

# EVOLUTIONARY DESIGN METHOD FOR MULTIPURPOSE BATCH PLANTS ON THE BASIS OF CYCLIC PRODUCTION

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Designing of multipurpose batch plants is a problem of optimizing the plant configuration and the equipment sizes under the constraint of the production plan. However, these decision variables are strongly interactive with each other through scheduling, so that simultaneous optimization is impossible.

In this study, the design problem of multipurpose batch plants is considered on the basis of cyclic production, and the evolutionary method is adopted from the analysis of this design problem. The plant configuration is decided as the evolutionary variable, and two IP (Integer Programming) models are developed to generate the initial and/or neighboring plant configurations. The initial plant configuration with minimum number of equipment units is obtained through these IP models, and the equipment sizes under this initial plant configuration are optimized through cyclic scheduling. The neighboring plant design can be generated repeatedly through the developed IP model and the cyclic scheduling from this initial one, and an evolutionary design method for the multipurpose batch plants is developed. The effectiveness of the developed method is demonstrated through an example design problem.

## Introduction

Multipurpose batch plants have become of interest recently because of their suitability for producing a variety of high value added products through respective task sequences in low volume. However, only well-designed plants can produce such products effectively.

In designing multipurpose batch plants, the production requirements, the recipe data for each product and the total production time available are specified beforehand as a production plan. Then the plant configuration and the equipment sizes become the decision variables to minimize the total equipment cost under the constraint of this production plan.

Several studies in design of these plants have been reported in the literature, and most of these studies adopted mathematical programming models. Suhani and Mah<sup>8)</sup> first formulated this problem into a MINLP (Mixed Integer Non Linear Programming) model, but their method required some heuristic preparations. Imai and Nishida<sup>4)</sup> and Coulman<sup>2)</sup> modified this model to eliminate these heuristics. Vaselenak *et al.*<sup>9)</sup> proposed a MINLP model embedding a superstructure. Papageorgaki and Reklaitis<sup>5, 6)</sup> decomposed this design problem into two sub-problems and formulated them into IP (Integer Programming) and NLP (Non Linear Programming) models. They used these two models recursively instead

of solving the MINLP model directly. Furthermore, Voudouris and Grossmann<sup>10)</sup> modified the MINLP problem into IP models by introducing discrete equipment sizes.

The equipment sizes satisfying the production plan cannot be decided without scheduling for a given plant configuration. On the other hand, a plant configuration cannot be evaluated without the equipment sizes. Thus these decision variables are strongly interactive with each other through scheduling, and the design problem is complicated. However, the previous studies were to optimize the decision variables simultaneously regardless of their interaction through scheduling. To formulate the design problem into mathematical programming models, they were forced to estimate the total production time from summations of the processing time in every equipment unit independently instead of scheduling. However, the tasks in every equipment unit are not independent in the multipurpose batch plants, so that scheduling is indispensable to consider this interaction in designing. Besides, scheduling can be carried out only for a given plant configuration. Thus the decision variables cannot be optimized simultaneously, and decomposition is essential.

In designing batch plants, scheduling according to cyclic production (cyclic scheduling) is appropriate (Birewar and Grossmann<sup>11)</sup>), because the interactions

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**Table 1.** Production requirements for small example

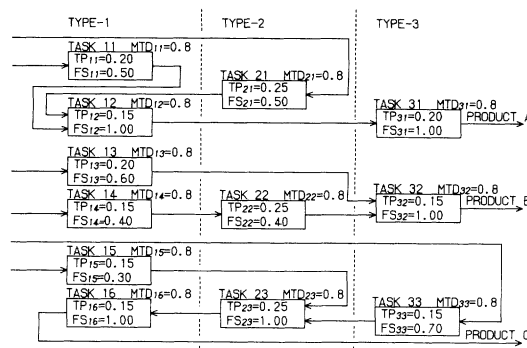
	Product (h)		
	A	B	C
$PR_h$	2500.0	2000.0	2500.0
$NB_h$	1	1	1

between the tasks in every equipment unit can be considered with a small computational load. Then the object of scheduling is converted into minimizing the cycle time, and the order of tasks in each equipment unit should be optimized in multipurpose batch plants. Fuchino *et al.*<sup>3)</sup> developed an IP model applicable to cyclic scheduling of these plants. The purpose of this study is to develop a design method for these plants on the basis of cyclic production, and the characteristics of this design problem are analyzed as the first step.

On the basis of cyclic production, the plant configuration can be generated from the production requirements, whereas the equipment sizes can be optimized only for a given plant configuration through cyclic scheduling. Thus this design problem should be decomposed into two sub-problems: deciding the plant configuration and optimizing the equipment sizes, and the second sub-problem can be solved under a solution of the first sub-problem. To obtain the optimal design, the plant configuration should be searched, but it cannot be evaluated without the result of the second sub-problem through cyclic scheduling. Therefore, only the evolutionary method can optimize the plant configuration, and generating the initial and/or neighboring ones become the essential points.

The tasks can be classified into several types from the viewpoint of common usage of equipment, and the plant configuration can be specified with two parameters: number of equipment units and equipment assignments to the tasks for each type. These two parameters should be specified to generate the initial and/or neighboring ones, and in this study, two IP models, IP model (1) and IP model (2), are developed for these parameters. IP model (1) provides the minimum number of equipment units which is suitable for a feasible and nearly optimal initial plant configuration from the viewpoint of scale merit. The evolution is started with this minimum number of equipment units in this study, so that the first parameter for the neighboring plant configurations can be provided by only increasing this number. Moreover, the second parameter for the initial and/or neighboring plant configurations should be chosen so as to minimize the equipment sizes under the given number of equipment units. IP model (2) optimizes the second parameter by unifying the production ratio of each equipment unit from consideration of the cycle time.

In the next section, the characteristics of this design problem are analyzed through a small example. The two IP models developed for generating the initial and/or neighboring plant configurations are explained in a fur-

**Fig. 1** Recipe data for Products A, B, and C

ther section. Finally, the effectiveness of the developed design method is demonstrated through an example problem, and the evolutionary rule is explained in this example.

## 1. Characteristics of the Design Problem

In this section, the characteristics of designing multipurpose batch plants on the basis of cyclic scheduling are analyzed through a small example. Before designing, the production plan (the production requirements, the recipe data for each product and the total production time available) and the data for the clean-up time are specified. The following items are given in the production requirements and the recipe data.

- Production requirements:

- 1) Total production volume ( $PR_h$ ) for each product ( $h$ ).
- 2) Number of batches per cycle ( $NB_h$ ).

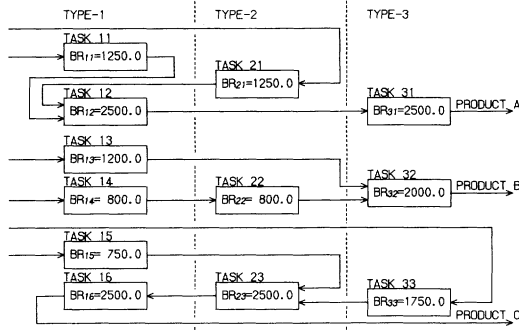
- Recipe data:

- 3) Task sequences for each product.
- 4) Type of tasks ( $i$ ) from the viewpoint of common usage of equipment.
- 5) Processing time ( $TP_{i,j}$ ) for  $j$ -th task in  $i$ -th type.
- 6) Characteristic sizes to produce unit volume of products (size factor:  $FS_{i,j}$ ).
- 7) Minimum operating capacity ( $MTD_{i,j}$ ).
- 8) Charging and/or discharging time.
- 9) Stability of intermediate products.

In this example, three kinds of products (A, B and C) are planned for production within a total production time available ( $TH$ :  $TH = 300$  here). The production requirements, and the recipe data (except for the above eighth and ninth items) for these products are shown in **Table 1** and **Fig. 1**. In these recipe data, tasks and their sequences for each product are expressed by squares and arrows, and these tasks are classified into three types ( $i = 1 \sim NT$ :  $NT = 3$  here) as shown in Fig. 1. The charging and/or discharging time is fixed at 0.5, and all the intermediate products are stable here. Thus holding the intermediate products in each equipment unit is allowed. Moreover, the clean-up time, which varies with the successive products in each equipment unit, is necessary for cyclic scheduling. This clean-up time can be estimated before designing, and the data shown in **Table 2** are used

**Table 2.** Clean-up time for small example

from	to		
	A	B	C
A	-	0.5	1.0
B	1.0	-	1.5
C	0.5	1.5	-



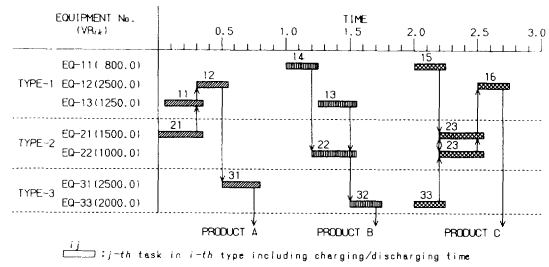
**Fig. 2** Required relative task volume

here.

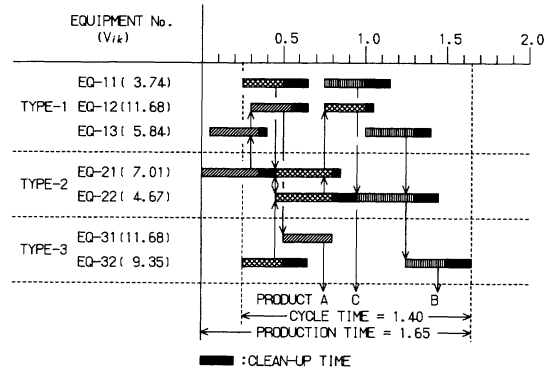
According to cyclic production, the products in one cycle are produced repeatedly, so that the total production volume ( $PR_h$ ;  $h \in \{A, B, C\}$ ) becomes the relative production volume per one cycle.  $PR_h$  divided by the number of batches per cycle ( $NB_h$ ) gives the relative batch sizes for each product. In this example,  $NB_h$  is one from the production requirements, so that the total production volume ( $PR_h$ ) becomes the relative batch sizes. Thus  $PR_h$  multiplied by  $FS_{i,j}$  gives the required relative task volume ( $BR_{i,j}$ ) to produce the products in the relative batch sizes as shown in Fig. 2. Therefore the plant configuration can be defined with two parameters: number of equipment units to carry out the tasks and assignments of these equipment units to the tasks (equipment assignments), satisfying the required relative task volume. Furthermore, tasks of the same type (for example, the first to sixth tasks in the first type shown in Figs. 1 and 2) can be carried out in the same category of equipment, so that these two parameters can be considered independently for each type.

When a plant configuration is given by specifying its two parameters, the number of equipment units ( $E_i$ ) and equipment assignments satisfying the required relative task volume ( $BR_{i,j}$ ) as shown in Fig. 3, then the relative equipment sizes ( $VR_{i,k}$ ;  $k = 1 \sim E_i$ ) are obtained for each type. The optimal one-cycle schedule for this plant configuration can be made through cyclic scheduling<sup>3)</sup> as shown in Fig. 4, and then the cycle time ( $TC$ ) and the production time ( $TP$ ) for one cycle are obtained. The number of cycles ( $NC$ ) within the total production time available ( $TH$ ) can be calculated by Eq. (1).

$$NC = \left\lceil \frac{TH - (TP - TC)}{TC} \right\rceil \quad (1)$$



**Fig. 3** Example of plant configuration



**Fig. 4** One-cycle schedule for Fig. 3

Then the optimal equipment sizes ( $V_{i,k}$ ) for this plant configuration satisfying the production plan can be calculated by Eq. (2).

$$V_{i,k} = \frac{VR_{i,k}}{NC} \quad (2)$$

The plant configuration can be generated from the production requirements on the basis of cyclic production, whereas the equipment sizes can be optimized through cyclic scheduling under the given plant configuration. Thus the design problem of the multipurpose batch plants should be decomposed into two sub-problems: generating the plant configuration and optimizing the equipment sizes. However, the one-cycle schedule shown in Fig. 4 cannot be made without the plant configuration shown in Fig. 3, so that the equipment sizes can be optimized only after generating a plant configuration. On the contrary, the plant configuration shown in Fig. 3 cannot be evaluated without its optimal equipment sizes shown in Fig. 4. Thus the plant configuration should be searched with optimizing of its own equipment sizes. Only the evolutionary method can optimize such a problem, and generating the initial and/or neighboring plant configurations become the essential points.

The initial plant configuration should be feasible and nearly optimal for the evolutionary method. The object for the design problem is minimizing the total equipment cost, and each equipment unit cost ( $C_{i,k}$ ) is estimated by Eq. (3).

$$C_{i,k} = \alpha_i \cdot V_{i,k}^{\beta_i} \quad (3)$$

where  $\alpha_i$  and  $\beta_i$  are constants depending on the type. Thus the initial one composed of the minimum number

of equipment units (Su and Motard<sup>7)</sup>) is suitable for near-optimality from the viewpoint of scale merit. However, equipment units are constrained by their minimum operating capacity (Coulman<sup>2)</sup>), and the minimum number of units should be decided under this constraint for the feasibility. Thus it is difficult to decide the number of units for a feasible and nearly optimal initial plant configuration by intuition. On the other hand, when the evolution is started from the minimum number of equipment units, the number of units for the neighboring plant configurations can be obtained by only increasing this number. Moreover, the equipment should be assigned to the tasks under the given number of equipment units for the initial and/or neighboring plant configurations. The equipment sizes are minimized through cyclic scheduling, so these assignments should be decided to minimize the cycle time under the constraint of the minimum operating capacity.

In this study, integer variables to relate the equipment and the tasks are introduced, and the constraint of the minimum operating capacity is formulated nonlinearly. This nonlinear constraint and the other necessary ones are linearized, and two IP models, IP model (1) and IP model (2) are developed. IP model (1) provides the minimum number of equipment units for the initial plant configuration. IP model (2) assigns the given number of equipment units to the tasks for the initial and/or neighboring plant configurations by unifying the production ratio of each equipment unit, and the optimal relative equipment sizes ( $VR_{i,k}$ ) for the initial and/or neighboring plant configurations are obtained. The optimal design can be searched by generating the neighboring plant configurations with optimizing of their equipment sizes repeatedly, and an evolutionary design method for multipurpose batch plants on the basis of cyclic production is developed.

In the next section, the two IP models developed for generating plant configurations are explained. The evolutionary rule for searching the optimal design is presented in a further section through an illustrative example.

## 2. Generating Plant Configurations

In this section, the two IP models developed to generate the initial and/or neighboring plant configurations are explained through the foregoing small example. First, the minimum number of equipment units ( $MI_i$ ;  $i = 1 \sim NT$ ) for the initial plant configuration is explained.

The maximum number of equipment units ( $ME_i$ ;  $i = 1 \sim NT$ ) for each type can be limited with the number of tasks ( $NE_i$ ;  $i = 1 \sim NT$ ). For example, the maximum number of equipment units in the first type of the small example is six, as shown in Fig. 2. Thus deciding the minimum number of equipment units is selecting the necessary equipment from  $ME_i$  candidates of every type with consideration of the minimum operating capacity.

In this study, two kinds of 0/1 integer variables ( $J_{i,k}$

and  $I_{i,j,k}$ ) to describe the conditions shown in Eqs. (4) and (5) are introduced.

$$J_{i,k} = \begin{cases} 1 & (k\text{-th equipment unit is introduced}) \\ 0 & (\text{otherwise}) \end{cases} \quad (4)$$

$$I_{i,j,k} = \begin{cases} 1 & (k\text{-th equipment unit is assigned to } j\text{-th task}) \\ 0 & (\text{otherwise}) \end{cases} \quad (5)$$

Then the objective function for this selecting problem for  $i$ -th type can be described with the integer variables ( $J_{i,k}$ ) as shown in Eq. (6).

$$\min \sum_{k=1}^{ME_i} J_{i,k} \quad (6)$$

To relate the selected equipment to the tasks, the following constraints are necessary, and they can be formulated into Eqs. (7) to (10).

- 1) Minimum operating capacity for each equipment unit.
- 2) Relation between  $VR_{i,k}$  and  $J_{i,k}$ .
- 3) Relation between  $I_{i,j,k}$  and  $J_{i,k}$ .
- 4) Prohibited tasks to carry out in the same equipment, if necessary.

$$1) \quad BR_{i,j} \leq \sum_{k=1}^{ME_i} VR_{i,k} \cdot I_{i,j,k} \leq BR_{i,j} / MTD_{i,j} \quad (j = 1 \sim NE_i) \quad (7)$$

$$2) \quad VR_{i,k} = \begin{cases} > 0.0 & (\text{if } J_{i,k} = 1) \\ = 0.0 & (\text{if } J_{i,k} = 0) \end{cases} \quad (j = 1 \sim NE_i) \quad (8)$$

$$3) \quad J_{i,k} = \max \{I_{i,1,k}, I_{i,2,k}, \dots, I_{i,NE_i,k}\} \quad (k = 1 \sim ME_i) \quad (9)$$

$$4) \quad I_{i,j1,k} + I_{i,j2,k} \leq 1 \quad (k = 1 \sim ME_i) \quad (10)$$

where  $MTD_{i,j}$  ( $MTD_{i,j} = 0.8$  here) is the minimum fraction of capacity of the  $j$ -th task in the  $i$ -th type, and  $j1$  and  $j2$  are prohibited tasks to carry out in the same equipment.

Only the assigned equipments to the  $j$ -th task should be constrained with the minimum operating capacity, so that the continuous variables ( $VR_{i,k}$ ) are multiplied by the integer ones ( $I_{i,j,k}$ ) in Eq. (7). The relative equipment size of the  $k$ -th equipment unit should be positive if and only if the  $k$ -th equipment unit is introduced. Moreover, the introduced equipment must be assigned to some task. Thus the ranges of  $VR_{i,k}$  are restricted by the value of  $J_{i,k}$  in Eq. (8), and Eq. (9) is the maximum value function. These constraints (Eqs. (7), (8) and (9)) are nonlinear, and this formulation becomes the MINLP model. However, all the constraints include the integer variables, so that it is impossible to optimize such a MINLP model directly. Therefore, linearization is necessary.

When the intermediate variables ( $VI_{i,j,k}$ ) defined in Eq. (11) are newly introduced, Eq. (7) can be converted into the linear constraint as shown in Eq. (12).

$$VI_{i,j,k} = VR_{i,k} \cdot I_{i,j,k} \quad (j = 1 \sim NE_i) \quad (k = 1 \sim ME_i) \quad (11)$$

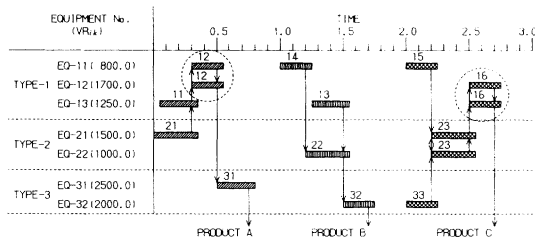


Fig. 5 Alternative plant configuration

$$BR_{i,j} \leq \sum_{k=1}^{ME_i} VI_{i,j,k} \leq BR_{i,j} / MTD_{i,j} \quad (12)$$

$$(j = 1 \sim NE_i)$$

$$(k = 1 \sim ME_i)$$

Eq. (11) is still nonlinear, but it can be linearized by setting up the boundary with sufficiently large constant ( $LN$ ) and the introduced integer variables ( $I_{i,j,k}$ ) as shown in Eq. (13).

$$LN \cdot (I_{i,j,k} - 1) \leq VI_{i,j,k} - VR_{i,k} \leq LN \cdot (1 - I_{i,j,k}) \quad (13)$$

$$(j = 1 \sim NE_i)$$

$$(k = 1 \sim ME_i)$$

This linearization technique is adoptable for Eqs. (8) and (9), and they can be linearized respectively as shown in Eqs. (14) and (15). The relative equipment sizes ( $VR_{i,k}$ ) are continuous variables, and their boundaries are set up with the sufficiently large constant ( $LN$ ) in Eq. (14).  $I_{i,j,k}$  are 0/1 integer variables to describe the assignment of an introduced equipment, and their summation is set up with the number of tasks ( $NE_i$ ) in Eq. (15).

$$VR_{i,k} \leq LN \cdot J_{i,k} \quad (k = 1 \sim ME_i) \quad (14)$$

$$\sum_{j=1}^{NE_i} I_{i,j,k} \leq NE_i \cdot J_{i,k} \quad (k = 1 \sim ME_i) \quad (15)$$

All the necessary constraints and the objective function are expressed with linear combinations, and the IP model for the minimum number of equipment units (IP model (1)) is developed. This IP model (1) is applied to the small example, provided that the tasks for the same products in the first type are prohibited to carry out in the same equipment with the following constraints.

$$I_{1,1,k} + I_{1,2,k} \leq 1 \quad (k = 1 \sim ME_i) \quad (16)$$

$$I_{1,3,k} + I_{1,4,k} \leq 1 \quad (k = 1 \sim ME_i) \quad (17)$$

$$I_{1,5,k} + I_{1,6,k} \leq 1 \quad (k = 1 \sim ME_i) \quad (18)$$

The minimum number of equipment units ( $MI_i$ ) for each type is obtained as shown in Eq. (19).

$$MI_i = \begin{cases} 3 & (i = 1) \\ 2 & (i = 2) \\ 2 & (i = 3) \end{cases} \quad (19)$$

The evolution is started from the minimum number of

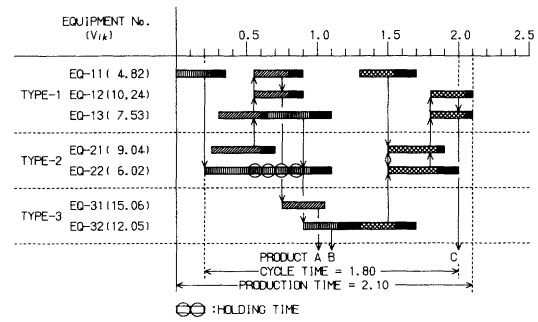


Fig. 6 One-cycle schedule for Fig. 5

equipment units in this study, so that the number of equipment units for the neighboring plant configurations can be obtained by only increasing this number.

Second, the equipment assignments to the tasks are explained. Even though the number of equipment units is decided from the consideration of the minimum operating capacity, their assignments to the tasks cannot be specified. For example, alternate plant configurations with the minimum number of equipment units can be considered for this example as shown in Fig. 3 and Fig. 5. The equipment assignments to the tasks in the first type, as well as the relative equipment sizes to fulfill the required relative task volume, are different from each other. The one-cycle schedules for these two plant configurations are shown in Fig. 4 and Fig. 6. Equipment in the first type (EQ-11, EQ-12 and EQ-13) in Fig. 3 is assigned to two tasks uniformly. On the other hand, EQ-12 is assigned to two tasks, but EQ-11 and EQ-13 are assigned to three tasks varyingly in Fig. 5. The production ratio of EQ-12 is decreased, so that the cycle time is extended from 1.40 to 1.80 as shown in Figs. 4 and 6. This difference in cycle time affects the equipment sizes in the other types as shown in Figs. 4 and 6. Therefore, a given number of equipment units should be assigned to the tasks to unify the respective production ratios for each type from the consideration of cyclic scheduling.

The production ratio can be considered with the total processing time ( $TTP_{i,k}$ ) of each equipment, and  $TTP_{i,k}$  is defined with the processing time ( $TP_{i,j}$ ) and the introduced integer variables ( $I_{i,j,k}$ ) respective to each type as shown in Eq. (20).

$$TTP_{i,k} = \sum_{j=1}^{NE_i} TP_{i,j} \cdot I_{i,j,k} \quad (k = 1 \sim E_i) \quad (20)$$

where  $E_i$  is the given number of equipment units, and is set to  $MI_i$  in case of the initial plant configuration. Unifying the total processing time can be considered as the minimizing problem of maximum total processing time ( $CT$ ), and the objective function can be formulated as shown in Eq. (21) with the constraints shown in Eq. (22).

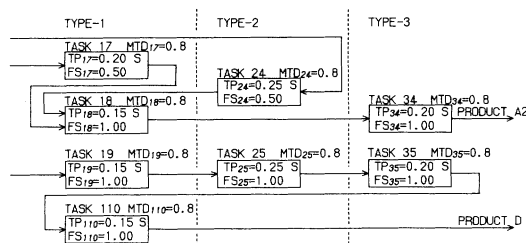
$$\min CT \quad (21)$$

$$CT \geq TTP_{i,k} \quad (k = 1 \sim E_i) \quad (22)$$

In addition to Eqs. (20) and (22), the following three constraints are necessary.

**Table 3.** Production requirements for illustrative example

	Product ( <i>h</i> )				
	A1	A2	B	C	D
$PR_h$	( $PR_A = 5000.0$ ) 2500.0 2500.0 2000.0 2500.0 1800.0				
$NB_h$	( $NB_A = 2$ ) 1 1 1 1 1				

**Fig. 7** Recipe data for products A2 and D

- 1) Minimum operating capacity for each equipment unit.
- 2) Prohibited tasks to carry out in the same equipment unit, if necessary.
- 3) Number of tasks carried out in each equipment unit.

The first and the second constraints have already been formulated into the linear combinations in IP model (1) as shown in Eqs. (10), (12) and (13). The third one is to assign all the introduced equipment to some task, and it can be expressed as shown in Eq. (23).

$$1 \leq \sum_{j=1}^{NE_i} I_{i,j,k} \leq NE_i \quad (k = 1 \sim E_i) \quad (23)$$

The equipment assignments to the tasks under the given number of equipment units are formulated into the IP model, and this model is called IP model (2) here. When this model is applied for the initial plant configuration of the small example respective to each type, the initial plant configuration is generated with the relative equipment sizes ( $VR_{i,k}$ ) as shown in Fig. 3.

Consequently, the initial plant configuration with minimum number of equipment units can be generated through IP model (1) and IP model (2), and the neighboring plant configurations can be generated through IP model (2) after increasing the number of equipment units respective to each type. The equipment sizes ( $V_{i,k}$ ) for these generated plant configurations are calculated through cyclic scheduling.

In the next section, the effectiveness of these IP models is demonstrated by solving an example design problem, and the evolutionary rule to search the optimal design is explained in this example. To solve IP model (1) and IP model (2), published software packages are available. In this study, the software AMPS by Fujitsu Ltd. on a Sun SPARCstation-IPX is used.

**Table 4.** Clean-up time for illustrative example

from	to				
	A1	A2	B	C	D
A1	-	-	0.5	1.0	1.0
A2	-	-	0.5	1.0	1.0
B	1.0	1.0	-	1.5	1.0
C	0.5	0.5	1.5	-	1.0
D	1.5	1.5	1.0	0.5	-

**Table 5.** Constants for cost estimation

Constant	Type ( <i>i</i> )		
	1	2	3
$\alpha_i$	250.0	350.0	300.0
$\beta_i$	0.6	0.6	0.6

### 3. Illustrative Example

In this section, an example design problem for a multipurpose batch plant producing four kinds of products (A, B, C and D) is solved by the developed evolutionary method. The production requirements and the recipe data (except for the charging and/or discharging time, and the stability of the intermediate products) for these products are shown in **Table 3**, Fig. 1 and **Fig. 7**. The number of batches of product A per cycle is two here, so that the total production volume for product A divided by two gives the relative batch sizes for the two independent products (A1 and A2) representing the product A as shown in Table 3. The recipe data for these two products are considered respectively in Figs. 1 and 7 (product A in Fig. 1 is A1 here). The transfer time for charging and/or discharging is fixed at 0.5, and all the intermediate products are assumed to be stable. Thus, holding the intermediate products in each equipment unit is allowed. The total production time available is 300, and the clean-up time for preparing the successive task in each equipment unit is shown in **Table 4**. The tasks for the same products in the first type are prohibited to carry out in the same equipment unit, the same as the previous section. The constants for the equipment cost of each type ( $\alpha_i$  and  $\beta_i$ ) are shown in **Table 5**.

The initial plant configuration with minimum number of equipment units is obtained through IP models (1) and (2), the equipment sizes for this initial plant configuration are optimized through cyclic scheduling as shown in **Fig. 8**, and the total equipment cost is obtained. From this initial design, the evolution is started by increasing the number of equipment units, and an evolutionary rule so as not to miss the optimal design is necessary.

In this study, the number of equipment units in each type is increased by one respectively, so that the neighbors for the number of types ( $NT$ ) are considered from the initial design. In this example, three neigh-

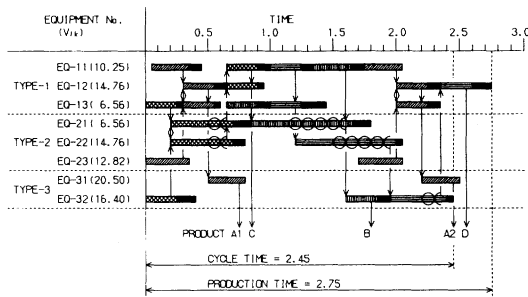


Fig. 8 One-cycle schedule for initial plant configuration

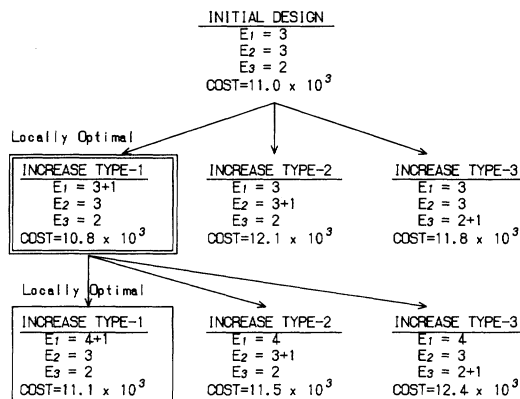


Fig. 9 Evolutionary search process

boring groups of equipment units can be considered from the initial design as shown in Fig. 9. The plant configurations and the total equipment costs for these neighbors can be obtained through IP model (2) and cyclic scheduling. Then the locally optimal design is obtained as shown in Fig. 9 by comparing the total equipment costs within these neighbors. This locally optimal design becomes the current design, because it is improved from the initial one. The evolution is continued from this current design, but the next locally optimal one is not improved from the current one in this example. Then the evolution is stopped, and the current design becomes the optimal one. The one-cycle schedule for this optimal design is shown in Fig. 10, and the results are summarized in Table 6.

The production ratio of equipment units in the type 3 is improved by increasing the number of equipment units in the first type as shown in Figs. 8 and 10. The cycle time for the optimal design is shortened from 2.45 to 2.05, and equipment sizes are decreased as shown in Table 6. This optimal design is found in the neighbors of the initial one, so that the initial plant configuration with minimum number of equipment units is appropriate as the starting point of searching.

## Conclusions

A design method for multipurpose batch plants on the basis of cyclic production is developed. The decision variables, namely the plant configuration and the equipment sizes, are interactive with each other through the

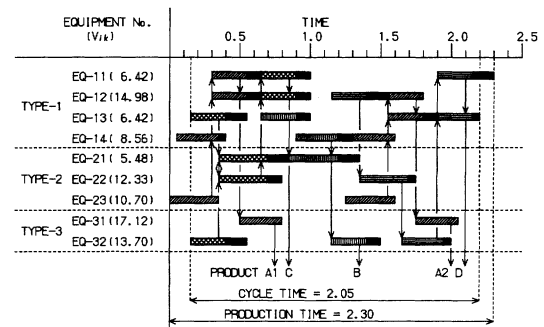


Fig. 10 One-cycle schedule for optimal plant configuration

Table 6. Summary

Type	Equipment	Initial Design				Optimal Design			
		$i$	EQ- $ik$	$VR_{i,k} (\times 10^2)$	$V_{i,k}$	$C_{i,k} (\times 10^3)$	$VR_{i,k} (\times 10^2)$	$V_{i,k}$	$C_{i,k} (\times 10^3)$
1	EQ-11			12.5	10.25	1.01	9.4	6.42	0.76
	EQ-12			18.0	14.76	1.26	21.9	14.98	1.27
	EQ-13			8.0	6.56	0.77	9.4	6.42	0.76
	EQ-14			-	-	-	12.5	8.56	0.91
2	EQ-21			8.0	6.56	1.08	8.0	5.48	0.97
	EQ-22			18.0	14.76	1.76	18.0	12.33	1.58
	EQ-23			15.6	12.82	1.62	15.6	10.70	1.45
3	EQ-31			25.0	20.50	1.84	25.0	17.12	1.65
	EQ-32			20.0	16.40	1.61	20.0	13.70	1.44
Total				11.0			Total	10.8	

cyclic scheduling. Only the evolutionary method is adoptable from the characteristics of this design problem, and the plant configuration is decided as the evolutionary variable to be searched. Then generating the initial and/or neighboring plant configurations becomes important.

To generate the initial and/or neighboring plant configurations, two parameters, namely the number of equipment units and the equipment assignments, should be decided, and two IP models (IP model (1) and IP model (2)) for these parameters are developed. IP model (1) provides the minimum number of equipment units, which is suitable for a feasible and nearly optimal initial plant configuration from the viewpoint of scale merit. The evolution is started with this minimum number of equipment units in this study, so that the number of units for the neighboring plant configurations can be provided by only increasing this number. Furthermore, the equipment assignments under the given number of equipment units should be decided for the initial and/or neighboring plant configurations, and IP model (2) optimizes these equipment assignments by unifying the production ratio of each equipment unit from consideration of the cycle time. The equipment sizes for these plant configurations can be optimized through cyclic scheduling.

The optimal design can be obtained by comparing the total equipment costs, and the effectiveness of the developed evolutionary design method is demonstrated through an example design problem.

## Nomenclature

<i>BR</i>	=	required relative task volume
<i>C</i>	=	cost
<i>CT</i>	=	maximum total processing time
<i>E</i>	=	number of equipment units
<i>FS</i>	=	size factor
<i>I</i>	=	integer variable
<i>J</i>	=	integer variable
<i>LN</i>	=	sufficiently large constant
<i>ME</i>	=	maximum number of equipment units
<i>MI</i>	=	minimum number of equipment units
<i>MTD</i>	=	minimum fraction of capacity
<i>NB</i>	=	number of batches per cycle
<i>NC</i>	=	number of cycles
<i>NE</i>	=	number of tasks
<i>NT</i>	=	number of types
<i>PR</i>	=	production requirement
<i>TC</i>	=	cycle time
<i>TH</i>	=	total production time available
<i>TP</i>	=	production time
<i>TTP</i>	=	total processing time
<i>V</i>	=	equipment size
<i>VI</i>	=	intermediate variable
<i>VR</i>	=	relative equipment size

$\alpha$	=	constant for cost estimation
$\beta$	=	constant for cost estimation

## <Subscripts>

<i>h</i>	=	product
<i>i</i>	=	type
<i>j</i>	=	task
<i>j1, j2</i>	=	prohibited tasks
<i>k</i>	=	equipment

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