Intra-cell manpower transfers and cell loading in labor-intensive manufacturing cells

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Abstract

Labor-intensive manufacturing cells consist of simple machines and equipment that require continuous operator attendance and involvement. Operators are often re-assigned to different machines when a new product is released to the cell. The main reason for this re-assignment is to maximize the output rate of the cell by balancing the flow of products through several machines with varying capacities. In this paper, first a product-sequencing problem with the objective of minimizing the total intra-cell manpower transfers is introduced. A three-phase hierarchical methodology is proposed to solve the problem optimally. Next, manpower transfer matrix values are modified considering the distances traveled among machines. In the second part of the paper, a machine-level-based similarity coefficient that uses the number of machines as a similarity measure is discussed. Later, these coefficients are used during the cell loading process to minimize makespan and also machine and space requirements. Manpower allocation decisions are made along with scheduling decisions that are critical in most labor-intensive manufacturing cells and both approaches are illustrated with an example problem.

Keywords: Cell loading; Manpower transfers; Labor-intensive manufacturing cells

1. Introduction

This paper focuses on labor-intensive cells where most of the operations require light weight, and small machines and equipment that require continuous operator attendance and involvement. Therefore, the assignment of operators to machines directly affects the output of the cell. The number of operators is...
greater than the number of operations. Therefore, it is expected that multiple-operators will be assigned to each operation as long as there are sufficient equipment and machinery. However, the number of operators needed for each operation might vary from one product to the next based on the balance due to different processing times. This requires operators to be continuously shifted among operations. As the number of products assigned to a cell increases, keeping track of operators and their correct assignments become increasingly difficult thus leading to a chaotic situation at times on the shop floor. In most companies, the supervisors in charge of operations in cell(s) are also expected to participate in various meetings, training sessions, and presentations, and they are not always available to supervise their cells on a continuous basis. One of the objectives of this study is to smooth the operations in a cell by sequencing products to minimize intra-cell manpower transfers.

On the other hand, moving equipment and machinery in labor-intensive manufacturing cells is not as difficult as in machine-intensive cells. Sometimes machines can be even on wheels, which make re-location much easier. Manufacturing cells can be quickly re-configured based on the product to be run. Although convenient, this flexibility at times brings complexity to the manufacturing system. In some cases, keeping track of equipment and machinery may become a challenging task. It is not unusual to try to locate where the equipment/machinery is. It requires a lot of co-ordination to move them from one cell to another in a multi-cell environment as many cells compete for them. Furthermore, exact schedule of machine/equipment requirements in cells is hardly known in advance. Even though the machines may not be expensive, procurement leadtimes and space limitations still force companies to use what they have efficiently. Some of these concerns can be handled at the cell loading level by carefully assigning products to cells considering their similarity with respect to the number of machines and equipment they need. Another objective of this study is to propose such a cell loading procedure.

Labor-intensive manufacturing cells can be found in apparel industry, jewelry manufacturing, shoe manufacturing, medical device industry, and some assembly operations among others. The best utilization of resources become very important and any improvement contributes to the survivability of the company.

2. Literature review

In previous work related to manpower decisions, Dagli and Süer (1986) developed a two level approach for determining appropriate manpower levels in the assembly line. Yano and Rachamadugu (1991) discussed the use of utility workers in the overloaded parts of the assembly line. Süer and Dagli (1994) developed a knowledge-based system to evaluate the performance of six rules and six algorithms they have recommended for resource allocation in highly flexible manufacturing environments. Lee and Vairaktarakis (1993) discussed the sequencing of products to minimize the total manpower requirements during all production cycle times. Russell, Huang, and Leu (1991) evaluated the performance of different labor scheduling policies and labor allocation strategies in a manufacturing cell. Wirth, Mahmoodi, and Mosier (1993) studied labor scheduling policies along with group scheduling heuristic in their study.

In the literature, only a few works have been reported addressing cell-loading issues. Greene and Cleary (1985) and Greene and Sadowski (1984) mentioned scheduling issues, benefits, drawbacks and system variables in a cellular manufacturing environment. Espino (1991) explained four cell loading algorithms to deal with the cell loading problem. Two of the algorithms she used were of product priority

3. Intra-cell manpower transfers

This paper focuses on two main issues: (1) product sequencing in a cell such that intra-cell manpower transfers will be minimized and (2) cell loading such that similar products will be assigned to cells to minimize machine and thus space requirements.

In this section, we will focus on the first issue. The problem on hand is to sequence \( n \) products in a labor-intensive manufacturing cell such that the total intra-cell manpower transfers is minimized. The number of operations \( s \) that can be performed in the cell is less than the total manpower available \( W \). Since no operator is allowed to be idle, some of the operations are performed on multiple identical machines by using multiple manning.

The total manpower available \( W \) is allocated to \( s \) operations of product \( i \) thus obtaining manpower levels for operation \( j \) \((m_{ij} \text{ for } j = 1, 2, \ldots, s)\). Even though all the products assigned to the cell have the same or very similar routings, the values of \( m_{ij} \) and \( m_{kj} \) for operation \( j \) may drastically vary for any product pair \((i) \) and \((k)\) depending upon their operation times. As a result, the manpower level for each operation may have to be modified when a new product is released to the cell. This causes a lot of traffic in narrowly spaced cells that lead to interruptions and further delays in production. Furthermore, keeping track of what the manpower level is or should be for each operation creates supervision problems as well. This also leads to longer preparation times for re-configuring the cell, moving the necessary machinery and equipment around and re-arranging them before production starts. The objective of this phase is to find the optimal sequence of products assigned to a cell to minimize the total intra-cell manpower transfers.

The problem introduced in this paper is especially significant in a JIT environment where uniform scheduling principles are adapted with short and frequent runs of product mix. The number of products included in the sequence as well as the variations in operation times from one product to the next contribute to the significance of the problem.

4. Solution methodology for minimizing manpower transfers

A three-phase methodology is proposed to solve the problem optimally. Even though, this objective has not drawn much attention in the literature so far, it can be seen in various industries listed before.

The proposed three-phase methodology is described as:

1. Finding optimal manpower levels

A mathematical programming model is developed to find the optimal manpower levels for each operation. The model is run for each product independently.
2. Forming sequence-dependent manpower transfer matrix
   A matrix showing the total number of manpower transfers between all pairs of products is formed. The elements of the matrix are determined based on the results of the previous phase.

3. Solving traveling salesman problem
   Finally, the problem is treated as a traveling salesman problem (TSP) to find the optimal sequence of products so that the total manpower transfers is minimized.

   An example from a real manufacturing environment is provided to facilitate the discussion of the procedure.

4.1. An example

   The example used in this paper is drawn from a jewelry manufacturing company. Assume that six products have been assigned to the cell. The standard time for operation \( j \) of product \( i \) is denoted by \( t_{ij} \) and they are given in Table 1. The value of \( W \) is 30 considering the space limitation and workstation arrangements.

4.2. Phase I—finding optimal manpower levels

   In this section, an integer-programming model is formulated to maximize the production rate and determine the optimal manpower levels for each operation. The proposed model is solved for each product independently. The decision variables are the production rate for product \( i \), \( R_i \), and manpower levels (number of machines) for each operation \( (m_{ij}, \text{ for } j = 1, 2, \ldots, s) \) of product \( i \). The upper limit for manpower level for operation \( j \) of product \( i \) is denoted by \( U_{ij} \). The values of \( U_{ij} \) are determined based on the maximum of number of machines or number of operators capable of performing operation \( j \). The formulation of the model is as follows:

   **Objective function:**

   \[
   \text{Max } Z = R_i
   \]  \hspace{1cm} (1)

---

**Table 1**

<table>
<thead>
<tr>
<th>Product</th>
<th>Operation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.07</td>
<td>0.45</td>
<td>0.37</td>
<td>0.88</td>
<td>0.38</td>
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<tr>
<td>2</td>
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<td>0.62</td>
<td>0.29</td>
<td>0.38</td>
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<tr>
<td>3</td>
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<td>0.29</td>
<td>1.18</td>
<td>0.86</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.04</td>
<td>0.31</td>
<td>0.55</td>
<td>0.47</td>
<td>0.40</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.08</td>
<td>0.41</td>
<td>0.43</td>
<td>1.38</td>
<td>0.43</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.07</td>
<td>0.32</td>
<td>1.18</td>
<td>0.55</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Subject to:

\[(m_{ij} \times (1/t_{ij}) - R_i) \geq 0, \quad j = 1, 2, 3, \ldots, s\]  \hspace{1cm} (2)

\[m_{ij} \leq U_{ij}, \quad j = 1, 2, 3, \ldots, s\]  \hspace{1cm} (3)

\[\sum_{j=1}^{s} m_{ij} \leq W\]  \hspace{1cm} (4)

\[m_{ij}, \text{integer and positive for all } i \text{ and } j,\]
\[R_i, \text{integer and positive.}\]

The objective is to maximize the production rate as given in Eq. (1). Eq. (2) guarantees that manpower level assigned to operation \((j)\) is sufficient to reach to the desired production rate. Eq. (3) establishes the upper limits on manpower levels for each operation and finally (4) specifies the upper limit on the total manpower level. The results of the model for each product included in the example are given in Table 2; they have been determined by using a mathematical programming package.

4.3. Phase II—forming sequence-dependent manpower transfer matrix

In this section, the results of the optimal manpower allocation phase are used to form the sequence-dependent manpower transfer matrix. Assume that product 3 is run after product 1. Optimal manpower allocation for product 1 is given in Fig. 1a. After the entire batch of product 1 is completed, product 3 is released to the cell. The number of operators for the first operation remains the same. Two of the operators of operation 2 are transferred to operation 3. Similarly, two more operators are transferred to operation 3 from operation 4. Finally, four operators are transferred from operation 5 to operation 3 as shown in Fig. 1b. The final configuration given in Fig. 1c is obtained with a total of eight operator transfers. The following relation is used for each

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal manpower levels</td>
</tr>
<tr>
<td>Product</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>
product pair to find the elements of the transfer matrix.

$$c_{ik} = \begin{cases} \max\{m_{ij} - m_{kj}, 0\} & \text{for } i = 1, 2, \ldots, n; \ k = 1, 2, \ldots, n \text{ and } (i) \text{ and } (k) \text{ are distinct} \\ M & \text{for } i = k, \ i = k = 1, 2, \ldots, n \end{cases}$$

where

- $c_{ik}$ manpower transfers required to run product $(k)$ after product $(i)$
- $M$ a very large number.

Referring back to the case discussed above, application of the formula would produce the following result:

$$C_{13} = \max\{m_{11} - m_{13}, 0\} + \max\{m_{12} - m_{32}, 0\} + \max\{m_{13} - m_{33}, 0\} + \max\{m_{14} - m_{34}, 0\} + \max\{m_{15} - m_{35}, 0\} = \max\{1 - 1, 0\} + \max\{6 - 4, 0\} + \max\{5 - 13, 0\} + \max\{12 - 10, 0\} + \max\{6 - 2, 0\} = 0 + 2 + 0 + 2 + 4 = 8$$

The manpower transfer matrix is a symmetrical one, that is, the manpower transfers required to run product $(i)$ after product $(k)$ is exactly the same as running product $(k)$ after product $(i)$. The elements of the transfer matrix for the example problem are calculated from the results presented in Table 2 and these values are given in Table 3.
4.4. Phase III—application of traveling salesman approach

Having formed the sequence-dependent manpower transfer matrix, the last step is to treat the problem as a traveling salesman problem (TSP) and find the optimal sequence of products to minimize the total number of manpower transfers in the cell.

Besides optimizing procedures such as branch and bound and dynamic programming, some heuristic procedures such as nearest-neighbor and cheapest-insertion are also available. The complexity of the problem on hand and the execution time requirements affect the procedure to be chosen. In this paper, the branch and bound procedure developed by Little, Murty, Sweeney, and Karel (1963) is used to solve this problem. The optimal sequence for the example problem is given as (5–1–4–2–6–3–5) with a total of 24 manpower transfers.

4.5. Modified version of the manpower transfer matrix

In this section, manpower transfer matrix values are modified considering the distances traveled between operations. This might be important if a cell consists of several different operations and/or the distances between operations are significant. A new relation is defined to handle this problem as shown here:

\[ w_{ik} = \begin{cases} \sum \sum U_{ijkl} d_{jl} & \text{for } i = 1, 2, \ldots, n; k = 1, 2, \ldots, n \text{ and } (i) \text{ and } (k) \text{ are distinct} \\ M & \text{for } i = k, i = k = 1, 2, \ldots, n \end{cases} \]

where

- \( w_{ik} \) weighted manpower transfer value for running product (k) after product (i)
- \( U_{ijkl} \) number of operators to be transferred from operation (j) of product (i) to operation (l) of product (k)
- \( d_{jl} \) distance between operation (j) and operation (l).

The example problem discussed previously is used assuming that the cell is linear and the distances between the operators are identical. As a result, unit weights are considered between any neighboring operations. Returning back to the case discussed in Section 4.4, two operators transferred from operation (2) to operation (3) \((U_{1234} = 2)\) and from operation (4) to operation (3) \((U_{1433} = 2)\) will move unit distances \(d_{23} = d_{43} = 1\). However, four operators who are transferred from operation (5) to operation (3)
(U_{1533} = 4) will have to move two unit distances (d_{53} = 2). Therefore, the entry in the matrix is modified as 12 (= 2*1 + 2*1 + 4*2). The results of the modified version of the sequence-dependent manpower transfer matrix are given in Table 4. The optimal sequence for the weighted version remains the same as before (5–1–4–2–6–3–5) with a total of 28 unit transfers.

5. Cell loading

In this section, the paper deals with the second main issue, namely cell loading. Cell loading involves determining to which cell, among the feasible cells, products should be assigned. This requires three major decisions: (1) selecting a product, (2) selecting a cell and (3) determining the order of products in the cell. If a product is selected first and then a feasible cell is chosen, this type of search is called ‘product priority’. If the search process is reversed, then it is called ‘cell priority’. Once products have been assigned to cells, the order of products in each cell can be determined by using a procedure determined based on the desired performance measure. The overall objectives of a cell loading process are to minimize the work-in-process inventory, minimize lateness, maximize the utilization of the cells and balance the load among the cells among others. In this study, it is assumed that the cells are independent, i.e. the raw materials arrive at the cell at one end and the finished products come off the cell at the other end without visiting any other cell for processing.

6. Cell loading methodology

The primary objective of cell loading is to minimize makespan and the secondary objective is to minimize the number of machines. Obviously, this also helps to reduce intra-cell manpower transfers, which was targeted in the earlier part of this paper. Makespan is defined as the maximum of all completion times (C_{max}). First several available methods for minimizing makespan are discussed and then the machine-level-based similarity coefficient is introduced and later the proposed approach is illustrated with an example.

6.1. Minimizing makespan

In this section, several approaches for minimizing makespan are discussed.
6.1.1. Mathematical programming formulation

The objective is to minimize makespan as given in the objective function (Eq. (5)). The first constraint guarantees that Makespan will not be smaller than any of the $C_{\text{max}}$ on each cell (Eq. (6)). The second constraint ensures that each job is assigned to only one cell (Eq. (7)).

Objective function:
\[
\text{Min } Z_0 = \text{MS} \tag{5}
\]

Subject to:
\[
\text{MS} - \sum_{i=1}^{r} p_i X_{ij} \geq 0, \quad 1 \leq j \leq f \tag{6}
\]
\[
\sum_{j=1}^{f} X_{ij} = 1, \quad 1 \leq i \leq r \tag{7}
\]

where
\[
X_{ij} = 1 \text{ if job } i \text{ is assigned to cell } j \text{ and 0 otherwise.}
\]
\[
r \text{ total number of products}
\]
\[
f \text{ number of cells}
\]
\[
\text{MS makespan}
\]
\[
p_i \text{ batch processing time for product } i.
\]

6.1.2. Heuristic procedure

The following heuristic procedure can also be used to minimize makespan in cell loading.

1. Order products by largest processing time (LPT).
2. Assign products to the cells based on minimum load.

6.1.3. Mathematical model when lot-splitting allowed

This is exactly the same model discussed in this section earlier except that decisions variables are allowed to take real values.

6.1.4. McNaughton's algorithm

When lot splitting is allowed, the algorithm developed by McNaughton (1959) can be used to find the optimal solution fast. This procedure ignores set-up times. The optimal makespan is computed as shown in Eq. (8).

\[
\text{Optimal makespan } = \text{MS}^* = (1/f) \sum_{i=1}^{r} p_i \tag{8}
\]

The algorithm is given in the following steps:

1. Select a product to begin on cell 1 at time zero.
2. Choose any unscheduled product and schedule it as early as possible on the same cell. Repeat this until the cell is occupied beyond MS* (or until all jobs are scheduled).
3. Re-assign the processing scheduled beyond MS* to the next cell starting at time zero.

6.2. Machine-level-based similarity coefficient

Su¨er and Ortega (1994) proposed machine-level-based similarity coefficient (MLB-SC\textsubscript{ij}) that measures not only processing similarity but indeed more importantly machine-level similarity between products (i) and (j) as given in the following relation:

\[
MLB-SC_{ij} = \left( \frac{\sum_{k=1}^{s} \min(m_{ki}, m_{kj})}{\sum_{k=1}^{s} \max(m_{ki}, m_{kj})} \right)
\]

(9)

These similarity coefficient values are used during the cell loading process as described in Section 6.3.

6.3. The proposed cell loading procedure

The proposed procedure modifies McNaughton’s algorithm to consider machine-level similarities among products during the assignment process. Having determined MS*, the proposed procedure continues with the following steps:

1. Select a product to begin on cell 1 at time zero.
2. Choose the unscheduled product with maximum similarity to the last assigned product and schedule it as early as possible on the same cell. Repeat this until the cell is occupied beyond MS* (or until all products are scheduled).
3. Re-assign the processing scheduled beyond MS* to the next cell starting at time zero.

Obviously, the output of this heuristic approach is affected by the first product selected. Therefore, based on the desired solution quality and time available to solve the problem, the user may repeat

Table 5
Optimal manpower levels and production rates for the example problem

<table>
<thead>
<tr>
<th>Product</th>
<th>Operations</th>
<th></th>
<th></th>
<th></th>
<th>Production rate (units/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>5</td>
<td>12</td>
<td>6</td>
<td>13.32</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>12</td>
<td>5</td>
<td>7</td>
<td>17.20</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>13</td>
<td>10</td>
<td>2</td>
<td>10.92</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>16.10</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>14</td>
<td>5</td>
<td>10.08</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>13</td>
<td>7</td>
<td>5</td>
<td>10.92</td>
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<td>5</td>
<td>9</td>
<td>8</td>
<td>6</td>
<td>13.04</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>11</td>
<td>9</td>
<td>5</td>
<td>9.78</td>
</tr>
<tr>
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<td>5</td>
<td>10</td>
<td>11</td>
<td>3</td>
<td>11.49</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>6</td>
<td>10.29</td>
</tr>
</tbody>
</table>
this procedure with up-to-\( n \) different starting products and then compare the results and finally select the best.

6.4. An example

Assume that manpower levels given in Table 5 have been determined for a crew size of 30 operators using the mathematical model introduced in Section 4.2.

The similarity coefficients are summarized in Table 6. For example, the similarity between products (1) and (2) is computed as follows:

\[
\text{MLB-SC}_{12} = \frac{\min\{1, 1\} + \min\{5, 6\} + \min\{5, 12\} + \min\{12, 5\} + \min\{6, 7\}}{\max\{1, 1\}} \\
+ \frac{\max\{5, 6\} + \max\{5, 12\} + \max\{12, 5\} + \max\{6, 7\}}{\max\{1, 1\}} \\
= \frac{[1 + 5 + 5 + 5 + 6]}{[1 + 6 + 12 + 12 + 7]} = \frac{22}{38} = 0.58
\]

Having determined the similarity coefficients, the next step is to determine MS*. Batch processing times are computed dividing demand by the optimal production rate and the results are given in Table 7.

Table 6
Machine-level-based similarity coefficients

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>( M )</td>
<td>0.58</td>
<td>0.58</td>
<td>0.72</td>
<td>( 0.88 )</td>
<td>0.58</td>
<td>0.72</td>
<td>0.67</td>
<td>0.72</td>
<td>0.85</td>
</tr>
<tr>
<td>P2</td>
<td>0.58</td>
<td>( M )</td>
<td>0.67</td>
<td>0.90</td>
<td>0.54</td>
<td>0.82</td>
<td>0.77</td>
<td>0.77</td>
<td>( 0.67 )</td>
<td>0.69</td>
</tr>
<tr>
<td>P3</td>
<td>0.58</td>
<td>( 0.67 )</td>
<td>( M )</td>
<td>0.67</td>
<td>0.58</td>
<td>0.82</td>
<td>0.67</td>
<td>0.82</td>
<td>0.82</td>
<td>0.69</td>
</tr>
<tr>
<td>P4</td>
<td>0.72</td>
<td>0.90</td>
<td>0.67</td>
<td>( M )</td>
<td>0.67</td>
<td>0.77</td>
<td>( 0.94 )</td>
<td>0.82</td>
<td>0.67</td>
<td>0.85</td>
</tr>
<tr>
<td>P5</td>
<td>0.88</td>
<td>0.54</td>
<td>0.58</td>
<td>0.67</td>
<td>( M )</td>
<td>0.58</td>
<td>0.67</td>
<td>0.67</td>
<td>0.72</td>
<td>( 0.79 )</td>
</tr>
<tr>
<td>P6</td>
<td>0.58</td>
<td>0.82</td>
<td>( 0.82 )</td>
<td>0.77</td>
<td>0.58</td>
<td>( M )</td>
<td>0.77</td>
<td>0.88</td>
<td>0.72</td>
<td>0.69</td>
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<tr>
<td>P7</td>
<td>0.72</td>
<td>0.77</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.77</td>
<td>( M )</td>
<td>( 0.82 )</td>
<td>0.77</td>
<td>0.85</td>
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<tr>
<td>P8</td>
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<td>0.77</td>
<td>0.82</td>
<td>0.82</td>
<td>0.67</td>
<td>( 0.88 )</td>
<td>0.82</td>
<td>( M )</td>
<td>0.82</td>
<td>0.79</td>
</tr>
<tr>
<td>P9</td>
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<td>0.67</td>
<td>0.82</td>
<td>0.67</td>
<td>0.72</td>
<td>0.72</td>
<td>0.77</td>
<td>0.82</td>
<td>( M )</td>
<td>0.79</td>
</tr>
<tr>
<td>P10</td>
<td>0.85</td>
<td>0.69</td>
<td>0.69</td>
<td>( 0.85 )</td>
<td>0.79</td>
<td>0.69</td>
<td>0.85</td>
<td>0.79</td>
<td>0.79</td>
<td>( M )</td>
</tr>
</tbody>
</table>

Table 7
Batch processing time computations

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (units)</td>
<td>2000</td>
<td>4000</td>
<td>3000</td>
<td>2500</td>
<td>2000</td>
<td>1500</td>
<td>2500</td>
<td>1000</td>
<td>2500</td>
<td>3000</td>
</tr>
<tr>
<td>Production rate (units/min)</td>
<td>13.32</td>
<td>17.20</td>
<td>10.92</td>
<td>16.10</td>
<td>10.08</td>
<td>10.92</td>
<td>13.04</td>
<td>9.78</td>
<td>11.49</td>
<td>10.29</td>
</tr>
<tr>
<td>Batch processing time (h)</td>
<td>2.50</td>
<td>3.88</td>
<td>4.58</td>
<td>2.59</td>
<td>3.30</td>
<td>2.29</td>
<td>3.20</td>
<td>1.70</td>
<td>3.63</td>
<td>4.86</td>
</tr>
</tbody>
</table>
The optimal makespan, $M_*^{S}$, is determined as 10.85 h, assuming three identical cells with 30 people each. The assignment process starts with randomly chosen product 1. The next product that has the maximum similarity with product 1 is product 5 and it is assigned to the first cell. Product 10 follows product 5 and it is scheduled to be completed at 10.67 h. Finally, product 4 is selected as the next product and it is run on that machine only for 0.18 h. The remaining balance of 2.41 h processing is done on cell 2. The procedure continues until all products are assigned. The final schedule is given in Fig. 2.

### 7. Conclusions

This paper discusses various approaches for cell loading and manpower allocation. A well-known parallel machine scheduling procedure is modified to adapt it to the cell loading by considering similarities among products with respect to the similarity of number of machines needed. As the similar products are grouped in the same cell, the number of machine requirements and thus space requirements are also minimized. Furthermore, this also reduces the need for a major reconfiguration of cellular layout. Finally, having completed cell loading, the paper also discusses the product sequencing to minimize intra-cell manpower transfers to simplify the operational control and smooth out the operations in the cell. Another implicit benefit of this work is that the need for diverse skill requirements is minimized. This also minimizes training costs that would be necessary otherwise. One of the future works considered though is to map the available skills with required skills per operator basis.

The cell loading methodology proposed in this paper is applied in every period to meet new demand figures. As the demand changes drastically, it might be necessary to adjust the manpower levels as well. Moreover, as new products are added to or dropped from the list, similarity coefficient values will have to re-computed. It is believed that the approaches proposed in this paper will simplify operations in most labor-intensive manufacturing cells.

### References


**Further reading**