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Optimal Production Sequence and Processing Schedules of Multiproduct Batch Processes for Heat Integration and Minimum Equipment Costs

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Abstract−The production sequence and the processing schedules of multiproduct batch processes can be changed for maximum heat recovery and minimum equipment costs between batch streams. However, the modified production sequence and processing schedule may increase the production cycle time, which causes the bigger equipment sizes required in batch processes. In this study, the required equipment sizes, the production sequence and the processing times of the multiproduct batch processes are mathematically formulated for maximum heat integration and low equipment costs in a mixed integer nonlinear programming. The optimal solution of this formulation was obtained by GAMS/DICOPT programming solver. Examples are presented to show the capabilities of the model.

Key words: Production Sequence, Process Scheduling, Multiproduct Batch Process, Heat Integration

INTRODUCTION

Multiproduct batch processes are suitable for the production of multiple products and for a little quantity [Ko et al., 2000]. Batch units are inherently more flexible than continuous units since the feed addition or the product removal can be scheduled. Also, the starting and the finishing process time of the batch units can be scheduled as a function of contact time more easily than in the continuous units. Batch processing units generally need heating or cooling for the processing. Those requirements are conventionally met through utilities rather than waste heat exchanges. Batch processes have more difficulties than continuous processes in heat exchanges because of the modification of the processing schedule [Jung et al., 1994; Lee and Reklaitis, 1995; Vaselenak et al., 1986]. Since the production sequences are also considered in multiproduct batch processes, the heat exchanges become more difficult [Corominas et al., 1999].

A principal advantage of multiproduct batch processes is the production of multiple products using the same set of equipment [Ko et al., 2000]. When products are similar in nature, they all require the same processing steps and hence pass through the same series of processing units. Batches of different or same products are formed sequentially in multiproduct batch processes. Because of the different processing time requirements, the total cycle time needed depends on the sequence in which the products are produced. The focus of this study is on the problem of determining the optimal production sequence and processing schedules of multiproduct batch processes considering heat exchanges between the batch streams at the initial stage of batch process design. Since the modified production sequence and processing times of multiproduct batch processes may increase the total production cycle time to produce the batch products, bigger batch processing units should be used to fulfill the annual production requirements. The recent researches for heat integration in batch processes have considered the modification of processing schedules of batch processes [Lee and Reklaitis, 1995; Cho et al., 1998; Corominas et al., 1999]. However, the modification of the production sequence in multiproduct batch processes also gives possibilities of heat integration. The determination of the production sequences including the processing schedules, the heat exchanges and the equipment sizes makes the problem into a large mixed integer nonlinear programming.

In this study, the optimization problem is to be formulated in which the objective function is the minimization of the equipment and energy costs and the constraints consist of the production sequence, the processing schedules, the heat exchanges and the required equipment sizes in multiproduct batch processes. A solution of this formulation is readily obtained with a commercial MINLP solver (GAMS/DICOPT, Brooke et al., 1988).

1. Mathematical Modeling

The optimization problem for heat integration in multiproduct batch processes has been approached by including the batch production sequence, the process schedule, the heat exchanges between the batch streams and the required equipment sizes.

1-1. Assumption for Scheduling

In order to formulate the mathematical model, the following must be assumed. The times required to transfer products from one unit to another are negligible compared to the processing times and the batch units are to process products as soon as the material enters the units. After the processing of a unit is finished, the batch material is readily transferred from the unit to the next batch unit. This is called zero-wait policy of the batch operation method that is generally used in industry [Cho et al., 1998]. In this paper, zero-wait policy is assumed to be used in the multiproduct batch process that is considered for the heat integration.

1-2. Assumption for Heat Exchange

To save energy cost by heat exchange, the modification of the production sequence and the processing schedule is considered. For this heat exchange, the following must be assumed: hot streams (the batch streams which require cooling) can exchange heat with cold streams (the batch streams which require heating), except that hot

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streams cannot exchange heat with hot streams and cold streams cannot exchange heat with cold streams; a batch stream cannot be matched to two or more streams. In addition, we propose the following assumption for the formulation to be simple: the specific heat capacity flow of each stream is a constant; the heat exchanged in a match is determined by its heat balances and is limited only by approach temperature [Lee, 1992]; heat losses and leaks are negligible. The heat deficit for each hot and cold stream after passing through the heat exchanger will be met through utilities.

1-3. Constraints According to Sequence and Scheduling

Two types of decisions are involved in part of scheduling. One is the determination of start and finish times of their processing on units, the other is the production order of multiple products. The timetable of operation will depend on the sequence of production and the processing times of products, so we must see how to compute the timetable for a given sequence. The ith product cannot leave unit k until it is processed, and in order to get processed on unit k, it must have left unit k−1. Therefore, the time at which it leaves unit k must be after the time at which it leaves unit k−1 plus its processing time on unit k. Thus we have the first set of constraints in our formulation,

$$TE_{ik} \geq TE_{i(k-1)} + \sum_i t_{pk} \cdot X_{pi} \tag{1}$$

Similarly, its product cannot leave unit k until i−1 product has left and the former has been processed.

$$TE_{ik} \geq TE_{(i-1)k} + \sum_i t_{pk} \cdot X_{pi} \tag{2}$$

The batch product cannot leave unit k until the downstream unit k+1 is free.

$$TE_{ik} \geq TE_{(i-1)(k+1)} \tag{3}$$

Having derived the constraints for completion times, let us turn our attention to the determination of sequence. In contrast to TE_{ik}, the decision variables here are discrete because we want to decide which products should be in which positions in the sequence. Such decisions in optimization problems are best handled by what are known as binary variables. Let us define X_{pi} as follows. $X_{pi}=1$ if product p is in slot i of the sequence, otherwise it is zero.

$$X_{1i}+X_{2i}+X_{3i}+\cdots+X_{Ni}=1 \tag{4}$$

$$X_{p1}+X_{p2}+X_{p3}+\cdots+X_{pN}=1 \tag{5}$$

The initial time TI_{ik} is given by

$$TI_{ik} = TE_{ik} - \sum_i t_{pk} \cdot X_{pi} \tag{6}$$

The product cycle time T_{ct} that is the maximum values of sum of processing times in each of units is given by

$$T_{ct} \geq TE_{i,k} - TI_{1,k} \tag{7}$$

If we only consider the Eq. (1)-(7) and the objective function of the minimization of the total production cycle time, the problem would be a mixed integer linear programming. However, since our formulation will consider the heat exchange between the batch streams and the required batch equipment cost, which are expressed as nonlinear, then the model will be a mixed integer nonlinear programming.

1-4. Constraints According to Heat Exchange

As previously stated, the heat exchange will be formulated in multiproduct batch processes. The modification of the production sequence and the processing schedules for the heat exchange may increase the total production cycle time. Then this causes the requirement of bigger sizes of the batch equipment. Therefore, the possibility of the heat exchange in batch processes has usually been neglected by the design engineer. However, some batch processes spend large energy cost comparable to the increased equipment costs that are in accordance with the total production cycle time of expanding. Both the energy cost and the required equipment cost mean the total production cost after all. The process consists of two or more units and the batch streams flow in batch units. Batch streams are specified as the hot stream needed for the cooling and as the cold stream needed for the heating, and finally, the heat exchange occurs between only hot and cold streams. Hot streams cannot match with hot streams, nor cold streams with cold streams. Also, a batch stream must maintain its integrity during a heat exchange; it cannot be divided to flow into two or more units for the heat exchange, unless specified by the processing requirements. The two batch fluids flow countercurrently through the heat exchanger, that is, the fluid exiting from the batch units experiences the conventional countercurrent type heat exchange until it reaches the next receiving units. Also, the time of heat exchange is considered to be negligible to processing time in batch processes. The minimum approach temperature for heat exchange ΔT_{min} is assumed to be a specified value.

1-4-1. Countercurrent Heat Exchange

Countercurrent heat exchange occurs when the processing requirements allow the fluids to transfer from their original units to receiving units while being heated or cooled, as shown in Fig. 1. At steady state, the temperature of the supply stream remains constant, as does the temperature of the final tank. Therefore, this system behaves as a semi-continuous process and results in a typical countercurrent heat exchange. Application of the first law of thermodynamics yields

$$(FC_p)_h(T_h^i - T_h^f) + (FC_p)_c(T_c^i - T_c^f) = 0 \tag{8}$$

where F is the flow rate of a fluid through the heat exchanger, C_p is heat capacity on constant pressure, (FC_p) is the heat content per degree per time, T^i is the initial temperature, T^f is the final temperature, subscript h is hot unit and subscript c is cold unit. If $(FC_p)_h$ is greater than $(FC_p)_c$, then a pinch point will occur at the hot end of the exchanger as shown in Fig. 2 [Lee and Yoo, 1995]. Setting the

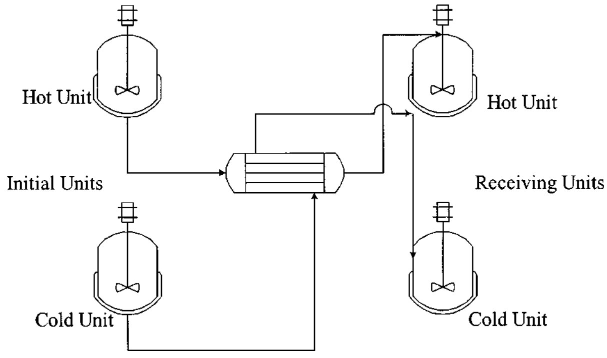

Fig. 1. Countercurrent heat exchange.

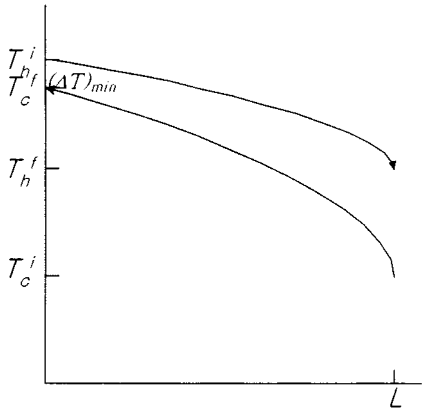

Fig. 2. Case of $(FC_p)_h>(FC_p)_c$ in countercurrent heat exchange.

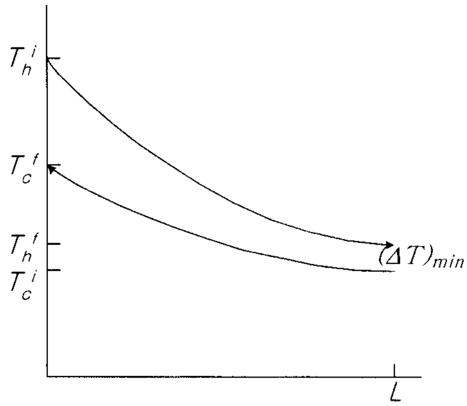

Fig. 3. Case of $(FC_p)_h<(FC_p)_c$ in countercurrent heat exchange.

hot outlet temperature equal to the cold inlet temperature plus margin, ΔT_{min}, yields

$$T_h^f=T_c^i+\Delta T_{min} \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields the expressions for T_c^f.

$$T_c^f=T_c^i+\{(FC_p)_h/(FC_p)_c\}(T_h^i-T_c^i-\Delta T_{min}) \tag{10}$$

If $(FC_p)_h$ is less than $(FC_p)_c$, then the pinch point occurs at the cold end of the exchanger, as seen in Fig. 3 [Lee and Yoo, 1995]. Similarly, we can get the following.

$$T_c^f=T_h^i-\Delta T_{min} \tag{11}$$

Substituting Eq. (11) into Eq. (8) yields the expressions for T_h^f.

$$T_h^f=T_h^i-\{(FC_p)_c/(FC_p)_h\}(T_h^i-T_c^i-\Delta T_{min}) \tag{12}$$

If $(FC_p)_h$ is equal to $(FC_p)_c$, then the pinch point occurs throughout the exchanger as shown in Fig. 4.

$$T_h^f=T_c^i+\Delta T_{min} \tag{13}$$

$$T_c^f=T_h^i-\Delta T_{min} \tag{14}$$

1-4-2. Maximum Heat Exchange Amount

Maximum amount of heat exchange between two batch streams is expressed as follows:

$$Q_{max}=\min[(B_pC)_c(T_c^d-T_c^s),\ (B_pC)_c\{(T_h^s-\Delta T_{min})-T_c^s\},\ (B_pC)_h(T_h^s-T_h^d),\ (B_pC)_h\{T_h^s-(T_c^s+\Delta T_{min})\}] \tag{15}$$

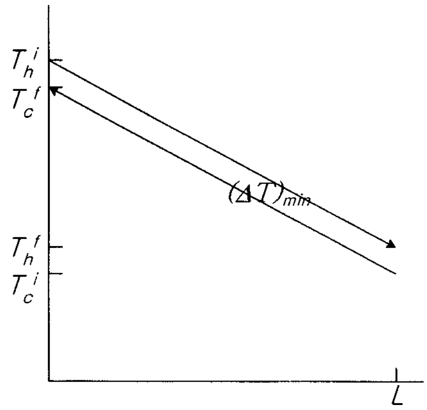

Fig. 4. of $(FC_p)_h=(FC_p)_c$ in countercurrent heat exchange.

where B_p is size of batch of product p[kg], superscript s indicates the starting temperature, and superscript d the desired temperature. Subscript c representws the cold stream and h the hot stream.

The amount of heat exchanged between the stream with the transfer time TI_{ik} and the stream with the transfer time TI_{jr} will be represented in Q_{ikjr}. In case of matching the streams with TI_{ik} and TI_{jr}, Q_{ijkr} is Q_{ikjr}^{max}, but in case of no matching them, Q_{ijkr} is zero. To describe a mathematical model of them, the binary variable Y_{ikjr} is used as follows:

$$Q_{ikjr}-Q_{ikjr}^{max}\cdot Y_{ikjr}\le 0 \tag{16}$$

where Q_{ikjr} is heat exchange between *i*th product from unit k and *j*th product from unit r. Q_{ikjr}^{max} equals the upper bound of Q_{ikjr}. Energy saving cost by the heat exchanges will be expressed as a sum of costs of the amounts of the utilities that are saved by the heat exchanges, and this is given by

$$\text{Energy saving cost for the year}=\sum cQ_{ikjr}\times(T/T_{ct}) \tag{17}$$

where c is the energy cost factor [Peters and Timmerhaus, 1991] and cQ_{ikjr} is energy cost saving when heat exchange is performed between stream i from unit k and stream j from unit r ; a number of cyclic batch productions for 1 year is expressed as T/T_{ct}.

1-5. Objective Function and the Other Constraints

The energy cost saving and the required equipment cost are considered together in the objective function. In order to obtain the expression of the required equipment cost, the batch size of the product p, B_p [kg] and the required equipment size of unit k, V_k [m^3] are explained. The batch size of the product p, B_p [kg] is expressed as the production requirement of product p, R_p [kg] divided by the number of the cyclic batch productions, T/T_{ct} and the equipment size of unit k, V_k [m^3] is the multiplication of the size factor, S_{pk} [Peters and Timmerhaus, 1991] and the batch size, B_p.

$$B_p=\frac{R_p}{T/T_{ct}} \tag{18}$$

$$V_k\ge S_{pk}B_p \tag{19}$$

where S_{pk} is the equipment size factor of unit k for product p [m^3/kg].

1-5-1. Binary Variables Selected for the Production Sequence of Multiproduct Batch Processes

Eq. (18) and (19) are reformed into Eq. (21) and (23) considering the production sequence of the multiproduct batch processes.

$$RS_i = \sum_i X_{pi} \times R_p \tag{20}$$

$$BS_i = \frac{RS_i}{T/T_{ct}} \tag{21}$$

$$SS_{ik} = \sum_i S_{pk} \times X_{pi} \tag{22}$$

$$SV_k \geq SS_{ik} BS_i \tag{23}$$

For the same reason, parameters of heat exchange are reformulated into

$$CcS_{jr} = \sum_j X_{pj} \times Cc_{pr} \tag{24}$$

Considering the production sequence, CcS_{jr} is the heat capacity of cooling batch stream j from unit r, whereas Cc_{pr} is the heat capacity of cooling batch stream, product p from unit r without considering the production sequence.

$$ChS_{ik} = \sum_i X_{pi} \times Ch_{pk} \tag{25}$$

Considering the production sequence, ChS_{ik} is the heat capacity of hot batch stream i from unit k, whereas Ch_{pk} is the heat capacity of hot batch stream, product p on unit k without considering the production sequence.

Similarly, the starting temperature and the desired temperature of cooling streams and hot streams are reformed into Eq. (26), (27), (28) and (29).

$$Tc^sS_{jr} = \sum_j Tc^s_{pr} \times X_{pj} \tag{26}$$

$$Tc^dS_{jr} = \sum_j Tc^d_{pr} \times X_{pj} \tag{27}$$

$$Th^sS_{ik} = \sum_j Th^s_{pk} \times X_{pi} \tag{28}$$

$$Th^dS_{ik} = \sum_j Th^d_{pk} \times X_{pi} \tag{29}$$

where the value of 1 of the binary variable, X_{pi} means the *p*th product is processed on unit i.

Considering the production sequence of the multiproduct batch processes, Q^{max}_{ikjr} is also reformed into

$$\begin{aligned} Q^{max}_{ikjr} = \min[&(BS_jCcS_{jr}) \times (|Tc^sS_{jr} - Tc^dS_{jr}|), \\ &(BS_jCcS_{jr}) \times (|Tc^sS_{jr} - Th^sS_{ik}| - \Delta T_{min}), \\ &(BS_iChS_{ik}) \times (|Th^sS_{ik} - Th^dS_{ik}|), \\ &(BS_iChS_{ik}) \times (|Tc^sS_{jr} - Th^sS_{ik}| - \Delta T_{min})] \end{aligned} \tag{30}$$

where Q^{max}_{ikjr} means the maximum amount of heat exchanged between the hot stream of *i*th product from unit k and the cold stream of *j*th product from unit r.

1-5-2. Heat Exchange by Matching Two Streams Considering the Production Sequence

In this study, it is assumed that a stream cannot be matched to two or more streams, a zero-wait policy is maintained through whole processes, and heat exchanges are occur only between the hot stream and the cold stream. In order to accomplish heat exchange between two batch streams, two continuous time variables, $TI_{i,k}$ and $TI_{j,r}$ must have the same value to satisfy the equality constraints. The starting time of batch i on unit k, TI_{ik} is the same with $TE_{i(k-1)}$ since a zero wait policy is adopted.

The binary variable Y_{ikjr} has the value of one if the heat exchange occurs between two streams that have the same value of the starting time of TIik and TI_{jr}. On the contrary, if heat exchange between two streams does not occur, Y_{ikjr} takes the value of zero. This condition can easily be satisfied by the following nonlinear equation:

$$Y_{ikjr} \cdot (TI_{ik} - TI_{jr}) = 0 \tag{31}$$

Since it is generally more difficult to find solutions of nonlinear problems than linear problems, it is useful to transform constraint Eq. (31) into linear form. This can be accomplished by using positive variables T^+_{ikjr} and T^-_{ikjr} [Lee and Reklaitis, 1995]:

$$TE_{i(k-1)} - TE_{j(r-1)} = T^+_{ikjr} - T^-_{ikjr} \tag{32}$$

$$T^+_{ikjr} \leq L(1 - Y_{ikjr}) \tag{33}$$

$$T^-_{ikjr} \leq L(1 - Y_{ikjr}) \tag{34}$$

where L is a suitably large number.

Let us consider Eq. (32), (33), (34) to fulfill the conditions of Eq. (31). If the binary variable Y_{ikjr} has the value of one (Y_{ikjr}=1), then Eq. (33) and (34) force two artificial positive variables, T^+_{ikjr} and T^-_{ikjr} both equal to zero. In Eq (32), since the right hand side equals to zero, the two time variables, $TE_{i(k-1)}$ and $TE_{j(r-1)}$ should be equal to each other.

The objective function of the formulation that minimizes the required equipment costs and the annual utilities costs is given by

$$\text{Minimize } \sum_k A_k V_k^{B_k} - n \sum (Q_{ikjr} c) \times T/T_{ct} \tag{35}$$

where A_k and B_k are empirical coefficients and exponents used for equipment cost of the batch unit k [Peters and Timmerhaus, 1991]. *n*[year] is useful life years of batch processes at which the increased equipment costs are recovered from the heat recovery.

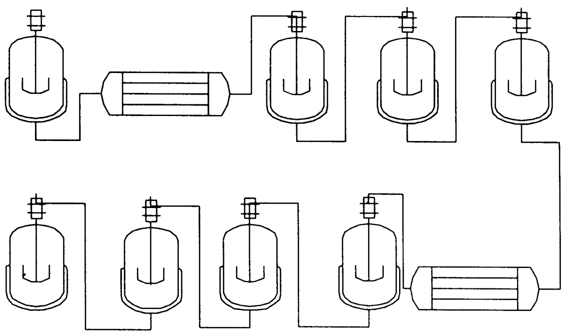

Fig. 5. Multi-product batch process consisting of 8 units and 2 heat exchangers.

Table 1. Batch processing time, t_{ip} [hr]

	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
Product1	2	1	2	2	3	2	3	1
Product2	3	1	3	2	2	1	1	2
Product3	4	1	2	1	3	1	2	2
Product4	3	2	1	1	1	2	3	1
Product5	1	3	2	2	2	3	1	2

Table 2. Empirical coefficient and empirical exponent used for equipment cost

	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
A_k	990	1062	2160	1404	666	1200	950	1134
B_k	0.65	0.40	0.52	0.34	0.67	0.47	0.58	0.47

Table 3. Heating and cooling requirements of batch streams

	C [kj/kg °C]	T^s [°C]	T^d [°C]	Status
Product2 (→unit3)	3.9	320	110	Hot
Product1 (→unit5)	3.7	95	270	Cold

Table 4. Production requirement of product p over year

	Product1	Product2	Product3	Product4	Product5
R_p [kg]	4,000,000	3,000,000	3,500,000	3,200,000	3,600,000

Table 5. Equipment size factor of unit k for product p

	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
Product1	1.2	1.4	1.0	1.3	1.5	1.1	1.8	1.2
Product2	1.1	1.2	1.5	1.2	1.3	1.4	1.0	1.3
Product3	1.4	1.0	1.2	1.4	1.3	1.2	1.3	1.1
Product4	1.3	1.0	1.3	1.2	1.4	1.2	1.1	1.0
Product5	1.1	1.3	1.4	1.1	1.5	1.3	1.4	1.3

EXAMPLES

Fig. 5 shows a multiproduct batch process consisting of 8 units and producing 5 products. The required batch processing times of each product in batch units are shown in Table 1. Heat exchange may occur between streams on unit 2 and streams on the unit 5. It is assumed that the useful life of the batch process is 10 years, total production time over 10 years is 80,000 hours, and the minimum approach temperature is 10 °C. Table 2 shows the empirical coefficients and exponents used for equipment cost and Table 3 shows the heating or cooling requirements of each batch stream. Table 4 shows the production requirement of product p over year and Table 5 shows the equipment size factors of unit k for product i. Utility cost factor is 9.7×10^{-6} [$/kJ] in case of using 278 °C steam [Peters and Timmerhaus, 1991]. The formulated problem is an MINLP and the optimal solution is obtained by a commercial programming solver GAMS/DICOPT. The first case (a) of examples minimized the equipment cost without considering the modification of the product sequence and the possibilities of heat exchanges at all. The second case (b) considered the modification of the product sequence and the process schedules without the heat exchanges. The last case (c) used the full formulation minimizing the equipment costs and the utilities costs with the consideration of the production sequence, the process scheduling and the heat exchanges.

The optimal costs (the minimum equipment cost with the maximum heat recoveries) of examples are $1,559,081 for case (a),

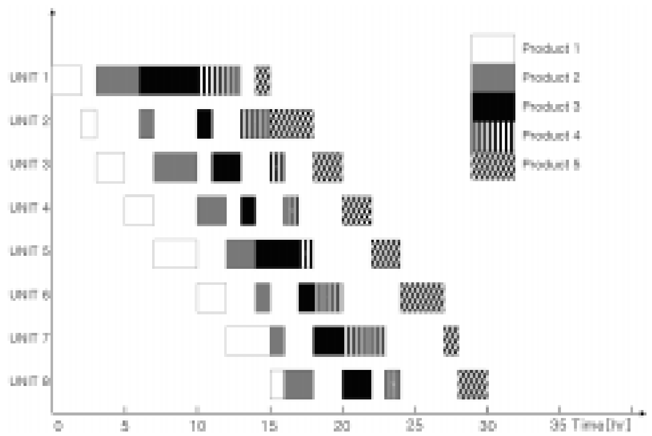

Fig. 6. Gantt chart of case study I-(a).

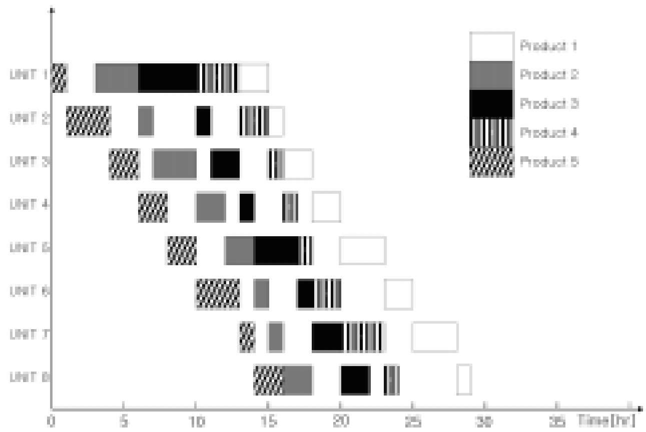

Fig. 7. Gantt chart of case study I-(b).

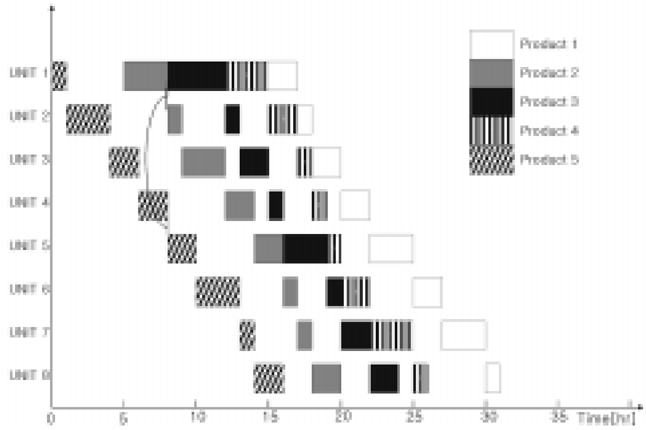

Fig. 8. Gantt chart of case study I-(c).

Table 6. Finishing time of case study I

TE_{ik}	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
Product1	2	3	5	7	10	12	15	16
Product2	6	7	10	12	14	15	16	18
Product3	10	11	13	14	17	18	20	22
Product4	13	15	16	17	18	20	23	24
Product5	15	18	20	22	24	27	28	30

Table 7. Finishing time of case study I

TE_{ik}	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
Product5	1	4	6	8	10	13	14	16
Product2	6	7	10	12	14	15	16	18
Product3	10	11	13	14	17	18	20	22
Product4	13	15	16	17	18	20	23	24
Product1	15	16	18	20	23	25	28	29

Table 8. Finishing time of case study I

TE_{ik}	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7	Unit8
Product5	1	4	6	8	10	13	14	16
Product2	8	9	12	14	16	17	18	20
Product3	12	13	15	16	19	20	22	24
Product4	15	17	18	19	20	22	25	26
Product1	17	18	20	22	25	27	30	31

$1,448,801 for case (b) and $1,394,751 for case (c). In case of (b), the production sequence is modified into order of product 5, 2, 3, 4, 1. Since the total cycle production time is decreased from 17 to 15, the required equipment cost is decreased compared with (a). In case of (c), because of the possible heat exchange, the process schedules are changed. The total cycle production time is increased from 15 to 17 compared with (b). However, the cost saving of heat exchange reduces total optimal cost compared with (b). These facts lead us to conclude the facilities of the formulation in this study.

CONCLUSION

The production sequence and the process schedules are changed to make heat exchanges between batch streams possible in multiproduct batch processes. The conventional countercurrent heat exchanging method by which the batch streams transferring from the batch units to the other units can exchange heat with other streams is adopted. In order to demonstrate the facility of the formulation derived in this study, a multiproduct batch process that produces 5 batch products with 8 batch units is applied to the formulation. The optimal solution of the MINLP problem is obtained by a commercial solver GAMS/DICOPT. The solution of the example confirms that the energy recovery cost over 10 years exceeds the increased equipment costs. In multiproduct batch processes, it is also confirmed that the modification of the product sequence and the process schedule brings more possibilities of heat exchanges than the consideration of the process schedules only.

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NOMENCLATURE

A_k : empirical coefficient used for equipment cost [$/m^3]
B_k : empirical exponent used for equipment cost [$/m^3]
B_p : batch size of product p [kg]
BS_i : batch size of *i*th product [kg]
c : steam and cooling water cost factor [$/kJ]
C_p : heat capacity of batch stream p [kJ/kg °C]
CcS_{jr} : heat capacity of cooling batch stream for *j*th product on unit r [kJ/kg °C]
ChS_{ik} : heat capacity of hot batch stream for *i*th product on unit k [kJ/kg °C]
Cc_{pr} : heat capacity of cooling batch stream for product p on unit r [kJ/kg °C]
Ch_{pk} : heat capacity of hot batch stream for product p on unit k [kJ/kg °C]
$(\Delta T)_{min}$: minimum approach temperature [°C]
F : flow rate of fluid [kg/hr]
L : a suitably large number
Q^{max} : upper bound amount of heat exchange [kJ]
Q_{ikjr} : heat exchanged between *i*th product on unit k and *j*th product on unit r [kJ]
R_p : production requirement of product p over year [kg]
RS_i : production requirement of *i*th product over year [kg]
Ss_{ik} : equipment size factor of unit k for *i*th product [m^3/kg]
SV_k : equipment size of unit k for sequence [m^3]
T : total production time over year [kg]
T_h^s : starting temperature of hot stream [°C]
T_h^d : desired temperature of hot stream [°C]
T_c^s : starting temperature of cold stream [°C]
T_c^d : desired temperature of cold stream [°C]
TE_{ik} : finishing time of *i*th product on unit k [hr]
TI_{ik} : starting time of *i*th product on unit k [hr]
T_{ct} : total production cycle time [hr]
t_{pk} : batch processing time of batch p unit k [hr]
Tc^sS_{jr} : starting temperature of cold stream of *j*th product on unit r [°C]
Tc^dS_{jr} : desired temperature of cold stream of *j*th product on unit r [°C]
Th^sS_{ik} : starting temperature of hot stream of *i*th product on unit k [°C]
Th^dS_{ik} : desired temperature of cold stream of *i*th product on unit k [°C]
Tc_{pr}^s : starting temperature of cold stream of product p unit r [°C]
Tc_{pr}^d : desired temperature of cold stream of product p unit r [°C]
Th_{pk}^s : starting temperature of hot stream of product p unit k [°C]
Th_{pk}^d : desired temperature of hot stream of product p unit k [°C]
T_{ikjr}^+ : artificial positive variable for match between TI_{ik} and TI_{jr}
T_{ikjr}^- : artificial positive variable for match between TI_{ik} and TI_{jr}
V_k : equipment size of unit k [m^3]
X_{pi} : 0-1 binary variable for sequence
Y_{ikjr} : 0-1 binary variable for heat exchange between two batch streams with transfer time TI_{ik} and TI_{jr}, respectively

REFERENCES

Bancheva, N., Vaklieva, B., Ivanov, B., Shah, N. and Pantelides, C. C., "Heat Exchanger Network Design for Multipurpose Batch Plants," *Computers and Chemical Engineering*, **20**, 989 (1996).

Brooke, A., Kendrick, D. and Meeraus, A., "GAMS Users Manual," Scientific Press (1988).

Cho, I., Lee, B., Lee, I.-B. and Lee, E. S., "Optimal Design and Production Plan of Multi-Product Batch Processes Considering Equipment Costs and Energy Savings," *HWAHAK KONGHAK*, **36**, 601 (1998).

Corominas, J., Espuna, A. and Puigjaner, L., "A New Look at Energy Integration in Multiproduct Batch Processes," European Symposium on Computer Aided Process Engineering-2, s15 (1999).

Jung, S. H., Lee, I.-B., Yang, D. R. and Chang, K. S., "Synthesis of Maximum Energy Recovery Networks in Batch Processes," *Korean J. Chem. Eng.*, **11**, 162 (1994).

Ko, D., Na, S., Moon, I. and Lee, I.-B., "Development of a Batch Manager for Dynamic Scheduling and Process Management in Multiproduct Batch Processes," *Korean J. Chem. Eng.*, **17**, 27 (2000).

Lee, B. and Reklaitis, G. V., "Optimal Scheduling of Cyclic Batch Processes for Heat Integration-I. Basic Formulation," *Computers and Chemical Engineering*, **19**, 883 (1995).

Lee, H. P., Lee, I. Y. and Yoo, K. O., "The System Separation Method for the Optimal Target of Heat Exchanger Network Synthesis with Multiple Pinches," *Korean J. Chem. Eng.*, **12**, 589 (1995).

Lee, I.-B., "Synthesis of Heat Exchanger Networks with Minimum Number of Units for Pinched Problems," *Korean J. Chem. Eng.*, **9**, 117 (1992).

Papageorgiou, Lazaros G., Shah, Nilay and Constantinos C. Pantelides, "Optimal Scheduling of Heat-Integrated Multipurpose Plants," *Ind. Eng. Chem. Res.*, **33**, 3168 (1994).

Peters, Max S. and Klaus D. Timmerhaus, "Plant Design and Economics for Chemical Engineers," McGraw-Hill, Fourth Edition (1991).

Vaselenak, Jane A., Ignacio E. Grossmann, and Arthur W. Westerberg, "Heat Integration in Batch Processing," *Ind. Eng. Chem. Processes Des.*, **25**, 357 (1986).

Yoo, D. J., Lee, H.-K., Jung, J. H. and Lee, I.-B., "Optimal Design of Pipeless Processes with Scheduling," *HWAHAK KONGHAK*, **34**, 742 (1996).