Tool placement problem for a given part sequence on a flexible machine

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Abstract

This paper addresses the problem of placing tools in a tool magazine with random-select capability on a flexible machine. The tool placement problem could be a significant portion of the total processing time. It is assumed that the total number of tools required to process a set of parts exceeds the available magazine capacity, and so tool switches may occur between two adjacent parts in a given part sequence. Two heuristics are presented so as to minimize the total travel distance of the tool magazine before the completion of all parts.

1. Introduction

A flexible machine can perform a series of different operations without the need to refix a part. Instrumental to this ability is the automatic tool changer with random-select capability, which replaces the used tool with a new tool in the tool slot of the magazine. The placements of tools in the magazine affect the tool magazine travel time, and could be a loss in machining time. That is, the time required to bring a new tool needed for the succeeding operation may be longer than the current operation time, causing a machine idle time. For example, for FMSs that machine aluminum parts, the processing time per cutter may be significantly shorter than the magazine positioning time.[4]

The tool placement problem has been investigated by several researchers. Agapiou[1] addressed the problem of determining the sequence of operations as well as tool positions to minimize the tool changing time. However, they only suggested a way to solve a simple case where each tool is needed by only one part. Levitin and Rubinovitz[3] addressed the problem of placing tools in a magazine, where the total number of tool types required by all parts do not exceed the tool magazine capacity. And so tool switches never occur in their model. In this paper, we develop a model of placing tools in a tool magazine with random-select capability when the total number of tools required by a set of parts exceeds the tool magazine capacity, and so tool switching may occur between two adjacent parts.

2. Problem description and Mathematical formulation

Consider an automated machining center with an automated tool changer which has a random-select capability. It is assumed that a sequence of N parts to be processed on the machine is known and each part needs a fixed sequence of operations characterized by a required set of tools. M tools required to process a set of parts exceed the available magazine capacity. As a result, in order to process a certain part, it may be necessary to bring new tools from the tool crib and to take some tools already in the magazine back to the tool crib by a tool transporter. The moment in time the tools have been switched for processing the nth part will be called instant n. It is also assumed that the tools to be inserted or removed in the magazine are known at each instant.

We want to determine the positions of the new tools in empty slots created by removing some existing tools in the tool magazine at each instant so as to minimize the total travel distance of the magazine before the completion of all parts. The further assumptions are made as follows:

(1) Each tool can fit in any slot of the magazine and needs only one slot.

(2) The weight balancing of the tool magazines is ignored.

(3) The number of the tools required to process a part does not exceed the magazine capacity.

(4) The magazine is fully loaded with the tools at the beginning.

The following notations for parameters and decision variables are introduced for the mathematical formulation.

P = number of positions in the magazine ($p, q = 1, \ldots, P$)

$T(n)$ = set of tools on the magazine at instant n

$T(0)$ = set of tools on the magazine at initial loading

S_n= number of tools required to process the nth part in the given part sequence

t_s^n = the sth tool in the operation sequence required to process the nth part

d_{pq}= the travel distance between position p and q.

instant s = the moment in time just before processing the sth operation of each part ($s = 1, \ldots, S_n$)

$$x_{nrp} = \begin{cases} 1 & \text{if tool } r \text{ is in } p \text{ position at instant } n \\ 0 & \text{otherwise} \end{cases}$$

$$y_{nrsp} = \begin{cases} 1 & \text{if tool } r \text{ for } s\text{th operation of } n\text{th part is in } p \text{ position at instant } s \\ 0 & \text{otherwise} \end{cases}$$

Mathematically, the tool placement problem can be formulated as follows.

$$\text{Min} \quad \sum_{n=1}^{N} \sum_{s=1}^{S_n-1} \sum_{p=1}^{P} \sum_{q=1}^{P} d_{pq} \cdot y_{nt_s^n sp} \cdot y_{nt_{s+1}^n sq} \tag{1}$$

$$\text{s.t.} \quad \sum_{r \in T(n)} x_{nrp} = 1 \qquad n=0,\dots,N \quad p=1,\dots,P \tag{2}$$

$$\sum_{p=1}^{P} x_{nrp} = 1 \qquad n=0,\dots,N \quad r \in T(n) \tag{3}$$

$$y_{nt_s^n(s+1)p} = y_{nt_{(s-1)}^n sp} \qquad s=1,\dots,S_n-1 \quad n=1,\dots,N \quad p=1,\dots,P \tag{4}$$

$$y_{nt_{S_n}^n S_n p} = y_{nt_1^n 1p} \qquad n=1,\dots,N \quad p=1,\dots,P \tag{5}$$

$$y_{nt_i^n(s+1)p} = y_{nt_i^n sp} \qquad i \neq s \quad n=1,\dots,N \quad p=1,\dots,P \quad s=1,\dots,S_n-1 \tag{6}$$

$$y_{nr1p} = x_{nrp} \qquad r \in T(n) \quad n=1,\dots,N \quad p=1,\dots,P \tag{7}$$

$$x_{(n-1)rp} = y_{nrS_n p} \qquad r \in [T(n) \cap T(n+1)] \quad n=1,\dots,N-1 \quad p=1,\dots,P \tag{8}$$

$$x_{1rp} = x_{0rp} \qquad r \in [T(0) \cap T(1)] \quad p=1,\dots,P \tag{9}$$

$$x_{nrp},\ y_{nrsp} \in \{0,\ 1\} \qquad n=1,\dots,N \quad p=1,\dots,P \quad r=1,\dots,M \quad s=1,\dots,S_n \tag{10}$$

The above problem is transformed into N quadratic assignment problem (QAP), that is sequentially dependent. It is difficult to obtain an optimal solution even for the QAP.[2] Then, we develops several heuristics based on the QAP.

3. Heuristics

We let a set F the set of tools which have been assigned to slots. Also, we use the notation $a(F)$ to indicate the set of slots where the tools in F are assigned. With these notations, we can state the general form of the heuristics as follows:

Step 1. $i = 1$, $F=\emptyset$ and $a(F)=\emptyset$.

Step 2. While $|F|<|S(i)|$, do the followings:

Step 2.1 Select some $t \in [S(i) \backslash F]$.

Step 2.2 Select some $p \notin a(F)$. In case of tie in steps 2.1 and 2.2, select the tool with a smallest tool type index

Step 2.3 $a(t)=p$.

Step 2.4 $F=F \cup \{t\}$, $a(F)=a(F) \cup \{a(t)\}$.

Endwhile

Step 3. if $i<N$, set $i=i+1$, set $F=F \backslash \{t\}$ and $a(F)=a(F) \backslash \{a(t)\}$ for all $t \in [S(i-1) \backslash S(i)]$ and Go to Step 2. Otherwise, stop.

A particular implementation of the general heuristic requires particular rules for performing steps 2.1 and 2.2. The rules used for step 2.1 are the followings:

(1) Random(R):select a tool randomly and

(2) Maximum usage frequency(F):select a tool i^* with $\max_i \left(\sum_j w_{nij}\right)$.

Also, the rule used for step 2.2 are the followings:

(1) Minimum rotation distance(D):select a tool slot p^* with $\min_{p \notin a(F)} \left[\sum_{j \in F} w_{ni^*j} \cdot d_{p,a(j)}\right]$.

With the above alternatives, we have 2 kinds of heuristics: R-D and F-D.

4. Computational experiments

We tested our heuristics on 120 random instances. The number of parts is 40, the number of tools is 60, the value of magazine capacity is 35 and the values of the filling rates (R) of the tools compared to the magazine capacity are DU[30, 60] and DU[50, 100]. DU[a, b] defines the discrete uniform distribution with the range [a, b]. The numbers of repetitions of each tool are DU[1, 1], DU[1, 3] and DU[1, 5]. We assumed that the distance between two adjacent slots is equal to one.

The performance of heuristic on problem instance is measured in terms of percentage above the best solution found. Table 1 displays the average performances over 20 randomly generated instances. The column labeled 'RAN' provides the length of magazine travel entailed when the tool and position are randomly selected in Steps 2.1 and 2.2. As the repetition increases, F-D heuristic produces better results than the others.

5. Conclusions

In this paper, we modeled the tool placement problem when the total number of tools required by a set of parts exceeds the tool magazine capacity. We suggested two heuristics based on reduction of the tool placement to quadratic assignment problem. On the tests, the F-D heuristic performed better than the others.

Table 1. Performance of the proposed heuristics

R	Repetitions	R-D	F-D	RAN
[30, 60]	[1, 1]	3.19(2.43)*	1.07(1.76)	9.82(4.49)
	[1, 3]	2.30(1.82)	0.63(1.39)	7.27(2.96)
	[1, 5]	1.44(1.26)	0.37(0.75)	5.70(2.08)
[50, 100]	[1, 1]	2.88(2.67)	2.20(2.46)	17.93(2.46)
	[1, 3]	1.46(1.19)	0.25(0.50)	10.63(1.72)
	[1, 5]	1.95(1.24)	0.01(0.04)	8.34(1.13)

*The figures in parentheses denote the standard deviation on 20 runs.

[References]

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