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AN APPROACH TO THE TOOL MANAGEMENT OPTIMIZATION FOR CIM SYSTEMS

Summary. The paper presents an attempt to establish a link between the tool life problems and models developped in the cutting of materials theory and the inventory theory developped in the operations research. A the kernel of such a link the tool circulation model based on the Markoff-chain theory was admitted as well as the tool replacement schemes applied in the multi-tool machining cases. The work was supported by the State Commitee for Scientific Research under grant number 77 137 91 02.

Introduction

In CIM systems distributed computing network and common databases are used for solving and coordinating all functions of CAD, CAM, CAQ etc. subsystems. The functions include: product design, manufacturing processes planning and scheduling, raw materials and bought parts purchasing, production, inspection, handling, storing, management and marketing. Flexible manufacturing systems (FMS) and flexible manufacturing lines (FML) are made up by flexible manufacturing cells (FMC) or flexible machining stations (FMSt) linked by material handling systems and partially decoupled by input/output buffering magazines for machined parts. Such flexible FMSt- systems are from the reliability theory point of view the systems with the time redundancy. The autonomy of the single FMSt depends upon the capacity of the tools and workpieces magazines and of the handling devices versatility.

The central tool magazine feeds all the FMSt tool magazines. FMSt's capability of performing a set of elementary machining operations decides of the productivity and the flexibility of the machining system. Here arise tool management and optimization problems. The production time and cost optimization gives a basis for the optimal tool management strategies.

The most severe difficulties distinguishing the tool management problems for FMSs and FMLs consist of:

- the tool features ought to be modelled by a set of the random variables (in order to include of both the normal wear and the catastrophical failure of a tool); the tool wear criteria create a state space in which the tool wear process may be treated as the stochastic process [2], [3], [4], [5], [6], [7];

- the tool life data can be described as random variables with probability distributions obtainable experimentaly, but the great difficulties arise when trying to establish the relations between the distributions parameters and the cutting parameters;
- the scheduled time spans for tools replacement take over the part of the decision variables in the optimization problems [2], [3], [6], [7];
- both the individual and the block replacement schemes should be considered [2], [8];
- there exist only algorithmic connections between the decision variables and the performance criteria values [2], [3], [6];
- the tools circulation model (as a part of the tool management system) ought to be involved, here the Markoff chains theory gives the helpfull means to solve some circulation dynamic problems [3], [6].

Tool circulation model

For multi-tool machining (MTM) there exist two principal stages of the tool replacement strategies determining:

- the process planning stage (the external optimization) when the deterministic but very approximate models for the tool life have to be admitted,
- the process realization stage when the information concerning the tool life exists in the form of the random variables.

For both stages a tool may be replaced individualy or in blocks (a block contains tools replaced as a group). The tool management systems optimization requires the data from the first as well as from the second stage.

The three forms of the optimization criteria are mostly used: the process time and cost components depending on the cutting parameters denoted as t_c and k_c and the auxiliary criterion

$$w = \beta t_c + (1 - \beta) k_c \qquad (1)$$

introduced for the multicriterial optimization (polyoptimization) [2], [3], [6], [7], [8], [9].

The entire mathematical model contains here several substages starting from the analysis of a directed cycle free graph representing the strict order relation on a set of the elementary operations forming the maching process. Such a graph, denoted as K-graph, is workpiece oriented. Structural transformations of the K-graph lead to the K'-graph mapping the machine- tool (machining centre, transfer machine) oriented ordering of the elementary operations. The laws of the transformations depend on the machine- tool structure (e.g. the number of the machining stations). The K'-graph gives a basis for the parametrical optimization of the process (the cutting parameters optimization). Such a procedure has been presented in the paper [9].

For the tool management systems planning and control the probabilistic models of the tool wear and tools circulation are necessary.

Such models contain on the level of a tool four random variables for any tool: Y, T, T^0, T^1 [3],

[6]. They result from the state space for a tool built on the random processes depicturing both the normal and catastrophical tool wear phenomena. The first process enables the formal discrimination of the tool failures forms:

$$X_1(t) = \begin{cases} 0 \text{ for the normal tool wear form} \\ 1 \text{ for the catastrophical tool wear form} \end{cases} \quad (2)$$

The further processes enable the formal representation of others forms of the wear, e.g.:
$X_2(t)$ - the lenght of the flank wear land, $X_3(t)$ - the depth of the crater, etc.
Any tool state space can be now represented by the four above mentioned random variables. Their sets of elementary events and distribution functions are:

$$1.\ E_y = \{X_1(t) = 0, X_1(t) = 1\} \qquad F_y = \begin{cases} 0 \text{ when } X_1(t) < 0 \\ p^0 \text{ when } 0 <= X_1(t) < 1 \\ 1 \text{ when } X_1(t) >= 1 \end{cases} \quad (3)$$

where:
p^0 - the probability that the tool will reach the boundary wear state without the failure,
$p^1 = 1 - p^0$ is the probability of the failure.

2. $E_T = R^+$ - set, F_T = Prob $(T <= t)$ (4)

where T is the tool life until the appearance of any boundary state.

3. $E_{T0} = R^+$ - set with the conditional distributions function

$$F_{T0|X1(t)=0} = \text{Prob } (T <= t\ |X_1(t) = 0) \quad (5)$$

for the random variable T^0 - the tool life under the condition of the normal wear.

4. $E_{T1} = R^+$ - set with the conditional distribution function

$$F_{T1|X1(t)=1} = \text{Prob } (T <= t\ |X_1(t) = 1) \quad (6)$$

for the random variable T^1 - the tool life under the condition of the catastrophical wear.

On the level of a tool station (a structural element of a machining station) a tool circulation model can be defined. If for tool the ith ω_i denotes the number of regrindings or insert replacements and $0 <= \omega_i <= \lambda_i$ - the boudary value, an imbedded Markoff - chain with the transitions matrix M can be applied:

$$M = \begin{bmatrix} p_0^1 & p_0^0 & 0 & 0...0 & 0 \\ p_1^1 & 0 & p_1^0 & 0...0 & 0 \\ ... & ... & ... & ... & ... \\ p_{\lambda-1}^1 & 0 & 0 & 0...0 & p_{\lambda-1}^0 \\ 1 & 0 & 0 & 0...0 & 0 \end{bmatrix} \quad (7)$$

For this chain the ergodic probabilities $p_{i1}, p_{i2} \ldots p_{i\omega} \ldots p_{i\lambda i}$ can be computed enabling - in the simulation procedures- to determine exactly the economical consequencies of different forms of the tools wear, the tools costs and the rejects costs.

Ergodic probabilities for process states indicates that the probability of finding the tool in the state ω_i after a large number of tool replacements tends toward the value given by $p_{i\omega}$. This tendency

manifests itself regardless of intial states or initial probability distributions, so it follows that $p_{i\omega}$ is an unoconditional probability for the state ω_i.
If a MTM problem concerns a machine -tool with n tools and u blocks the replacement strategy involves the replacement of the tools belonging to the rth block ($1 <= r <= u$) after every $\hat{Q} = \hat{a}\,h$ machined pieces where: $\hat{a}$ = the least common multiple of numbers $\{h_1, h_2, \ldots h_r \ldots h_u\}$, h_r - integers defining the structure of the tools replacement scheme (schedule) TRS, h- the basic number of the workpieces forming the module of the TRS. If the ith tool belongs to the rth block and is replaced after every $\hat{Q}_r$ workpieces the expected number of the replacements during the repetitiveness period of the TRS $\hat{Q} = \hat{a}\,h$ is

$$1 + p_i^0 N_i^0(\hat{Q}_r) + p_i^1\, N_i^1(\hat{Q}_r) \tag{8}$$

where $N_i^0(\hat{Q}_r)$ and $N_i^1(\hat{Q}_r)$ are renewal functions. Introducing the costs and replacement times k^0 and t^0 for the cases of planned and unplaned but resulting of normal wear process replacements and then the costs and replacement times k^1 and t^1 for the cases of catastrophical tool wear leads to the expected values

$$k_{ir} = k_i^0 [P_i^0\; N_i^0(\hat{Q}_r) + 1] + k_i^1\; p_i^1\; N_i^1\;(\hat{Q}_r) \tag{9}$$

$$t_{ir} = t_i^0 [P_i^0\; N_i^0(\hat{Q}_r) + 1] + t_i^1\; P_i^1\; N_i^1(\hat{Q}_r) \tag{10}$$

forming the parts of the optimization criteria

$$k_c = f_c(m, K') + \frac{1}{h} \sum_{r=1}^{n} \sum_{i=1}^{n_r} k_{ir}/h_r \tag{11}$$

$$t_c = f_t(m, K') + \frac{1}{h} \sum_{r=1}^{n} \sum_{i=1}^{n_r} t_{ir}/h_r \tag{12}$$

$$n = n_1 + n_2 + \ldots n_r \ldots + \ldots n_u \tag{13}$$

where component f_c and f_t depend on the machining times vector $m = (m_1, m_2, \ldots m_n)$ and the K'-graph structure.

Optimization of tool inventories

Definitions (1) - (6) and (8) - (13) enable to formulate optimization models for tool replacement strategies and to establish mean value for any ith tool life - μ_i as well as the standard deviation σ_i. The ith tool stays in any of its $0, 1 \ldots \omega_i \ldots \lambda_i$ states with the probability defined now as $p_{i\omega}$. So the mean value of the number of states possible to use in the machining process:

$$S_i = 1 + \sum_{\omega=0}^{\lambda_i} \omega \cdot p_{i\omega} \tag{14}$$

And the mean accumulated tool life (assuming the statistical independance of S_i and μ_i):

$$l_i = S_i\, \mu_i \tag{15}$$

with the standart deviation σ_{li} that can be computed by the simulation procedure.
The analysis and management of tool inventories ought to form an important part of the optimization process in a TMS. Stocks and flows of tools are the element of the inventory optimization models. The above given flows analysis determines the start point for the stocks and inventory strategies optimization.
The mean accumulated tool life l_i is expressed in numbers of machined workpieces. So output plan determines the demand D_i for the ith tool in the admitted time span (e.g. a month or a year). Inventory optimization may be divided in two stages.

1. Preliminary stage with following assumptions made in this model:
   - demand D_i is known with certainty and is a constant rate;
   - lead time is known with certainty;
   - stockouts are not to admit;

then the classic EOQ Model (Economic Order Quantity) may be applied, [1], [10], leading to the optimum order quantity of the ith tool EOQ_i (establishing here the re-order level ROL_i) and the optimum lenth of the inventory cycle t_{ic} [1] (the criterion to be minimized is the sum of ordering and holding cost):

$$ROL_i = EOQ_i + \sqrt{\frac{2\,D_i\,C_o}{C_h}} \tag{16}$$

$$t_{ic} = EOQ_i / D_i \tag{17}$$

Here C_o denotes the ordering cost per order and C_h the holding cost per unit of tool per time period.

2. Extention of the preliminary model, involving some stochastic aspects, with following assumptions:

- the lenth of the inventory cycle is given by (17);
- the re-order level for the ith tool (ROL_i) ought to be augmented by the value of the buffer stock V_i [10]:

$$ROL_i = EOQ_i + \sqrt{\frac{2D_i C_o}{C_h}} + V_i(\alpha) \tag{18}$$

where α is the service level (the probability of the stockout appearance);

- the gamma - distribution for V_i is admitted [10] its parameter depending upon the l_i and σ_{li} values.

Under the assumptions of the second stage of the inventory optimization level the more realistic i.e.

stochastic procedures can be developped. They are based on the algorithms given e.g. in [1] and [10].

Concluding Remarks

The tool life features ought to be modelled by a set of the random variables enabling the mapping of both the normal and catastrophical tool wear. Block replacement strategies and preventive replacement principle are the most effective for the MTM. Proper formulation of the optimization criteria and the state space representation for the TRS supported by simulation techniques lead to the system enabling the effective tool management in the machining systems.

Typical models of the inventories optimization developped in the operations research can be involved in the complex tool management optimization models.

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