Appendix A

A.1 1-Unit Cycles

Sethi et al. [142] define 1-unit cycles in the context of single-part-type production and prove that there are exactly $m!$ potentially optimal 1-unit cycles in an m machine cell ((problem $RF_m|$*(free,A,MP,cyclic-1)*$|\mu$),). Here we discuss how to develop these cycles for $m = 2$, 3, and 4. In such a cell, we define $m + 1$ *basic activities* as follows:

M_i^-: Load a part on machine $M_i, i = 1, \ldots, m$.
M_m^+: Unload a finished part from machine M_m.

This appendix provides a brief tutorial on how to interpret a robot move cycle composed of these basic activities. A convenient point from which to begin the interpretation is with the unloading of a part from the last machine M_m, denoted by M_m^+. Note that M_m^+ implies that the next action of the robot is M_{m+1}^-, i.e., the robot moves to the output device O to drop the completed part. Consider the sequence ξ of basic activities from one occurrence of M_m^+ to the next such occurrence. Within ξ, there must be exactly one occurrence of each activity $M_1^-, M_2^- \ldots, M_m^-$. The machines that are occupied by parts at the time when M_m^+ occurs can be determined as follows. For $i = 1, \ldots, m-1$, machine M_i is occupied by a part when M_m^+ occurs if and only if M_{i+1}^- precedes M_i^- in ξ. This interpretation provides a starting point for the cycle. Since exactly which machines are occupied is known, the sequence of basic activities following M_m^+ uniquely determines the ordering of loading and unloading of the machines and, thus, also the robot movements between activities. Examples for two- and three-machine robotic cells are given below.

Note that every basic activity must be carried out exactly once in a 1-unit cycle. Moreover, any two consecutive activities uniquely determine the robot moves between those activities. Therefore, a cycle can be uniquely described by a permutation of the above $m + 1$ activities. The following are the 1-unit robot move cycles for $m = 2$.

A.1.1 1-Unit Cycles in Classical Notation

We describe 1-unit cycles for $m = 2, 3$, and 4, using the classical notation used by Sethi et al. [142].

$$\pi_{1,2} = \{M_2^+, M_1^-, M_2^-, M_2^+\} \qquad \pi_{2,2} = \{M_2^+, M_2^-, M_1^-, M_2^+\}.$$

We now interpret these two cycles. In cycle $\pi_{1,2}$, we observe that following M_2^+, activity M_2^- does not precede M_1^-. Therefore, we know that machine M_1 is free when M_2^+ occurs. By contrast, in cycle $\pi_{2,2}$, activity M_2^- precedes M_1^-. Therefore, we know that machine M_1 is occupied by a part when M_2^+ occurs.

The six robot moves cycles for $m = 3$ can be developed from the above two cycles by first replacing the starting and ending activities by M_3^+, as shown below.

1. $\{M_3^+, M_1^-, M_2^-, M_3^+\}$
2. $\{M_3^+, M_2^-, M_1^-, M_3^+\}$.

Each of the last two cycles generates three cycles in a three machine cell, depending upon where the M_3^- activity is inserted, thus creating a total of six cycles:

$$\begin{aligned} \pi_{1,3} &= \{M_3^+, M_1^-, M_2^-, M_3^-, M_3^+\} & \pi_{2,3} &= \{M_3^+, M_1^-, M_3^-, M_2^-, M_3^+\} \\ \pi_{3,3} &= \{M_3^+, M_3^-, M_1^-, M_2^-, M_3^+\} & \pi_{4,3} &= \{M_3^+, M_2^-, M_3^-, M_1^-, M_3^+\} \\ \pi_{5,3} &= \{M_3^+, M_2^-, M_1^-, M_3^-, M_3^+\} & \pi_{6,3} &= \{M_3^+, M_3^-, M_2^-, M_1^-, M_3^+\}. \end{aligned}$$

We briefly interpret two examples of these cycles. In cycle $\pi_{5,3}$, since M_2^- precedes M_1^-, machine M_1 must be occupied by a part when M_3^+ occurs; also, since M_3^- does not precedes M_2^-, machine M_2 must be free at that time. In cycle $\pi_{6,3}$, since M_3^- precedes M_2^-, machine M_2 must be occupied by a part when M_3^+ occurs; also, since M_2^- precedes M_1^-, machine M_1 must be occupied by a part at that time.

Each of the above three machine cycles generates four cycles in a four machine cell, depending upon where the M_4^- activity is inserted, thereby creating a total of 24 cycles, as shown below.

$$\begin{aligned}
\pi_{1,4} &= \{M_4^+, M_1^-, M_2^-, M_3^-, M_4^-, M_4^+\}, & \pi_{2,4} &= \{M_4^+, M_1^-, M_2^-, M_4^-, M_3^-, M_4^+\},\\
\pi_{3,4} &= \{M_4^+, M_1^-, M_4^-, M_2^-, M_3^-, M_4^+\}, & \pi_{4,4} &= \{M_4^+, M_4^-, M_1^-, M_2^-, M_3^-, M_4^+\},\\
\pi_{5,4} &= \{M_4^+, M_1^-, M_3^-, M_2^-, M_4^-, M_4^+\}, & \pi_{6,4} &= \{M_4^+, M_1^-, M_3^-, M_4^-, M_2^-, M_4^+\},\\
\pi_{7,4} &= \{M_4^+, M_1^-, M_4^-, M_3^-, M_2^-, M_4^+\}, & \pi_{8,4} &= \{M_4^+, M_4^-, M_1^-, M_3^-, M_2^-, M_4^+\},\\
\pi_{9,4} &= \{M_4^+, M_3^-, M_1^-, M_2^-, M_4^-, M_4^+\}, & \pi_{10,4} &= \{M_4^+, M_3^-, M_1^-, M_4^-, M_2^-, M_4^+\},\\
\pi_{11,4} &= \{M_4^+, M_3^-, M_4^-, M_1^-, M_2^-, M_4^+\}, & \pi_{12,4} &= \{M_4^+, M_4^-, M_3^-, M_1^-, M_2^-, M_4^+\},\\
\pi_{13,4} &= \{M_4^+, M_2^-, M_3^-, M_1^-, M_4^-, M_4^+\}, & \pi_{14,4} &= \{M_4^+, M_2^-, M_3^-, M_4^-, M_1^-, M_4^+\},\\
\pi_{15,4} &= \{M_4^+, M_2^-, M_4^-, M_3^-, M_1^-, M_4^+\}, & \pi_{16,4} &= \{M_4^+, M_4^-, M_2^-, M_3^-, M_1^-, M_4^+\},\\
\pi_{17,4} &= \{M_4^+, M_2^-, M_1^-, M_3^-, M_4^-, M_4^+\}, & \pi_{18,4} &= \{M_4^+, M_2^-, M_1^-, M_4^-, M_3^-, M_4^+\},\\
\pi_{19,4} &= \{M_4^+, M_2^-, M_4^-, M_1^-, M_3^-, M_4^+\}, & \pi_{20,4} &= \{M_4^+, M_4^-, M_2^-, M_1^-, M_3^-, M_4^+\},\\
\pi_{21,4} &= \{M_4^+, M_3^-, M_2^-, M_1^-, M_4^-, M_4^+\}, & \pi_{22,4} &= \{M_4^+, M_3^-, M_2^-, M_4^-, M_1^-, M_4^+\},\\
\pi_{23,4} &= \{M_4^+, M_3^-, M_4^-, M_2^-, M_1^-, M_4^+\}, & \pi_{24,4} &= \{M_4^+, M_4^-, M_3^-, M_2^-, M_1^-, M_4^+\}.
\end{aligned}$$

The second index in $\pi_{i,j}$ will be omitted when it is clear from the context.

A.1.2 1-Unit Cycles in Activity Notation

We now describe 1-unit cycles for $m = 2, 3$, and 4, using the more popular activity notation. Recall from Chapter 2 that activity A_i represents the following:

- The robot unloads a part from M_i.
- The robot travels from M_i to M_{i+1}.
- The robot loads this part onto M_{i+1}.

The sequence of actions $(M_2^- M_4^- M_5^-)$ is represented as $(A_1 A_3 A_4)$. Since a part must be processed on all m machines and then placed into the output buffer, one instance of each of the $m+1$ activities $A_0, A_1, \ldots, A_m$ is required to produce a part. Then,

$$\pi_{1,2} = \{A_0, A_1, A_2\} \qquad \pi_{2,2} = \{A_0, A_2, A_1\}.$$

$$\begin{aligned}
\pi_{1,3} &= \{A_0, A_1, A_2, A_3\} & \pi_{2,3} &= \{A_0, A_2, A_1, A_3\}\\
\pi_{3,3} &= \{A_0, A_1, A_3, A_2\} & \pi_{4,3} &= \{A_0, A_3, A_1, A_2\}\\
\pi_{5,3} &= \{A_0, A_2, A_3, A_1\} & \pi_{6,3} &= \{A_0, A_3, A_2, A_1\}.
\end{aligned}$$

$$\begin{aligned}
\pi_{1,4} &= \{A_0, A_1, A_2, A_3, A_4\} & \pi_{2,4} &= \{A_0, A_1, A_3, A_2, A_4\}\\
\pi_{3,4} &= \{A_0, A_3, A_1, A_2, A_4\} & \pi_{4,4} &= \{A_0, A_1, A_2, A_4, A_3\}
\end{aligned}$$

$$\begin{array}{ll}
\pi_{5,4} = \{A_0, A_2, A_1, A_3, A_4\} & \pi_{6,4} = \{A_0, A_2, A_3, A_1, A_4\} \\
\pi_{7,4} = \{A_0, A_3, A_2, A_1, A_4\} & \pi_{8,4} = \{A_0, A_2, A_1, A_4, A_3\} \\
\pi_{9,4} = \{A_0, A_1, A_3, A_4, A_2\} & \pi_{10,4} = \{A_0, A_3, A_1, A_4, A_2\} \\
\pi_{11,4} = \{A_0, A_1, A_4, A_2, A_3\} & \pi_{12,4} = \{A_0, A_1, A_4, A_3, A_2\} \\
\pi_{13,4} = \{A_0, A_3, A_4, A_1, A_2\} & \pi_{14,4} = \{A_0, A_4, A_1, A_2, A_3\} \\
\pi_{15,4} = \{A_0, A_4, A_1, A_3, A_2\} & \pi_{16,4} = \{A_0, A_4, A_3, A_1, A_2\} \\
\pi_{17,4} = \{A_0, A_2, A_3, A_4, A_1\} & \pi_{18,4} = \{A_0, A_3, A_2, A_4, A_1\} \\
\pi_{19,4} = \{A_0, A_2, A_4, A_1, A_3\} & \pi_{20,4} = \{A_0, A_2, A_4, A_3, A_1\} \\
\pi_{21,4} = \{A_0, A_3, A_4, A_2, A_1\} & \pi_{22,4} = \{A_0, A_4, A_2, A_1, A_3\} \\
\pi_{23,4} = \{A_0, A_4, A_2, A_3, A_1\} & \pi_{24,4} = \{A_0, A_4, A_3, A_2, A_1\}.
\end{array}$$

The second index in $\pi_{i,j}$ is typically omitted when it is clear from the context.

Appendix B

B.1 The Gilmore-Gomory Algorithm for the TSP

The Gilmore-Gomory algorithm [67] solves a special case of the traveling salesman problem (TSP) in polynomial time. In this special case, each city $i, i = 1, ..., n$, is associated with two numerical parameters e_i and f_i, and the cost (distance) of traveling from city i to city j is given by $h_{ij} = \max\{e_j, f_i\}$. The objective is to find a tour ψ (i.e., a permutation of the cities) that minimizes the total cost $\sum_{i=1}^{n} \max\left\{e_{\psi(i+1)}, f_{\psi(i)}\right\}$. The classical two-machine no-wait flowshop problem, denoted $F_2|$*no-wait*$|C_t$, can be formulated as a TSP with the same cost structure and can be solved in time $O(n \log n)$ by the Gilmore-Gomory [67] algorithm. Several $O(n \log n)$ implementations of this algorithm are available; see, for example, Lawler et al. [103] and Vairatarakis [152]. In this appendix we describe the steps of the Gilmore-Gomory algorithm and illustrate them with a simple example. We first present a brief introduction to Problem $F_2|$*no-wait*$|C_t$, as this problem is closely related to several robotic cell problems discussed in this book. One simple implementation of the Gilmore-Gomory algorithm is then illustrated.

B.1.1 The Two-Machine No-Wait Flowshop Problem

In no-wait flowshops, each job must be processed from start to finish without any interruption on or between the machines. In $F_2|$*no-wait*$|C_t$, job $J_j, j = 1, 2, ..., n$, in a minimal-part-set (MPS) is processed first on machine $M_1^{'}$ for e_j time units and then immediately processed on the

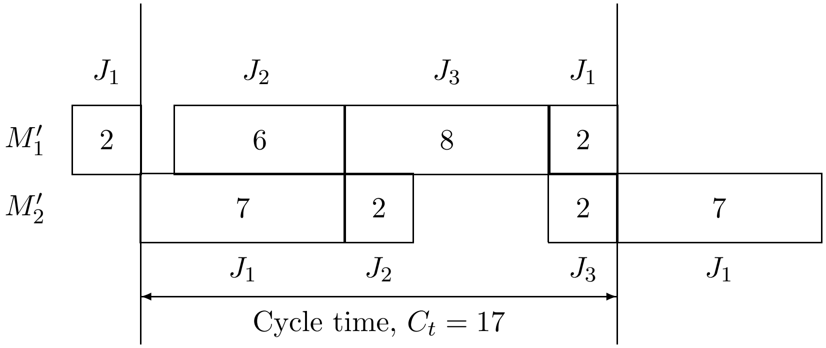

Figure B.1. A No-Wait Schedule in a Two-Machine Flowshop Corresponding to the Sequence $\psi = \{1, 2, 3\}$.

second machine M_2' for f_j time units. An MPS is processed repetitively every C_t units of time. The objective is to find a sequence ψ of the jobs that minimizes the cycle time C_t. To illustrate, consider an MPS of three jobs J_1, J_2, and J_3; their processing times on M_1' and M_2' are as follows: $e_1 = 2$, $f_1 = 7$; $e_2 = 6$, $f_2 = 2$; $e_3 = 8$, $f_3 = 2$. Figure B.1 shows a Gantt chart of the no-wait schedule that produces this MPS in the job sequence (J_1, J_2, J_3); that is, $\psi(i) = i, i = 1, 2, 3$. This schedule has a cycle time of 17. Because of the no-wait constraint, job J_2 cannot start immediately after the completion of J_1 on M_1'.

B.1.2 Formulating a TSP

To formulate Problem $F_2|no\text{-}wait|C_t$ as a TSP, we define inter-city distances $h_{ij}, 1 \leq i, j \leq n, i \neq j$, as follows. Conceptually, we can let the next "cycle" begin and end with job J_1 (Figure B.2). The distance h_{ij} between cities i and j for the corresponding TSP is defined as the time between the start time of job J_i on M_2' and the start of job J_j on M_2'. Thus,

$$h_{ij} = \max\{e_j, f_i\}.$$

The cycle time C_t may now be expressed as

$$C_t = \textstyle\sum_{i=1}^{n} h_{\psi(i),\psi(i+1)},$$

where we let $e_{\psi(n+1)} = e_{\psi(1)}$, since we need a cyclic schedule.

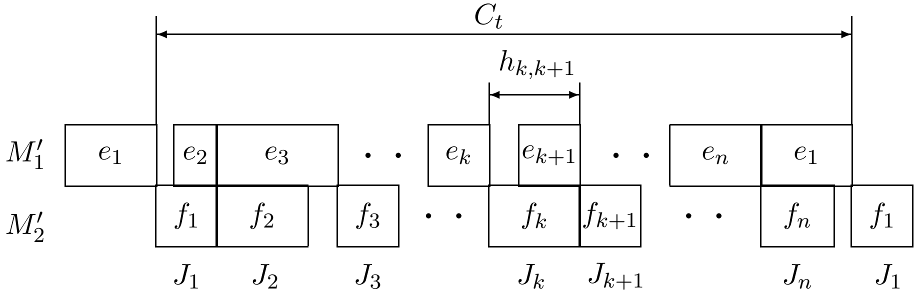

Figure B.2. Formulating $F_2|no\text{-}wait|C_t$ as a TSP.

Thus, by expressing the elapsed time between the start of two successive jobs J_i and J_j on the second machine M_2' as the distance between cities i to j, the no-wait problem $F_2|no\text{-}wait|C_t$ can be converted to a TSP (see Figure B.2). The Gilmore-Gomory algorithm solves the TSP under this special distance matrix in time $O(n \log n)$. The intuition behind the algorithm is that, ideally, the shortest processing time on the first machine should be concurrent with that on the second machine; similarly for the second shortest processing times on the two machines, and so on. If this is possible, we clearly have an optimal tour. If not, we have subtours. In the latter case, an optimal subtour-patching procedure moves the current schedule towards feasibility at minimum cost. We provide the algorithm in the next subsection; this procedure is also described in Kabadi [87] and Pinedo [132].

B.1.3 The Gilmore-Gomory Algorithm

Step 1: Sort $f_j, j = 1, 2, ..., n$, in non-decreasing order and re-number the jobs so that with the new numbering $f_j \leq f_{j+1}$, $j = 1, 2, ..., n-1$.

Step 2: For $p = 1, ..., n$, let $\phi(p)$ denote the index of the pth smallest element of the set $\{e_j; j = 1, ..., n\}$ in the new numbering of Step 1. It follows that $e_{\phi(j)} \leq e_{\phi(j+1)}$, $j = 1, 2, ..., n-1$.

Step 3: Compute the cost of arcs $(j, j+1), j = 1, 2, ..., n-1$ as follows:

$$c_{j,j+1} = \max\{0, \{\min(f_{j+1}, e_{\phi(j+1)}) - \max(f_j, e_{\phi(j)})\}\}.$$

Step 4: Construct an undirected graph with n nodes and arcs $(j, \phi(j))$, $j = 1, 2, ..., n$.

Step 5: If the current graph has only one component, go to Step 7. Otherwise, select the smallest value $c_{j,j+1}$ such that j is in one component and $j+1$ in another. In the case of tie for smallest, choose arbitrarily.

Step 6: Add an undirected arc $(j, j+1)$ to the graph, where j is the index selected in Step 5. Return to Step 5.

Step 7: Divide the arcs added in Step 6 into two groups. Arcs $(j, j+1)$ for which $f_j \leq e_{\phi(j)}$ are included in Group 1, while arcs with $f_j > e_{\phi(j)}$ are included in Group 2.

Step 8: Let there be r arcs in Group 1. Let $j_i, i = 1, ..., r$, be such that j_i is the ith largest index such that arc $(j_i, j_i + 1)$ is in Group 1.

Step 9: Let there be k arcs in Group 2. Let $t_i, i = 1, ..., k$, be such that t_i is the ith smallest index such that arc $(t_i, t_i + 1)$ is in Group 2.

Step 10: For an arc (p, q) in Group 1 or Group 2, let $\alpha_{p,q}$ be defined as follows: $\alpha_{p,q}(p) = q, \alpha_{p,q}(q) = p$ and $\alpha_{p,q}(j) = j$, if $j \neq p, q$. The minimal cycle time is obtained by following the jth job by the job $\psi^*(j) = \phi(v)$, where v, computed recursively, equals

$$\alpha_{j_1,j_1+1}(\alpha_{j_2,j_2+1} \ldots (\alpha_{j_r,j_r+1}(\alpha_{t_1,t_1+1}(\alpha_{t_2,t_2+1} \ldots (\alpha_{t_k,t_k+1}(j))...)))...).$$

EXAMPLE B.1 Consider the eight-job problem given in Table B.1; j is the job number; e_j and f_j are the processing times on machines M_1' and M_2', respectively.

j	e_j	f_j	j	e_j	f_j
1	2	10	5	8	6
2	12	9	6	17	22
3	16	23	7	4	12
4	1	5	8	20	12

Table B.1. Jobs and Their Processing Times.

- After sorting f_j's in non-decreasing order and re-numbering the jobs, we obtain Table B.2 (Step 1).

j	Renamed jobs	f_j	e_j	j	Renamed jobs	f_j	e_j
1	J_1	5	1	5	J_5	12	4
2	J_2	6	8	6	J_6	12	20
3	J_3	9	12	7	J_7	22	17
4	J_4	10	2	8	J_8	23	16

Table B.2. Jobs Sorted in Non-decreasing Order of $f_j, j = 1, ..., n$ (Step 1).

- Sorting the entries in column e_j of Table B.2 in non-decreasing order, we get column $e_{\phi(j)}$ in Table B.3. Column $\phi(j)$ gives the corresponding job number of e_j's in Table B.2. Next, we calculate the maximum and minimum of columns f_j and $e_{\phi(j)}$ for each j. Using these and the equation in Step 3 of the Gilmore-Gomory algorithm, we calculate the costs $c_{j,j+1}$ (Table B.3).

j	f_j	$e_{\phi(j)}$	$\phi(j)$	$\max\{f_j, e_{\phi(j)}\}$	$\min\{f_j, e_{\phi(j)}\}$	$c_{j,j+1}$
1	5	1	1	5	1	0
2	6	2	4	6	2	0
3	9	4	5	9	4	0
4	10	8	2	10	8	2
5	12	12	3	12	12	0
6	12	16	8	16	12	1
7	22	17	7	22	17	0
8	23	20	6	23	20	-

Table B.3. Computation of the Arc-Costs $c_{j,j+1}, j = 1, ..., n-1$ (Step 3).

- Next, we construct a undirected graph (Figure B.3) with nodes corresponding to job numbers $j = 1$ to 8. By referring to columns j and $\phi(j)$ of Table B.3, we draw the undirected edges j-$\phi(j)$ on the graph (Step 4). Thus, we obtain edges (2, 4), (3, 5), and (6, 8) in Figure B.3.

  The graph in Figure B.3 has five components. Node 1 is in the first component, nodes 2 and 4 are in the second component, nodes 3 and

5 are in the third component, nodes 6 and 8 are in in the fourth component, and node 7 is in the fifth component.

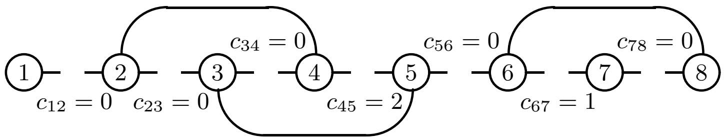

Figure B.3. Undirected Graph with Five Components (Step 4).

- Except edges (4, 5) and (6, 7), all other edges have a cost of zero. We, therefore, add undirected arcs (1, 2), (2, 3), (5, 6), and (7, 8) to the graph to obtain a single-component graph (Figure B.4). Steps 5 and 6 are now complete. Figure B.4 shows the final result.

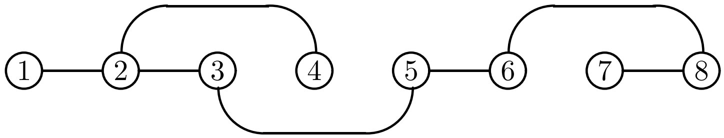

Figure B.4. A Single-Component Graph (Steps 5-6).

- An inspection of Table B.3 shows that the condition $f_j \leq e_{\phi(j)}$ is satisfied only by the arc (5, 6) (Step 7). Hence, from Step 7, we obtain two groups: Group 1 containing the arc (5, 6), and Group 2 containing arcs (1, 2), (2, 3), and (7, 8).

Group 1	Group 2
$f_j \leq e_{\phi(j)}$	$f_j > e_{\phi(j)}$
(5,6)	(1,2) (2,3) (7,8)

- Next, we execute Steps 8 and 9. The largest index j_1 such that arc (j_1, j_1+1) is still in Group 1 is 5; so, $j_1 = 5$. The smallest index t_1 such that arc (t_1, t_1+1) is in Group 2 is 1; thus, $t_1 = 1$. Similarly, $t_2 = 2$ and $t_3 = 7$.

- To obtain the index of the job following job j, we apply the permutation $\psi^*(j) = \phi(\alpha_{5,6}(\alpha_{1,2}(\alpha_{2,3}(\alpha_{7,8}(j)))))$. For example, for $j = 1$, $\psi^*(1) = \phi(\alpha_{5,6}(\alpha_{1,2}(\alpha_{2,3}(\alpha_{7,8}(1))))) = \phi(2) = 4$ (see Table B.3). Thus, job 4 follows job 1; the other computations can be done in a similar manner. An optimal job sequence (J_1, J_4, J_2, J_5, J_8, J_7, J_6, J_3) can be obtained from the pairs $(j, \psi^*(j))$ in Table B.4.

j	$\psi^*(j) = \phi(\alpha_{5,6}(\alpha_{1,2}(\alpha_{2,3}(\alpha_{7,8}(j)))))$
1	4
2	5
3	1
4	2
5	8
6	3
7	6
8	7

Table B.4. An Optimal Job Sequence.

- The Gantt chart in Figure B.5 gives the optimal makespan for this sequence. Note that the cycle time $C_t = 103$. For solving $F_2|no\text{-}wait|C_{max}$, we introduce an artificial job J_0 with $e_0 = 0$ and $f_0 = 0$, and re-run the above algorithm. In this case, we obtain the same job sequence with $C_{max} = 104$.

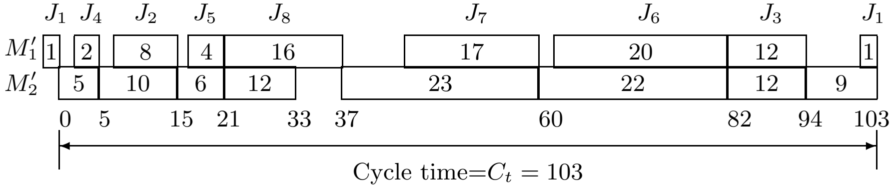

Figure B.5. A Gantt Chart for the Optimal Sequence.

B.2 The Three-Machine No-Wait Flowshop Problem as a TSP

In $F_3|no\text{-}wait|C_t$, job $J_j, j = 1, 2, ..., n$, in a minimal-part-set (MPS) is processed first on machine $M_1^{'}$ for e_j time units, then immediately processed on the second machine $M_2^{'}$ for f_j time units and then immediately on the third machine $M_3^{'}$ for g_j time units. An MPS is processed repetitively every C_t units of time. The objective is find a sequence ψ of the jobs that minimizes the cycle time C_t. The schedule corresponding to $\psi(i) = i, i = 1, 2, ..., n$, is shown in Figure B.6.

To formulate this problem as a TSP, we define inter-city distances $h_{ij}, 1 \leq i, j \leq n, i \neq j$, as follows. The distance h_{ij} between cities i and j for the corresponding TSP is defined as the time between the start time of job J_i on $M_1^{'}$ and the start of job J_j on $M_1^{'}$. Thus,

$$h_{ij} = \max\{e_i, e_i + f_i - e_j, e_i + f_i + g_i - e_j - f_j\}.$$

The cycle time C_t may now be expressed as

$$C_t = \textstyle\sum_{i=1}^{n} h_{\psi(i),\psi(i+1)},$$

where we let $e_{\psi(n+1)} = e_{\psi(1)}$ and $f_{\psi(n+1)} = f_{\psi(1)}$, since we need a cyclic schedule.

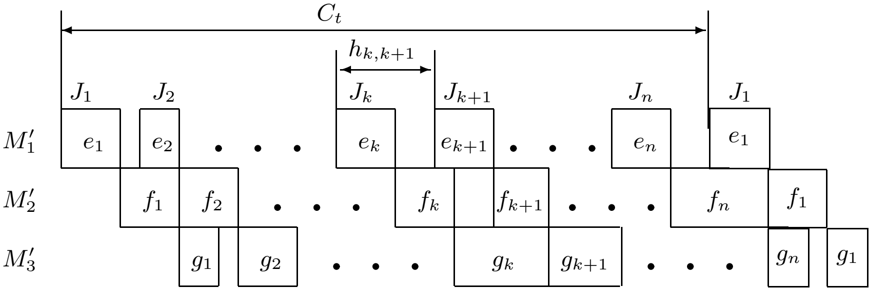

Figure B.6. Formulating $F_3|no\text{-}wait|C_t$ as a TSP.

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