.72	154.4	77.3
Feed preheating 2 C11	60	128	2	3	−0.912	−62.0	−62.0
Column reboil 2 C12	127	128	3	6	−273.4	−273.4	−820.2
Column reflux 2 H13	128	127	3	6	273.4	273.4	820.2

and increase the time where all streams appear simultaneously.

Table 6 shows that the steps 1-3 is applied to the previous problem 2. The combination, (C1/H4, C3/H2), is selected. Streams rescheduled by using step 5 are illustrated on Gantt chart, Fig. 5-6. Fig. 6 represents the optimal schedule in which utility usage is reduced by 178 kWhr. In the long run, we can change the original schedule to minimize the utility targets by using only simple calculation in a short time.

2. The Utility-BCT Minimization

The most of streams occurring in the multiproduct batch plant or the repeated single batch plant, belong to the dependent process. In changing the schedule of the stream comprised in the class, we ought to consider how it affects on the ones of the connected streams. Rescheduling is done for a group of dependent process rather than for a particular process. In this research, we fix the duration of all process. We suggest how to adjust the start time of the streams under the fixed duration to reduce the utility consumption and the batch cycle time. The steams included in the dependent process is showed on the Gantt chart subject to the following constraints 1-4.

(1) When the output i stream becomes the input of j stream, the difference of level, (j's level-i's level), has to be one.

(2) The streams sharing an equipment have the same level.

(3) The start time of the stream taking the larger level should be greater than the finish time of the smaller one in a group of dependent processes.

(4) The streams having same level can not be overlapped in time.

(5) Overlap the previous batch with the next batch on the Gantt chart so that hot and cold streams may place at the same time.

(6) Select the schedule which gives the shortest cycle time among the ones owning the same targets.

The following case study was carried out using the Cascade analysis by Kemp and Macdonald and Clayton. Table 10 lists the stream data. The speciality chemicals plant studied can be divided into two sections. In Section I, the primary feed is heated to 85℃ over one hour period, at which temperature it undergoes an exothermic reaction lasting half an hour. The product is then discharged and cooled, and passed to storage after minor intermediate processing not involving heat. In Section II, the liquid is heated to 120℃ where it is reacted under reflux conditions. After conditioning, the reflux is repeated at 128℃ for a longer period to give the final product, which is not cooled. Total processing time is 20 hr, but the batches overlap so that the cycle time is only 14 hr. Two batches (denoted A and B) are required from Section I to give sufficient feed for Section II.

The rescheduling by using the Utility-BCT Minimization is showed in Fig. 9. Both schedules shown in Fig. 8-9 have some hot and cold streams placed at the same time so that the utility targets of the original schedule may be made to reduce. The difference of the rescheduling shown in Fig. 9 from one in Fig.

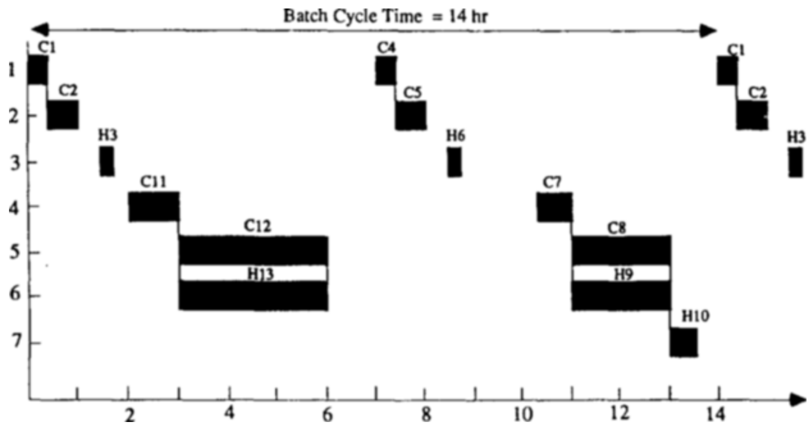


Fig. 7. Initial schedule for problem 3.

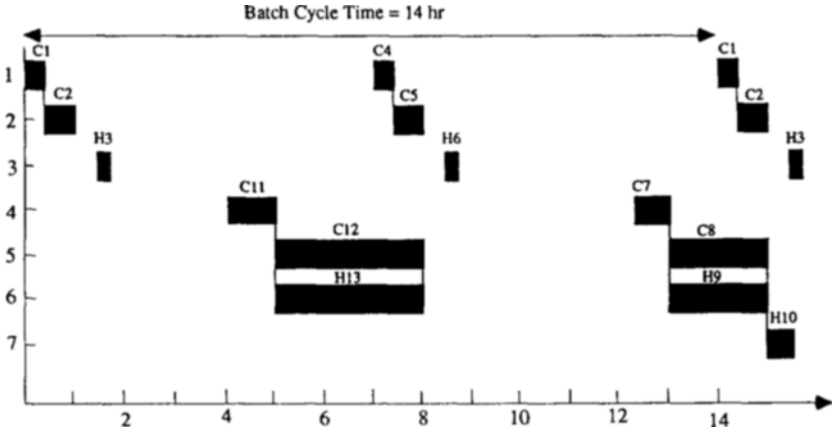


Fig. 8. Revised schedule by the cascade analysis for problem 3.

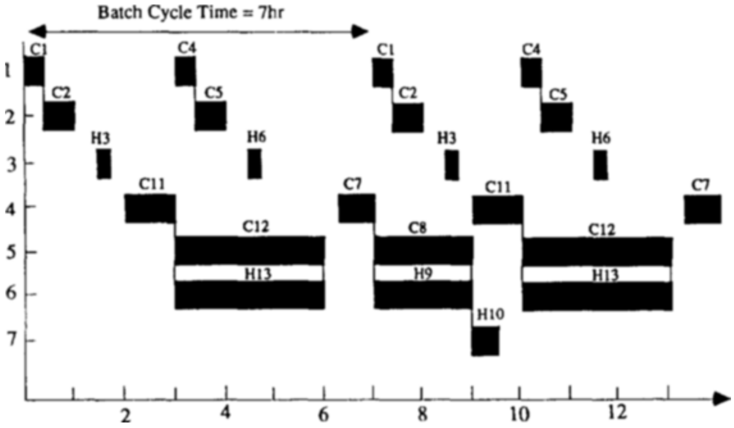


Fig. 9. Revised schedule by the utility-BCT minimization for problem 3.

Table 8. Results of the three different schedules for problem 3

	Initial schedule	Cascade analysis	Utility-BCT min.
DHX (kWhr/cycle)	0.0	323.6	346.4
Hot utility target (kWhr)	2654.0	1730.4	1707.6
Cold utility target (kWhr)	2066.1	1742.5	1719.7
BCT (hr)	14.0	14.0	7.0

8 is that the batch cycle time is regarded as of great importance on the other hand the heat recovered via heat storage is ignored. The amount of the direct heat exchange (DHX) and BCT are represented in Table 8 for the three different schedules. In the revised schedule by the proposed method utility usage is reduced by 346 kWhr per batch cycle and productivity is improved owing to the reduction of BCT.

CONCLUSION

We can find the optimal matching sequence between hot and cold tanks by using the modified H/H algorithm for the cocurrent type batch plant. The rescheduling considered the batch cycle time can be easily applied to the practical situations by using the proposed methods, the Utility-Deviation Minimization and the Utility-BCT Minimization, for the countercurrent type batch plant. During the rescheduling procedure to reduce the conventional utility consumption, the related calculations in these methods are easier and smaller than in the existing ones. All of the proposed heuristics aim to reach the maximum heat recovery in batch plant.

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NOMENCLATURE

ΔT_{min} : minimum allowable temperature approach
$T_{initial}$: initial temperature of tank
$T_{desired}$: target temperature of tank
T_c : temperature of cold tank
T_c^i : initial temperature of cold tank
T_c^f : final temperature of cold tank
T_{cj} : temperature of the j-th cold tank
T_{cj}^{int} : initial temperature of the j-th cold tank
T_{cj}^t : target temperature of the j-th cold tank
T_h : temperature hot tank
T_h^i : initial temperature of hot tank
T_h^f : final temperature of hot tank
T_{hi} : temperature of the i-th hot tank
T_{hi}^{int} : initial temperature of the i-th hot tank
T_{hi}^t : target temperature of the i-th hot tank
$Q_{heating}$: summation of heating requirements for cold tanks
$Q_{cooling}$: summation of cooling requirements for hot tanks
VC_p : heat capacity flow rate
$VC_{p,cj}$: heat capacity flow rate of the j-th cold tank
$VC_{p,hi}$: heat capacity flow rate of the i-th hot tank

Abbreviations

TAM : time average model
TSM : time slice model
MER : maximum energy recovery
BCT : batch cycle time

REFERENCES

1. Vaselenak, J. A., Grossmann, I. E. and Westerberg, A. W.: *Ind. Eng. Chem. Process Des. Dev.*, **25**, 357 (1986).
2. Obeng, E. D. A. and Ashton, G. J.: *Chem. Eng. Res. Des.*, **66**(3), 255 (1988).
3. Kemp, I. C. and Macdonald, E. K.: *IChemE Sym. Ser.*, **109**, 239 (1988).
4. Kemp, I. C. and Deakin, A. W.: *Chem. Eng. Res. Dev.*, **67**, 495 (1989).