JUST-IN-TIME SCHEDULING WITH TOOL REPLACEMENT CONSIDERATIONS

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ABSTRACT

This paper addresses the combined JIT scheduling and tool replacement problem on a machining centre. The objective is to determine job sequence, tool spare requirement and corresponding replacement intervals so that the total *expected* processing cost is minimized. Due to the combinatorial nature of the problem, a tabu search approach is proposed to find good and quick solutions. An example problem is solved to illustrate the proposed procedure.

Key Words: JIT Scheduling, Tabu Search, Tool Replacement

1. INTRODUCTION

Part sequencing and tool provisioning are among the most important planning problems in automated machining centres. However, these issues have often been treated individually. Most studies on the part sequencing problem have overlooked the sequence-dependent setup times. It is also assumed that tools are completely reliable throughout the production period. Similarly, with a few exceptions, tool provisioning policies have been studied under the assumption that part sequence is known in advance. In addition, fixed intervals of tool replacement are usually suggested in literature. These obviously undermine the usefulness of the most outcomes for real life manufacturing practice.

In view of the above, this study presents a tabu search approach to solve the combined Just-In-Time (JIT) scheduling and tool provisioning problems. The formulation of the problem and development of the proposed solution procedure are given in the following sections.

2. PROBLEM STATEMENT AND ANALYSIS

Consider an automated machining centre that can perform a number of operations for various parts. Each part has a fixed operation sequence defined by a set of required tools and its own distinct due date. Once a part is setup, unless a tool fails during operation, it will stay on the machine until all of its operations are completed. If an in-process tool failure occurs, both the tool and the part become defective. Each tool may have different tool life distributions when processing different parts and it may or may not be replaced at the beginning of each operation depending on the trade-off between the tool cost and the possible defective cost. Also, to achieve the JIT goal it is desirable to process each job as close to its due date as possible. The objective is to find the best part sequence, tool spares level and tool replacement interval so that the total *expected* processing cost is minimized.

2.1 Notation

The following notation will be used in this paper: I=tool type index, j,k=job index, l=position index, s=job sequence index, a_j/b_j=penalty cost per unit time of tardiness/earliness, c/C= setup/ machining cost per unit time, E_j/T_j=earliness/tardiness of job j, d_j =due date of job j, $G(s)$=total cost of sequence s, $h_{ij}(t)$=hazard rate when tool i is used for job j, I_j=a set of tools required for job j, $\mu(s,l)$=the job associated with the lth position in sequence s, m_{ij}=a tool replacement indicator; if tool i is replaced before processing job j, m_{ij}=1; otherwise, m_{ij}=0, M_i=available number of spares for tool i, Π_{ij}=cumulative dollar value on job j up to the time when the operation performed by tool i is completed, π_j=raw material cost of job j, Q_i=cost of tool type i, R_{ij}/r_{ij} =reliability of tool i operating on job j if it is/is not replaced before processing job j, Y_{ij}=machining time spent by tool i on job j.

2.2 Problem Formulation

To minimize the total expected processing cost, the combined part sequencing and tool replacement problem with JIT consideration can be formulated as follows:

$$\underset{s}{Min}\{G(s)\} =$$

$$Min\{\sum_{l=1}^{J}[\sum_{i\in I_{\mu(s,l)}} \min(Zr_{i\mu(s,l)}, ZR_{i\mu(s,l)}) + ct_{\mu(s,l-1)\mu(s,l)}] + a_{\mu(s,l)}T_{\mu(s,l)} + b_{\mu(s,l)}E_{\mu(s,l)}\} \quad (1)$$

subject to:

$$\sum_{l=1}^{J} m_{i\mu(s,l)} \le M_i \qquad \forall s,l \in I_{\mu(s,l)} \quad (2)$$

$$\sum_{k=1}^{l}\left(\sum_{i\in I_{\mu(s,l)}} Y_{i\mu(s,l)} + ct_{\mu(s,k-1)\mu(s,k)}\right) - d_{\mu(s,l)} \le T_{\mu(s,l)} \qquad \forall s,l \quad (3)$$

$$d_{\mu(s,l)} - \sum_{k=1}^{l}\left(\sum_{i\in I_{\mu(s,l)}} Y_{i\mu(s,l)} + ct_{\mu(s,k-1)\mu(s,k)}\right) \le E_{\mu(s,l)} \qquad \forall s,l \quad (4)$$

$$E_{\mu(s,l)} \ge 0 \qquad \forall s,l \quad (5)$$

$$T_{\mu(s,l)} \ge 0 \qquad \forall s,l \quad (6)$$

Where

$$Zr_{i\mu(s,l)} = (Q_i + \Pi_{i\mu(s,l)})(1 - r_{i\mu(s,l)}) + (CY_{i\mu(s,l)} r_{i\mu(s,l)}) \qquad \forall s,l,i \in I_{\mu(s,l)} \quad (7)$$

$$ZR_{i\mu(s,l)} = (Q_i + \Pi_{i\mu(s,l)})(1 - R_{i\mu(s,l)}) + (CY_{i\mu(s,l)} R_{i\mu(s,l)}) \qquad \forall s,l,i \in I_{\mu(s,l)} \quad (8)$$

$$\Pi_{i\mu(s,l)} = \pi_{\mu(s,l)} + \sum_{n=1}^{O(l,\mu(s,l))} CY_{n\mu(s,l)} \qquad \forall s,l,i \in I_{\mu(s,l)} \quad (9)$$

$$R_{i\mu(s,l)} = \exp\left(-\int_0^{Y_l} h_{i\mu(s,l)}(t)dt\right) \qquad \forall s,l,i \in I_{\mu(s,l)} \quad (10)$$

$$r_{i\mu(s,l)} = \left(\prod_{q\in\tau_i(l)} R_{iq}\right) R_{i\mu(s,l)} \qquad \forall s,l,i \in I_{\mu(s,l)} \quad (11)$$

$$m_{i\mu(s,l)} = \begin{cases} 1 & \text{if } ZR_{i\mu(s,l)} < Zr_{i\mu(s,l)} \\ 0 & \text{otherwise} \end{cases}$$

$$\forall s,l,i \in I_{\mu(s,l)} \qquad (12)$$

The objective function consists of three cost components: setup cost $ct_{\mu(s,l-1),\ \mu(s,l)}$ which is deterministic and sequence-dependent, tool replacement cost $Zr_{i\mu(s,l)}$ (or $ZR_{i\mu(s,l)}$), and earliness/tardiness penalty cost. The last two cost components are probabilistic and dependent on the job sequence as well as historical decision of tool replacements. Constraints (5) and (6) determine the amount of tardiness or earliness of each job in the sequence. If tool I is replaced before processing job $\mu(s,l)$, the sum of the expected tool cost, defective job cost and machining cost is $Zr_{i\mu(s,l)}$ as shown in Equation (7); otherwise the sum is $ZR_{i\mu(s,l)}$ given by Equation (8). These costs for each tool-job combination are computed or updated, using Equations (10) to (12). The above model can not be solved efficiently using commercial software due to its combinatorial nature. To provide quick and good solutions a tabu search approach is used. A description of this procedure is given below.

3. PROPOSED SOLUTION PROCEDURE

Tabu search, first introduced by Glover [1], is an optimization technique used to solve combinatorial optimization problems. Tabu search starts with an initial feasible solution and moves stepwise towards a good solution. Such a move, however, may not necessary be an improving one. A distinct characteristic of tabu search is its ability to avoid local optima by using a list of forbidden moves (tabu list). During the search process the best solution found is recorded and updated. The search is terminated after a specific number of moves or maximum allowed search time is reached.

4. ILLUSTRATIVE EXAMPLE AND RESULTS

The proposed procedure is applied to sequence 30 jobs on a machining centre with 20 tool types. In the following examples, tool lives are assumed to follow Weibull distribution. Both machining cost and setup cost are set at \$2/minutes. Due to the space limitation, the rest of the input data including machining and setup times, earliness/tardiness penalties, and raw material and tool costs have been omitted here. However, they can be found in Kolahan [2]. To determine the actual spare requirements, the available copies for each tool type is set at a high number (8 copies). The results for the best search parameters and 15 minutes of search time are presented in Table 1 which lists the final job sequence, deviations from the due dates, actual spare consumption for each tool type, and the tool replacement intervals. Based on these results the job sequence and tool replacement decisions can be made simultaneously.

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Table 1 Solution for the example problem ($M_i = 8$)

Tool type		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Seq[a]	ET	Replacement intervals																			
4	16	0	---	0	---	---	0	0	---	---	0	---	---	0	0	---	---	---	---	---	---
21	-6	0	0	---	0	0	---	---	---	---	0	0	---	0	---	---	---	0	---	---	0
27	21	0	---	0	0	---	---	---	---	0	0	---	0	---	---	---	0	---	---	0	---
1	0	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	0	0	0
28	0	0	---	0	---	---	0	0	---	---	0	---	---	0	0	---	---	---	---	---	---
22	12	1	---	0	---	---	1	0	---	---	1	---	---	1	1	---	---	---	---	---	---
16	29	1	---	0	---	---	1	0	---	---	1	---	---	0	1	---	---	---	---	---	---
30	3	---	---	---	0	---	---	0	1	---	---	---	0	0	---	---	---	0	1	---	---
10	53	1	---	1	---	---	0	1	---	---	1	---	---	0	1	---	---	---	---	---	---
9	0	0	0	---	0	0	---	---	---	---	0	0	---	0	---	---	---	0	---	---	0
17	12	---	1	0	---	1	---	---	---	0	---	1	---	---	---	0	0	---	---	---	---
13	-4	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	0	0	1
23	11	---	0	0	---	1	---	---	---	0	---	0	---	---	---	0	0	---	---	---	---
29	-8	---	0	0	---	0	---	---	---	0	---	0	---	---	---	1	1	---	---	---	---
5	3	---	0	1	---	0	---	---	---	0	---	0	---	---	---	1	0	---	---	---	---
18	-5	---	---	---	1	---	---	0	1	---	---	---	0	0	---	---	---	0	1	---	---
11	-77	---	0	0	---	0	---	---	---	1	---	0	---	---	---	0	0	---	---	---	---
3	-26	1	0	---	0	0	---	---	---	---	0	0	---	0	---	---	---	1	---	---	0
6	-14	---	---	---	1	---	---	1	0	---	---	---	1	0	---	---	---	0	0	---	---
26	-18	---	---	1	0	---	---	---	---	0	---	---	---	---	1	1	---	1	---	1	---
25	-16	---	1	---	---	---	1	---	0	---	---	---	1	---	---	---	---	---	0	1	0
2	-36	---	---	0	0	---	---	---	---	0	---	---	---	---	1	0	---	0	---	0	---
8	-25	---	---	0	0	---	---	---	---	0	---	---	---	---	1	0	---	0	---	0	---
20	-31	---	---	0	0	---	---	---	---	1	---	---	---	---	0	1	---	0	---	1	---
7	-19	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	1	0	0
14	-5	---	---	1	0	---	---	---	---	1	---	---	---	---	1	1	---	1	---	1	---
19	-3	---	0	---	---	---	0	---	0	---	---	---	1	---	---	---	---	---	0	1	1
24	-22	---	---	---	1	---	---	1	0	---	---	---	0	1	---	---	---	1	0	---	---
12	-102	---	---	---	0	---	---	1	1	---	---	---	0	0	---	---	---	0	1	---	---
15	-226	1	1	---	0	0	---	---	---	---	1	1	---	0	---	---	---	0	---	---	0
Spares[b]		6	3	5	3	1	3	4	3	3	4	2	3	2	7	5	1	4	4	5	2

"---" no operation is assigned
" 1 " tool replacement is required
" 0 " no tool replacement is required

[a] : Total expected cost =$5085
[b] : Tool spare cost =$654
ET: Tardiness or earliness of jobs

5. CONCLUSION AND DISCUSSIONS

A model for the combined JIT scheduling and tool replacement problem with probabilistic tool life distribution has been formulated in this paper. To solve this problem a tabu-search approach has been proposed. The computational results indicate that the tool spare level has a saturation point. This is evident from the actual spare requirements shown in Table 1. In addition, as presented below, tool replacement intervals are not fixed. They may be different in terms of both cutting time and number of completed jobs.

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2. Kolahan, F., Modelling and Analysis of Integrated Machine-Level Planning Problems for Automated Manufacturing. *Ph.D Dissertation,* Department of Mechanical Engineering, University of Ottawa, 1999.

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The following notation will be used in this paper: I=tool type index, j,k=job index, l=position index,

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2.2 Problem Formulation

To minimize the total expected processing cost, the combined part sequencing and tool replacement problem with JIT consideration can be formulated as follows:

$$\underset{s}{Min}\,\{G(s)\} =$$

$$\underset{s}{Min}\left\{\sum_{l=1}^{J}\left[\sum_{i\in I_{\mu(s,l)}}\min(Zr_{i\mu(s,l)}, ZR_{i\mu(s,l)}) + ct_{\mu(s,l-1)\mu(s,l)}\right] + a_{\mu(s,l)}T_{\mu(s,l)} + b_{\mu(s,l)}E_{\mu(s,l)}\right\} \tag{1}$$

subject to:

$$\sum_{l=1}^{J} m_{i\mu(s,l)} \le M_i \qquad \forall s, i\in I_{\mu(s,l)} \tag{2}$$

$$\sum_{k=1}^{l}\left(\sum_{i\in I_{\mu(s,l)}} \mathrm{Y}_{i\mu(s,l)} + ct_{\mu(s,k-1)\mu(s,k)}\right) - d_{\mu(s,l)} \le T_{\mu(s,l)} \qquad \forall\, s,l \tag{3}$$

$$d_{\mu(s,l)} - \sum_{k=1}^{l}\left(\sum_{i\in I_{\mu(s,l)}} \mathrm{Y}_{i\mu(s,l)} + ct_{\mu(s,k-1)\mu(s,k)}\right) \le E_{\mu(s,l)} \qquad \forall\, s,l \tag{4}$$

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Where

$$Zr_{i\mu(s,l)} = (Q_i + \Pi_{i\mu(s,l)})(1 - r_{i\mu(s,l)}) + (C\mathrm{Y}_{i\mu(s,l)} r_{i\mu(s,l)}) \qquad \forall s,l,i\in I_{\mu(s,l)} \tag{7}$$

$$ZR_{i\mu(s,l)} = (Q_i + \Pi_{i\mu(s,l)})(1 - R_{i\mu(s,l)}) + (C\mathrm{Y}_{i\mu(s,l)} R_{i\mu(s,l)}) + Q_i \qquad \forall s,l,i\in I_{\mu(s,l)} \tag{8}$$

$$\Pi_{i\mu(s,l)} = \pi_{\mu(s,l)} + \sum_{n=1}^{O(i,\mu(s,l))} C\mathrm{Y}_{n\mu(s,l)} \qquad \forall s,l,i\in I_{\mu(s,l)} \tag{9}$$

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27	21	0	---	0	0	---	---	---	---	0	0	---	0	---	---	---	0	---	---	0	---
1	0	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	0	0	0
28	0	0	---	0	---	---	0	0	---	---	0	---	---	0	0	---	---	---	---	---	---
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17	12	---	1	0	---	1	---	---	---	0	---	1	---	---	---	0	0	---	---	---	---
13	- 4	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	0	0	1
23	11	---	0	0	---	1	---	---	---	0	---	0	---	---	---	0	0	---	---	---	---
29	- 8	---	0	0	---	0	---	---	---	0	---	0	---	---	---	1	1	---	---	---	---
5	3	---	0	1	---	0	---	---	---	0	---	0	---	---	---	1	0	---	---	---	---
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6	-14	---	---	---	1	---	---	1	0	---	---	---	1	0	---	---	---	0	0	---	---
26	-18	---	---	1	0	---	---	---	---	0	---	---	---	---	1	1	---	1	---	1	---
25	-16	---	1	---	---	---	1	---	0	---	---	---	1	---	---	---	---	---	0	1	0
2	-36	---	---	0	0	---	---	---	---	0	---	---	---	---	1	0	---	0	---	0	---
8	-25	---	---	0	0	---	---	---	---	0	---	---	---	---	1	0	---	0	---	0	---
20	-31	---	---	0	0	---	---	---	---	1	---	---	---	---	0	1	---	0	---	1	---
7	-19	---	0	---	---	---	0	---	0	---	---	---	0	---	---	---	---	---	1	0	0
14	- 5	---	---	1	0	---	---	---	---	1	---	---	---	---	1	1	---	1	---	1	---
19	- 3	---	0	---	---	---	0	---	0	---	---	---	1	---	---	---	---	---	0	1	1
24	-22	---	---	---	1	---	---	1	0	---	---	---	0	1	---	---	---	1	0	---	---
12	-102	---	---	---	0	---	---	1	1	---	---	---	0	0	---	---	---	0	1	---	---
15	-226	1	1	---	0	0	---	---	---	---	1	1	---	0	---	---	---	0	---	---	0
Spares[b]		6	3	5	3	1	3	4	3	3	4	2	3	2	7	5	1	4	4	5	2

"---" no operation is assigned

" 1 " tool replacement is required

" 0 " no tool replacement is required

[a] : Total expected cost =$5085

[b] : Tool spare cost =$654

ET: Tardiness or earliness of jobs

5. CONCLUSION AND DISCUSSIONS

A model for the combined JIT scheduling and tool replacement problem with probabilistic tool life distribution has been formulated in this paper. To solve this problem a tabu-search approach has been proposed. The computational results indicate that the tool spare level has a saturation point. This is evident from the actual spare requirements shown in Table 1. In addition, as presented below, tool replacement intervals are not fixed. They may be different in terms of both cutting time and number of completed jobs.

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