CHAPTER 9

9.0 SCHEDULING OF FLEXIBLE MANUFACTURING CELL

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9.1 INTRODUCTION

The world has witnessed spectacular progress of Flexible Manufacturing Systems (FMS) during the recent years. At present, the most feasible approach for automation, of the job shop is through FMC. Recently, FMC has evinced more interest as a new manufacturing system for low-volume, high variety applications with cost effectiveness. A typical FMC has two or three machines with a robot for inspection and internal material handling. In any shop-floor, scheduling is a day-to-day problem and the total manufacturing time plays a major role in the productivity of FMC.

9.2 IDENTIFICATION OF THE PROBLEM

The set-up operation of components, especially, centering is the most important and complicated operation in the flexible machining cell. However, this centering of components has not yet been automated at present time in automated job shops. Hence a FMC has been considered consisting of a machining center, an industrial robot, a loading/unloading station and an index-pallet changer with work piece clamping stands. This kind of FMC is considered for analysis as a two-machine flow-shop problem with finite buffer spaces that is fully automated for setting (centering) and machining operations.

Deterministic flow-shop sequencing problems have received considerable attention over the past two decades, as reported by Conway[69] and Elmaghraby [82], chapter-2. Based on this survey, the problem is of sequencing N components on the two-machines of a flow-shop with finite-intermediate storage has been taken for the analysis to minimise total manufacturing time.
9.3 CONSTRUCTIONAL FEATURES OF FMC

The FMC considered in this work comprises of a machining center, an industrial robot, a loading/unloading station and an index-pallet changer as shown in Fig.9.1. The industrial robot performs two functions - handling and the positioning of components. A number of clamping stands are installed on an index-pallet changer to hold the components. While a component mounted on one of the clamping stands is being machined on the machining center, the other component is positioned on another clamping stand by the industrial robot. The remaining clamping stands serve as buffer stations. Thus both machining and positioning operations can be simultaneously performed in the FMC.

The clamping stand has a number of fingers for clamping a component as shown in Fig. 9.2 (photographic view obtained from the computer). Each of the fingers can be independently driven by stepper motors. These fingers serve as a fixture. They may be exchanged for other fingers having suitable shapes corresponding to component configurations. Figure 9.3 shows the full configuration of the measuring axes \( k, k+1, k+2, \ldots, k+N \) for the centering operation which are defined on the clamping stand. There are several reference points on these measuring axes, \( k \) and \( k+1 \). In this example two reference points, \( i^k \) and \( j^k \), are determined on a measuring axis \( k \). By approaching the measuring probe in the direction \( u_i^k \) from the reference point \( i^k \), the difference between the reference point and the contour point of a component is measured. The difference from another reference point \( j^k \) can be measured in a similar manner. Thus the difference between the center of a clamping stand and the center of a component is identified by the industrial robot with the measuring probe. All of these operations are systematically controlled by a microcomputer.
Fig. 9.1 CONSTRUCTIONAL FEATURES OF FMC

Fig. 9.2 CLAMPING FINGERS WITH AUTOMATIC SETUP
9.3.1. CONTROL SYSTEM OF FMC

This FMC is controlled by two kinds of computers, a supervisory computer and a dedicated microcomputer. The supervisory computer conducts the process planning and scheduling of processing components. Based on the results, the driving units of the clamping stand, the index-pallet changer, the industrial robot and the controller of the measuring probe are systematically controlled by the dedicated microcomputer, which is connected to the supervisory computer on-line. This hierarchical computer control of the overall system is schematically illustrated in Fig. 9.4. The FMC can be efficiently operated based on the optimum process planning and scheduling through these supervisory and dedicated microcomputers.
9.3.2. CONTROL ALGORITHM OF FMC

The FMC considered for this study is operated according to the control algorithm as follows.

STEP 1

Identify whether or not any clamping stand on the index-pallet changer are empty. If there are any components on the loading station, one of the component is transported to one of the empty clamping stands by a robot; go to STEP 3. If there is no empty clamping stand or no component on the loading station, go to STEP 2.
STEP 2

If the machining of a component has been completed on any clamping stand, it is transported to the unloading station by a robot; return to STEP 1. If all the clamping stands are empty, the operation of FMC is stopped (END).

STEP 3

Using the measuring probe, the centering operation is done on the clamping stand as follows.

3.1

Determine the number of measuring axes, N. Set k = 1.

3.2

On axis k, measure the difference $|u^k_i|$ between the reference point $i^k$ and the contour point of the component by approaching the measuring probe in direction $u^k$, from the reference point $i^k$. Also measure the difference $|u^k_j|$ from the reference point $j^k$ in a similar manner.

3.3

Correct the position of a component in direction $u^k_i$ or $u^k_j$ on axis k by using a finger mounted on the clamping stand, such that $|u^k_i|$ becomes equal to $|u^k_j|$.

3.4

If $k = N$, go to STEP 3.3. Otherwise, go to STEP 3.5.
3.5
Replace k with k+1, and return to STEP 3.2.

3.6
If a component is fixed with four fingers mounted on the clamping stand, go to STEP 4. Otherwise, after clamping the component with four fingers, return to STEP 3.1.

STEP 4
After finishing the centering operation, a component is directly transported to the machining center. Otherwise, it is transported to the buffer spaces, and waits until the machining starts on the machining center. Return to STEP 1.

9.4 ASSUMPTIONS
1. This is a deterministic flow shop sequencing problem i.e. N components are simultaneously available.

2. Robot and Machining Center can be operated simultaneously.

3. Either robot or machining center may not process more than one component at a time, nor may a component be processed by robot and machining center simultaneously.

4. The processing times of ith component(1 ≤ i ≤ N) on the Robot and Machining Center, denoted A[i], B[i] respectively, are known constants.

5. There is a buffer of some known finite capacity designated by Z (Z ≥ 0), that is (M-2) clamps between robot and machining center.
6. When the Machining Center is through its current component and buffer is full, the Robot can be blocked for some period of time during which no component may be processed on a robot.

7. The release of components from the buffers on to the machining center is done in the same order as that of their arrival into it from the Robot.

8. The time required to transport components from and to the buffer is negligible.

9. All components are of equal importance and are processed without any pre-emption.

9.5 OUTLINE OF FMC SCHEDULING

The scheduling problem of FMC is considered as two machine flow-shop with finite intermediate storage as shown in Fig. 9.5. As per the construction of FMC with automatic setup feature, the index-pallet changer has 'M' number of clamping stands. At the beginning of the operation of the FMC, N components (W1, W2, ..., WN) are ready for setup on the loading station when one of the empty clamping stands is used for the centering of a component by the robot. After the centering operation is over, the component Wi is transported to the machining center by rotating the index-pallet changer. While this component, Wi is being machined, the next component, Wj, is transported from the loading station to one of the empty clamping stands for the centering operation. When the machining operation on component Wi has been completed on the machining center, it is transported to the unloading station by the robot. Then the same process continues for the next component, Wj.
During the time at which a component is being machined on the machining center, any other component loaded and clamped after centering is ready for the next machining operation. In this case centering and machining operations are conducted smoothly in succession. Sequencing of centering and machining operations for N components greatly influence the total elapsed time of completion for all the components assigned on the FMC. In order to increase the productivity of the FMC, operations scheduling of components should be done to minimise total elapsed time.

9.6 DYNAMIC PROGRAMMING MODEL FOR TOTAL ELAPSED TIME

9.6.1 Mathematical Formulation

Let

\[ S(n) = \text{Total elapsed time on robot for } n^{th} \text{ component.} \]
\[ T(n) = \text{Total elapsed time on machining center for } n^{th} \text{ component.} \]
\[ A(n) = \text{Processing time on robot for } n^{th} \text{ component.} \]
\[ B(n) = \text{Processing time on machining center for } n^{th} \text{ component.} \]

A stepwise dynamic programming formulation that obtains an optimal solution to the problem which is developed by Dutta and Cunningham [85] as follows:

1. State Variable: k th choice of component has to be made; (k-1) components have already been processed.
2 Decision Variable: \(x(k)\) - the component chosen to be processed at stage \(k\), WHERE, \(x(k) = 1,2,...,N\).

3 State Variables:

(I) \(Y(k)\)-the subset of components already processed up to stage \(k-1\) i.e \(Y(k) = \{x_1,x_2,x_3,...,x_{(k-1)}\}\).

(II) \(W(K)\)-\(\{S(K-1), T(K-1),...,T(K-Z-2)\}\) where \(S(k)\) and \(T(k)\) are times elapsed when the \(k\)th component is through with the robot and machining center respectively, \(i \leq k \leq N\).

4 Transition Relations: \(Y(k+1) = Y(k) U\{x(k)\}\)
\(W(k+1) = \{S(k), T(k),...,T(k-Z-2)\}\)
where \(S(k) = \text{MAX} \{S(k-1)\}\),
\(T[k-(Z-2)] + \) processing time on robot \(A(k)\).
\(T(k) = \text{MAX} \{S(k), T(k-1)\} + \) processing time on machining center \(B(k)\).

5 Constraint: \(x(k) \epsilon/ Y(k) = \{ x_1,x_2,x_3,...,x_{k-1}\}\)

6 Economic Function : Minimise \(T(N)\).

7 Recurrence Relations:

\[ f(k)\{Y(k),W(k)\} = \text{MIN} f(k+1)\{Y(k+1),W(k+1)\} \]
\(k=1,2,...,N\) where
\[ f(N)\{Y(N), W(N)\} = \text{MAX} \{S(N-1) + A(N), T(N-Z-2) + A(N), T(N-1)\} + B(N).f(k)\{W(k), Y(k)\}\]
\(Y(k)\) is defined as the maximum flow time starting from the stage \(k\) when the information regarding the already processed by \(Y(k)\) and \(W(k)\).
From the above mathematical formulation the make-span time with respect to the natural sequence of the components (1, 2, 3, ..., \(N\)) is given by the following recurrence relations:

\[
T(n) = \max\{S(n), T(n-1)\} + B(n) \quad 1 \leq n \leq N
\]

\[
S(n) = \max\{S(n-1), T(n-Z-2)\} + A(n) \quad n \geq Z+2
\]

\[
S(n) = \sum_{i=1}^{n} A[i] \quad n \leq Z+2
\]

\[
S(0) = T(0) = 0.
\]

The above recurrence relations are useful when the buffer spaces \(Z\) are greater than zero. If there are no buffers between robot and machining center, this type of problem has been discussed by Reddi and Ramamoorthy [22] and Wismer [84]. Their research show that the problem can be reduced to a travelling sales man problem. For \(Z = 0\) the equations as given above can reduce to the following simple expression:

\[
N
\]

\[
T(N) = A[1] + \sum_{j=2}^{N} \max\{A(j), B(j-1)\} + B(N).
\]

9.6.2 Analytical Procedure

The scheduling problem for the two-machine flow-shop system is formulated by using Enumeration Method. There are \(N\) components, each of which is processed in the order of machine I (robot) and machine II (machining center). The buffer capacity between the two machines is \(Z\) (i.e \(M-2\): two clamping stands for centering and for machining operations are subtracted from the number of clamping stands). The centering operation time on the first machine and machining time on the second machine for all the components are fed in advance. A mathematical programming model for obtaining the optimum sequence of components and to minimise the time of completion is presented.
1 State of Transformation Process

The decision variable, \( x(k) \) is the component to be processed at stage \( k \), \( x(k) = 1, 2, 3, \ldots, N \). \( P(k) \) is the permutation or one subsequence of having \( k \) components. \( k = 1, 2, 3 \ldots, N \).

\( \{P(k)\} \) is the set of \( k! \) subsequences and \( f\{P(k)\} \) is defined as the set of \( P(k) \) capable of yielding the optimum subsequences of \( k \) components.

2 Relation of Dominance when both subsequences \( P(k) \) and \( P'(k) \) included in \( \{P(k)\} \), the relation of dominance as follows:

If \( P(k) \) dominates \( P'(k) \), then \( T\{P(k)\} \leq T\{P'(k)\} \), where \( T\{P(k)\} \) and \( T\{P'(k)\} \) mean the elapsed times at which the sequences are given as \( P(k) \) and \( P'(k) \) respectively. Therefore a set of subsequences, \( P(k) \), not dominated by any other subsequences in the set of \( \{P(k)\} \), that is \( D\{P(k)\} \) is determined by using the relation of dominance and can be represented by the following relations:

\[
f\{P(k)\} = D\{P(k)\}, \quad k = 2, 3, \ldots, N \quad \text{------------------1}
\]

3 State of Equation for Determining \( D\{P(K)\} \)

\( P\{k-x(i)\} \) is a permutation of \( (k-1) \) components, in which component \( x(i) \) is excluded from the \( k \) components.

\[
\{[P(k-x(i))]x(i)\} \text{ -- sum of sets} \quad \text{------------------2}
\]

where \( \{[P(k-x(i))]\} \) is the set of the sequences in which component \( x(i) \) is processed first i.e before the sequences of \( P(k-x(i)) \) by using the relation

\[
f\{P(k)\} = D\{ \{ P(k - x(i) ) \} x(i) \}, \quad x(i)=1, 2, \ldots N \quad \text{------------------3}
\]
4 Transformation Conditions

Transformation conditions are represented by the following relations:

\[ S(k) = \max\{S(k-1), T(k-Z-2)\} + A(k) \]  \hspace{1cm} (4)

\[ T[j] = \max\{S(k), T(k-1)\} + B(k) \]  \hspace{1cm} (5)

where \(S(k)\) and \(T(k)\) are times elapsed when the \(k\)th work piece is through the first and second machines at stage \(k\). The \(f\{P(k)\}\) is given by minimising \(T(k)\). This solution minimises the total manufacturing time.

9.6.3 Computational Algorithm for Scheduling with Enumeration Method

**STEP 1**

*Input the number of components and initialise MIN value.*

**STEP 2**

*Generate a permutation of having \(k\) components \(k = 1, 2, \ldots N\).*

**STEP 3**

*Determine the value of total elapsed time by using the information given by the equations 4 and 5.*

**STEP 4**

*If the value is less than or equal to the MIN, it is the dominated sequence \(f\{P(k)\}\). Otherwise go to STEP 5.*

**STEP 5**

*Generate next permutation of \(k\) components and go to STEP 3.*
9.6.4 Optimum Number of Clamping Stands as Buffer Spaces

Based on the processing times for the first and second machines the optimum number of buffer spaces $Z$ is analysed to minimise the total manufacturing time. The computational algorithm for determining the $Z$ is as follows:

STEP 1

*Input the number of components $N$ and set $Z = 1$.*

STEP 2

*Using the scheduling algorithms which are developed before finding the minimum total manufacturing time $T[N]$.*

STEP 3

*If $Z = 1$. Then $\text{MIN} \leftarrow T(N)$ and go to STEP 4. If $Z$ not equal one and if $T(N)$ is less than value of $\text{MIN}$. Then $\text{MIN} \leftarrow T(N)$ and go to STEP 4.*

STEP 4

*If $Z = N-1$ go to STEP 6. Otherwise go to STEP 5.*

STEP 5

*If $Z = Z + 1$ and return to STEP 2.*
STEP 6

The number of buffer spaces, \( Z \), given by \textit{MIN} is the optimum solution \( Z \) (END).

9.7 SOFTWARE MODEL

The scheduling software has been developed in the 'Turbo'C' language with reference to the earlier work done. This software mainly comprises two modules.

MODULE I

Determining the optimum sequence with minimum total manufacturing time and also the optimum buffer spaces required.

The first module of the software takes the number of components as input by displaying "\textit{ENTER THE NUMBER OF COMPONENTS}". After the user entering the number of components, it asks about the process times of each components which is entered through the display "\textit{ENTER THE PROCESSING TIME ON MACHINE I - A[I]}" and "\textit{ENTER THE PROCESSING TIME ON MACHINE II - B[I]}". With the above data the software leaves the choice to the user to choose the option for the method (Dynamic programming or Enumeration Method) of calculation.

* Robot
** Machining Center
MODULE II

Monitor displays of GANTT CHART by using the scheduling results.

By giving the Inputs the software calculate the minimum total manufacturing time and best possible sequence to be scheduled. The Output come on the monitor as follows:

"THE SEQUENCE IS . . . . WITH BUFFER SPACES Z = . . . AND MINIMUM TOTAL MANUFACTURING TIME = . . . "

In the second module the software displays the GANTT CHART by using the scheduling results in 'C' graphics. This type of Output comes for each buffer space Z. Finally the software displays the optimum sequence and minimum total manufacturing time with optimum buffer spaces and also the optimum GANTT CHART.

9.8 VALIDATION

Table.9.1. shows the timings for centering and machining operations.

<table>
<thead>
<tr>
<th>Component No.</th>
<th>Centering operation time (minutes)</th>
<th>Machining operation time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>02.0</td>
<td>20.0</td>
</tr>
<tr>
<td>W2</td>
<td>09.0</td>
<td>06.0</td>
</tr>
<tr>
<td>W3</td>
<td>03.0</td>
<td>09.0</td>
</tr>
<tr>
<td>W4</td>
<td>30.0</td>
<td>23.0</td>
</tr>
<tr>
<td>W5</td>
<td>05.0</td>
<td>08.0</td>
</tr>
<tr>
<td>W6</td>
<td>16.0</td>
<td>09.0</td>
</tr>
<tr>
<td>W7</td>
<td>18.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Table 9.2. Sequence of Components

<table>
<thead>
<tr>
<th>Buffer Space</th>
<th>Total Possible Sequence</th>
<th>Manufacturing Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>W1 W4 W7 W6 W5 W3 W2</td>
<td>103 97</td>
</tr>
<tr>
<td></td>
<td>W3 W5 W1 W4 W7 W6 W2</td>
<td>091 85</td>
</tr>
<tr>
<td></td>
<td>W3 W5 W1 W4 W7 W6 W2</td>
<td>089 83</td>
</tr>
</tbody>
</table>

Figures 9.6, 9.7, 9.8, show the Gantt charts for sequences specified in Table 9.2. The number of clamping stands to be installed on the index-pallet changer is to be four. The installation of two or more clamping stands shows the same manufacturing time. Therefore the use of three or more buffer spaces are not necessary to minimise the total manufacturing time. The result for the case of no buffer spaces is 103.0 min. The use of two buffer spaces resulted in decreasing this total manufacturing time by about 13.6% [(103-89)/100*103] compared to the case of no buffer spaces. So by using the algorithms, the optimal sequence with minimum total manufacturing time and optimum number of buffer spaces can be obtained.

This software has the feature for sequencing 1 to N number of components. Due to restrictions in computing facilities the number of components for sequencing is limited to seven only.
9.9 CONCLUSION

A new type of FMC with automatic set-up which can simultaneously process both setting (centering) and machining operations on an index-pallet changer has been considered for scheduling. This model with automatic set-up is regarded as the two-machine (machining center and robot) flow-shop model with buffers. A generalization of N-jobs and two-machine sequencing problem is effected by restricting the buffer capacity to some finite quantity. The dynamic programming model presented in this chapter generates an optimal solution to the problem. An operating/scheduling procedure is developed that helps to minimise the total manufacturing time by considering a complete Enumeration Method. The optimum number of clamping stands to be installed on the index-pallet changer is determined by solving the scheduling problem for minimum total manufacturing time. This problem is solved through iterations process to get the optimal solution. This software has been developed in "Turbo C" to get the OPTIMAL GANTT CHART for every buffer space with the results of scheduling.
Fig. 9.6 Gantt Chart with Buffer Z=0

TIME (IN MINUTES) PRESS ANY KEY TO CONTINUE

ROBOT CENTRING OPERATION

MACHINING OPERATION

Submitted By: V. SELLADURAI
Guide: Dr. P. Aravindan, Prof. of Mech. Engg., PSG Tech.
Fig. 9.7 GANTT CHART WITH BUFFER Z = 1
Fig. 9.8 GANTT Chart with Buffer Z = 2