DESIGN OF MULTIPURPOSE BATCH PLANTS WITH MULTIPLE PRODUCTION PLANS BASED ON CYCLIC PRODUCTION

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The design challenge in multipurpose batch plants is optimizing plant configuration and equipment size under the constraints of multiple production plans, and these decision variables are interactive with each other through scheduling. To optimize these decision variables, the evolutionary design method on the basis of cyclic production (cyclic scheduling) is appropriate, and batch composition of a cycle (number of batches and their relative batch sizes per one-cycle) for respective production plans should be specified beforehand. In this study, a method to specify the batch composition that enables optimal design is developed. From the viewpoint of optimizing plant configuration, the common batch sizes for a multiple number of production plans (core batch sizes) are introduced for each product, and specifying the batch composition on the basis of these core batch sizes is converted to assignment problems, from the viewpoint of optimizing equipment sizes. These assignment problems are formulated into IP (Integer Programming) models, and the optimal design satisfying multiple production plans becomes possible. The effectiveness of this method is demonstrated through an example problem.

Introduction

Multipurpose batch plants are suitable for producing a variety of high-value-added products through respective task sequences in low volume. These plants by nature are adaptable to a variety of production requirements. However, only well-designed plants can achieve such flexible production effectively.

In design of these plants, multiple production plans (production requirements and total production time available) and recipe data are specified beforehand, and the plant configuration (equipment units composing the plant) and equipment sizes become decision variables. These decision variables are strongly interactive with each other through scheduling, and all the production requirements of every production plan should be fulfilled simultaneously to consider flexibility in production. A few studies (for example, Shah and Pantelides, 1992, Wellons and Reklaitis, 1989) were concerned with multiple production plans, and the design problem was formulated into mathematical programming models. These models aimed to optimize the decision variables simultaneously regardless of their interaction through scheduling, so that an impractical simplistic in scheduling was necessary.

To consider the interaction between decision variables sufficiently, scheduling according to cyclic production (cyclic scheduling) is appropriate (Birewar and Grossmann, 1989). The authors developed an evolutionary design method on the basis of cyclic scheduling (Fuchino et al., 1994a), and the plant configuration was decided as an evolutionary variable. Firstly, a plant configuration was generated, and the relative equipment sizes were obtained. Secondly, the equipment sizes for this plant configuration were interpolated from their relative sizes through cyclic scheduling. These two steps were repeated until the total equipment cost was converged.

Essentially, each equipment unit is constrained by the minimum operating capacity ratio (Coulman, 1989, Fuchino et al., 1994a), and the generated plant configurations differ widely with batch composition of a cycle (number of batches and their relative batch sizes for each product per one-cycle). Therefore, to design batch plants on the basis of cyclic scheduling, the batch composition of each cycle for every production plan must be specified simultaneously before optimizing the decision variables. However, the previous study (Fuchino et al., 1994a) focused attention to the interaction between the decision variables through scheduling so that the batch composition of a cycle was assumed to be given.

The purpose of this study is developing a method to specify the batch composition of each cycle for every production plan to enable optimal design on the basis of cyclic scheduling. From the viewpoint of optimizing the plant configuration, the number of equipment units is preferably minimized, and common usage of them among the production plans should be increased. However, if different relative batch sizes are introduced for respective

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production plans, common usage of equipment units becomes difficult because of the constraint of minimum operating capacity ratio. Therefore, to optimize the plant configuration, each cycle should be composed of common batch sizes for a multiple number of production plans (core batch sizes). Then, the key to specify the batch composition of each cycle for every production plan is deciding the following three items.

1) Number of core batch sizes.
2) Relative core batch sizes.
3) Combinations of relative core batch sizes for each production plan.

Among these three items, the second and third ones can be considered only after the first one is fixed, and the first one can be decided with direct searching. Thus, the second and third items are considered for a given number of core batch sizes in this study.

On the other hand, to satisfy all the production plans,
minimize the number of batches for the critical production plan is minimizing that number uniformly for all production plans. It is necessary to consider that number within each product to decide the relative core batch sizes, and then their combinations are decided among the products through the production plans. Such problems can be categorized into the assignment problem, and two IP (Integer Programming) models are formulated in this study.

In the following sections, the characteristics of batch composition is analyzed, and the formulated IP models are explained. The effectiveness of the developed method to specify the batch composition is demonstrated through an example design problem.

1. Characteristic of Batch Composition

In this section, the characteristics of batch composition are analyzed by using a small example (example 1). Before design of batch plants, NP production plans, the recipe data for each product and data for the clean-up time are specified. In each production plan, the production requirements and the total production time available are specified, and the recipe data include the following information (Fuchino et al., 1994a)

1) Task sequences for each product.
2) Task type (i).
3) Processing time \( TP_{i,j} \) for \( j \)-th task in \( i \)-th task type.
4) Size factor \( FS_{i,j} \) for \( j \)-th task in \( i \)-th task type.
5) Minimum operating capacity ratio \( MTD_{i,j} \).
6) Charging and/or discharging time.
7) Stability of intermediate products.

In example 1, three products (A, B and C) and three production plans \( NP = 3 \) are considered. The production requirements in volumetric units \( PR_{h,k} \) for product \( h \) in the \( k \)-th production plan and the total production time available \( TH_k \) are shown in Table 1. The recipe data (except for 6) and 7) for these three products are shown in Fig. 1, and the tasks are classified into three types \( (i = 1 \ to \ 3) \) from the viewpoint of common usage of equipment units. The charging and/or discharging time is fixed at 0.05. All the intermediate products are stable here, and holding them in each equipment unit is allowed. The data for clean-up time, which varies with the successive products in each equipment unit, are shown in Table 2. Moreover, equipment units are prohibited to carry out multiple tasks for the same batch, and minimum operating capacity ratio \( MTD_{i,j} \) for all equipment units is 0.8, the same as the previous study (Fuchino et al., 1994a) here. Originally, scheduling in design of multipurpose batch plants consists of two sub-problems: the production scheduling and constrained resource scheduling, and these two sub-problems should be optimized simultaneously (Fuchino et al., 1994b). However, only production scheduling is considered here for ease of calculation.

In cyclic production, products are produced repeatedly in a cycle, so that the production requirement \( PR_{h,k} \) becomes relative production volume per one-cycle (Fuchino et al., 1994a). To generate the plant configuration, batch composition for respective \( NP \) \( (NP = 3 \) here) production plans satisfying the relative production volumes \( PR_{h,k} \) should be specified. If the number of batches per one-cycle for each product is assumed to be one, then the batch composition is fixed definitively as shown in Table 3. However, in this batch composition, the relative batch sizes
for each product differ with production plans. For example, the relative batch size of product A in the first production plan is 3000, but 2000 and 1000, respectively, in the second and third production plans. When design is considered for such batch compositions, common usage of equipment units among the production plans becomes difficult from the constraint of minimum operating capacity ratio. To work out this problem, core batch sizes are introduced, and two core batch sizes ($NCB_h = 2$) for each product $h$ (where $h = 1$ to 3) are considered here, from the viewpoint of optimizing plant configuration. When the relative core batch sizes ($BRC_{h,n}$, $n = 1$ to $NCB_h$) and their combinations as shown in Table 4 are assumed, then the relative production volume ($PR_{h,k}$) can be satisfied. In such batch composition, each $BRC_{h,1}$ is a common relative size for two production plans. For example, $BRC_{A,1} (= 2000)$ is
common for the first and second production plans, and BRC_{A-2} (= 1000) is common for the first and third ones. Moreover, the number of batches composing a cycle becomes four uniformly through the production plans.

For a given batch composition of a cycle as shown in Table 3, the decision variables can be optimized by using the previous evolutionary method (Fuchino et al., 1994a). Concerning the initial design, the minimum number of equipment units (M_{f,i}) for each task type (i) become five, three and three, respectively, and the relative equipment sizes (VR_{i,f}) are calculated by assigning the tasks to equipment units. The one-cycle schedules for each production plan can be made by using the production scheduling method (Fuchino et al., 1992) as shown in Figs. 2, 3 and 4. The cycle time and the production time are obtained, and the results are summarized in Table 5. The number of cycles (NC_{f}) is obtained in Eq. (1), and the necessary equipment sizes for respective production plans (V_{i,f}) are calculated by interpolating their relative sizes (VR_{i,f}) as shown in Eq. (2), and as explained in the previous study (Fuchino et al., 1994a).

\[ NC_{f} = \frac{TH_{f} - (PT_{f} - CT_{f})}{CT_{f}} \]  

(1)

\[ V_{i,f} = \frac{VR_{i,f}}{NC_{f}} \]  

(2)

where, PT_{f} and CT_{f} are the production time and the cycle time for the k-th production plan. The equipment sizes (V_{i,f}) should be the maximum of V_{i,f,k} to satisfy all the production requirements, as shown in Eq. (3).

\[ V_{i,f} = \max \{ V_{1,f,1}, V_{1,f,2}, \ldots, V_{1,f,n_{f}} \} \]  

(3)

Supposing the production requirements (PR_{i,f,k}) are specified for the same total production time available as shown in Table 1 (TH_{i} = 300; k = 1 to 3), and TH_{i} is sufficiently large compared with PT_{f} and CT_{f}, then NC_{f} is approximately in inverse proportion to CT_{f} as shown in Eq. (1). Thus, a production plan with the longest cycle time requires the maximum V_{i,f,n_{f}} and such a production plan is called critical here. To optimize the equipment sizes, it is necessary to shorten the cycle time of the critical production plan. In this example, cycle time for the third production plan is the longest as shown in Table 5, thus the third one becomes critical. Thus, equipment sizes (V_{i,f}) should be decided on the basis of the third production plan, and Table 6 is obtained. According to the schedules shown in Figs. 2 to 4 for this initial design, all the equipment units are commonly used among the production plans. Thus, introducing core batch sizes is appropriate from the viewpoint of optimizing the plant configuration, and three items; 1) number of core batch sizes, 2) relative core batch sizes, and 3) combinations of relative core batch sizes, should be decided.

Concerning these items, the relative core batch sizes and their combinations satisfying the production plans can be considered only for a given number of core batch sizes. Moreover, for a given batch composition on the basis of a fixed number of core batch sizes (NC_{f} = 2 here) as shown in Table 4, the initial design as shown in Table 6 can be obtained. If it is necessary to optimize the decision variables precisely, the evolutionary search should be continued from this initial one according to the previous study (Fuchino et al., 1994a). A suitable number of core batch sizes can be searched for directly by evaluating the results of design. Therefore, the relative core batch sizes and their combinations are considered for a given number of core batch sizes in this study, and these two items should be decided to minimize the cycle time of the critical production plan from the viewpoint of optimizing equipment sizes.

In deciding the batch composition with core batch sizes, the cycle time of each production plan can be evaluated with the number of batches composing each cycle. Therefore, the task of shortening the cycle time of the critical production plan can be converted into minimizing the number of batches uniformly through the production plans. In the batch composition for two core batch sizes shown in Table 4, 2000 and 1000 are adopted as the relative core batch sizes (BRC_{k,n}; n = 1 to 2) for each product satisfying the production requirements, and then combinations of these core batch sizes, which enable unification of the number of batches composing each cycle through the production plans, can be obtained. According to this batch composition, the number of batches within each product is also minimized to two, one each for the respective production plans. Consequently, to minimize the number of batches uniformly through the production plans, the relative core batch sizes should be decided within each product for the first step, and their combinations should be decided among the products. In this study, the above two optimization problems are formulated into IP models, and these models are explained in the next section.

### Table 5 Results of scheduling for example 1

<table>
<thead>
<tr>
<th>Production Plan ((k))</th>
<th>Cycle Time</th>
<th>Production Time</th>
<th>Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.60</td>
<td>1.70</td>
<td>187</td>
</tr>
<tr>
<td>2</td>
<td>1.40</td>
<td>1.80</td>
<td>214</td>
</tr>
<tr>
<td>3</td>
<td>1.80</td>
<td>1.80</td>
<td>166</td>
</tr>
</tbody>
</table>

### Table 6 Equipment sizes for example 1

<table>
<thead>
<tr>
<th>Type ((i))</th>
<th>Equipment Number ((l))</th>
<th>VR_{i,l}</th>
<th>V_{i,l}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1000</td>
<td>6.03</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>850</td>
<td>5.13</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>650</td>
<td>3.92</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>500</td>
<td>3.02</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>350</td>
<td>2.11</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1000</td>
<td>6.03</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1000</td>
<td>6.03</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>500</td>
<td>3.02</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1625</td>
<td>9.79</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1250</td>
<td>7.54</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>875</td>
<td>5.28</td>
</tr>
</tbody>
</table>
2. IP models

In this section, the two formulated IP models to decide the relative core batch sizes and their combinations are explained by using the three-gle example 1. The number of core batch sizes (NCB_h) for each product (h: h = A to C) is fixed at two here, the same as in the previous section. First, the relative core batch sizes (BRC_h,n; n = 1 to NCB_h) are explained.

BRC_h,n for given NCB_h should satisfy the production requirements (PR_h,k) through the production plans (k = 1 to NP), and deciding BRC_h,n can be considered as an assignment problem for respective products (h). In this study, a 0/1 integer variable (J_h,k,m,n) describing the conditions as shown in Eq. (4) is introduced for a product h, and then J_h,k,m,n must satisfy Eqs. (5) and (6).

\[
J_{h,k,m,n} = \begin{cases} 1 & \text{(product h is produced m times with n-th core batch sizes per one-cycle k-th production plan)} \\ 0 & \text{(otherwise)} \end{cases} \quad (4)
\]

\[
\sum_{m=1}^{MC_h} J_{h,k,m,n} \leq 1 \quad (k = 1 \text{ to } NP, n = 1 \text{ to } NCB_h) \quad (5)
\]

\[
\sum_{k=1}^{NP} \sum_{m=1}^{MC_h} J_{h,k,m,n} \geq 1 \quad (n = 1 \text{ to } NCB_h) \quad (6)
\]

where, MC_h is the limited times of batches for product h per one-cycle, and a reasonably large number should be used (MC_h = 3 here). Eq. (5) defines the production times (m) per one-cycle, and Eq. (6) forces use of core batches in some production plans. BRC_h,n should be decided to minimize the number of batches per one-cycle on average within each product, so that the objective function for this minimization problem can be defined as Eq. (7).

\[
\min \frac{\sum_{i=1}^{N} \sum_{j=1}^{C} \sum_{n=1}^{NCB_h} m \cdot J_{h,k,m,n}}{NP} \quad (7)
\]

Moreover, to formulate this minimization problem into the IP model, the relative sizes of core batches (BRC_h,n) and the relative production volume with n-th relative core batch size per one-cycle (RPV_h,k,m,n) are introduced as variables. Then, the following material balance equations are necessarily expressed in constraints as Eqs. (8) and (9).

1) Material balance between production requirements (PR_h,k) and RPV_h,k,m,n:

\[
PR_{h,k} = \sum_{n=1}^{NCB_h} RPV_{h,k,m,n} \quad (k = 1 \text{ to } MP) \quad (8)
\]

2) Material balance between BRC_h,n and RPV_h,k,m,n:

\[
RPV_{h,k,m} = \begin{cases} m \cdot BRC_{h,n} & \text{if } J_{h,k,m,n} = 1 \\ 0 & \text{if } \sum_{m=1}^{MC_h} J_{h,k,m,n} = 0 \end{cases} \quad (k = 1 \text{ to } MP, n = 1 \text{ to } NCB_h) \quad (9)
\]

Eq. (9) is a nonlinear constraint, but it can be linearized by setting up the boundaries with sufficiently large number (LN) and the introduced integer variables of Eqs. (10) and
expressed with linear combinations, and an IP model to decide $BRC_{b,n}$ for a given $NCB_{b}$ is formulated. When this model is applied for each product of example 1, the relative core batch sizes shown in Table 4 are obtained.

Second, the combinations of these core batch sizes are explained. Their combinations should be decided to minimize the number of batches composing each one-cycle uniformly. This unifying problem can be considered as minimizing the maximum number of batches through the production plans. The maximum number of batches ($MB$)

\[ LN \cdot (J_{k,l,m,n} - 1) \leq RP_{V_{b,k,n}} - m \cdot BRC_{b,n} \leq LN \cdot (1 - J_{k,l,m,n}) \quad (10) \]

\[ (k = 1 \text{ to } NP, \ m = 1 \text{ to } MX_{b}, \ n = 1 \text{ to } NCB_{b}) \]

\[ RP_{V_{b,k,n}} \leq LN \cdot \sum_{m=1}^{M_{b}} J_{b,k,m,n} (k = 1 \text{ to } NP, \ n = 1 \text{ to } NCB_{b}) \quad (11) \]

Therefore, the objective function and the constraints are
can be defined as Eq. (13) by using the 0/1 integer variables $(J_{h,k,m,n})$, and the objective function becomes Eq. (12).

$$\min MB$$  \hspace{1cm} (12)

<stand for>

$$\sum_{h=1}^{NCH} \sum_{k=1}^{MK} \sum_{m=1}^{MX} m \cdot J_{h,k,m,n} \leq MB(k = 1 \text{ to } NP)$$  \hspace{1cm} (13)

where $\Phi$ is a set of products. Moreover, the following two items should be described in constraints as shown in Eqs. (14) and (15).

1) Definition of the production times $(m)$ per one-cycle.

$$\sum_{n=1}^{NP} J_{h,k,m,n} \leq 1(k = 1 \text{ to } NP, n = 1 \text{ to } NCR_h, h \in \Phi)$$  \hspace{1cm} (14)

2) Material balance for the production requirements $(PR_{h,k})$.
Table 10 Results of scheduling for example 2

<table>
<thead>
<tr>
<th>Production Plan (k)</th>
<th>Cycle Time</th>
<th>Production Time</th>
<th>Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.20</td>
<td>2.65</td>
<td>136</td>
</tr>
<tr>
<td>2</td>
<td>2.10</td>
<td>2.85</td>
<td>142</td>
</tr>
<tr>
<td>3</td>
<td>2.35</td>
<td>2.65</td>
<td>127</td>
</tr>
<tr>
<td>4</td>
<td>2.15</td>
<td>2.70</td>
<td>139</td>
</tr>
</tbody>
</table>

Table 11 Equipment sizes for example 2

<table>
<thead>
<tr>
<th>Type (i)</th>
<th>Equipment Number (l)</th>
<th>VR_{l,i}</th>
<th>V_{l,i}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3000</td>
<td>23.63</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1250</td>
<td>9.85</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>625</td>
<td>4.93</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>500</td>
<td>3.94</td>
</tr>
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<td>5</td>
<td>5</td>
<td>375</td>
<td>2.96</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>313</td>
<td>2.47</td>
</tr>
</tbody>
</table>

| 2        | 1                    | 1250     | 9.85    |
| 3        | 2                    | 1250     | 9.85    |
| 4        | 3                    | 500      | 3.94    |

| 3        | 1                    | 2125     | 16.74   |
| 2        | 2                    | 1000     | 7.88    |
| 3        | 3                    | 875      | 6.89    |

\[
\sum_{h=1}^{NCB} \sum_{k=1}^{MK} \sum_{m=1}^{MX} m \cdot BRG_{h,n} \cdot J_{h,k,m,n} = PR_{h,k} \\
[h \in \Phi, k = 1 to NP] \quad (15)
\]

In Eq. (15), \( BRG_{h,n} \) is multiplied by \( J_{h,k,m,n} \). However, \( BRG_{h,n} \) is given in the first IP model, so that Eq. (15) is the linear constraint. Therefore, deciding the combinations of core batches can be formulated into an IP model. When this model is applied for example 1, the combinations shown in Table 4 are obtained. On the basis of these combinations, the optimal design satisfying all the production plan can be made by using the pervious method (Fuchino et al., 1994a), and one-cycle schedules for each production plan are obtained through the cyclic scheduling method (Fuchino et al., 1992) as shown Figs. 2, 3 and 4.

In the next section, the effectiveness of the developed method to decide the parameters for cyclic production is demonstrated by solving an example design problem. To solve IP models, published software packages are available. In this study, the software AMPS by Fujitsu Ltd. was used on a Sun SPARCstation-IPX.

3. Illustrative Example

In this section, an example design problem for a multipurpose batch plant (example 2) is solved. Four kinds of products (A, B, C and D) are planned to be produced, and four production plans shown in Table 7 are considered as the design basis. The recipe data (except for the charging and/or discharging time, and the stability of the intermediate products) for these products are shown in Fig. 1 and Fig. 5. The transfer time for charging and/or discharging is fixed at 0.05, and all the intermediate products are assumed to be stable. The clean-up time for preparing the successive task in each piece of equipment is shown in Table 8, and the tasks for the same batch in the first task type are prohibited from being carried out in the same equipment unit. Moreover, the number of core batches (NCB) for each product is fixed at two.

First, the relative core batch sizes are calculated for respective products, and second, the combinations of these relative core batch sizes are optimized by using the two formulated IP models. The batch composition as shown in Table 9 is obtained. On the basis of this batch composition, the plant configuration and the relative equipment sizes for the initial design are obtained. Moreover, the cyclic schedules for each production plan are made as shown in Figs. 6, 7, 8 and 9, and the third production plan is found to be critical as shown in Table 10. The equipment sizes are interpolated on the basis of this critical production plan as shown in Table 11.

In this initial design, all the production requirements of the production plans can be satisfied, and all the equipment units are commonly used through the multiple production plans as shown in Figs. 6 to 9. Moreover, the number of batches composing each cycle are minimized uniformly through the production plans, so that the preferable initial design for a given number of core batch sizes is obtained. To optimize the number of core batch sizes, changing this number, and design with the above procedure are to be carried out repeatedly. Furthermore, if the decision variables are optimized precisely, the evolutionary search should be started.

Conclusions

The design problem in multipurpose batch plants is optimizing plant configuration and equipment sizes under the constraints of multiple production plans, and these decision variables are interactive for each other through scheduling. To optimize these decision variables, the evolutionary design method on the basis of cyclic scheduling is appropriate, and batch composition of a cycle for respective production plans should be specified beforehand.

In this study, a method to specify the batch composition to enable the optimal design is developed. From the viewpoint of optimizing the plant configuration, core batch sizes are introduced for each product, and specifying the batch composition is converted into a problem to decide the following three items: 1) number of core batch sizes, 2) relative core batch sizes. 3) combinations of relative core batch sizes. Among these three items, the first one can be decided by direct searching, so that the remainder of two items are considered for a given number of core batch size in this study. From the viewpoint of optimizing equipment sizes, deciding these two items can be considered as the assignment problems under the constraints of production plans, and two IP models for these assignment problems are formulated. Consequently, the optimal design satisfying multiple production plans becomes possible, and the effectiveness of this method is demonstrated through an example problem.
Nomenclature

$BRC$ = relative core batch size
$CT$ = cycle time
$FS$ = size factor
$J$ = integer variable
$MB$ = maximum number of batches
$MI$ = minimum number of equipment units
$MTD$ = minimum operating capacity
$MX$ = limited times of batches per one-cycle
$LN$ = sufficiently large constant
$NC$ = number of cycles
$NCB$ = number of core batch sizes
$NP$ = number of production plans
$PR$ = production requirement in volumetric unit
$PT$ = production time
$RPV$ = relative production volume per one-cycle
$TH$ = total production time available
$TP$ = processing time
$v$ = necessary equipment size for a production plan in volumetric unit
$V$ = equipment size in volumetric unit
$VR$ = relative equipment size

$\phi$ = set of products

$i$ = task type
$j$ = task
$h$ = product

$k$ = production plan
$l$ = equipment unit
$n$ = core batch

Literature Cited


(Presented in part at the 59th Annual Meeting of the Society of Chemical Engineers, Japan at Sendai, March, 1994)