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Heuristics for Batch Machining at Reconfigurable Rotary Transfer Machines

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Abstract: A problem of design of reconfigurable rotary transfer machines is considered. Parts are divided into batches. Parts of a batch are located at the loading position of rotary table in a given sequence and they are processed simultaneously. Operations are partitioned into groups which are performed by spindle heads or by turrets. Constraints related to the design of spindle heads, turrets, and working positions, as well as precedence constraints related to operations, are given. The problem consists in minimizing the estimated cost of the transfer machine, while reaching a given output and satisfying all the constraints. The proposed methods to solve the problem are based on sequential assignment of operations to machining modules. Experimental results with different heuristics are reported.

Keywords: Computer-aided design, machining, optimization, heuristics.

1. INTRODUCTION

In large serial production machining systems composed of multi-purpose and multi-position equipment with sufficiently high concentration of manufacturing operations in working positions are used. These manufacturing systems provide high productivity and working accuracy resulting in increased manufacturing efficiency. Nevertheless, the trend in today's market place requires more flexible and adaptive manufacturing systems (Makssoud et al., 2014, 2015). A possible solution is to employ reconfigurable manufacturing systems (RMS). RMS are able to manufacture different types of products by batches without losing all other advantages of large series production systems.

This paper deals with a problem of the optimal design of a reconfigurable rotary transfer machine with turrets for parallel machining of multiple parts. Such a machine is multi-positional, i.e. parts are sequentially machined on m_0 (1, 2, …, m_0) working positions. One position of the machine (zero) is exclusively used for loading new billets and unloading finished parts. At each working position, several machining modules (spindle heads) can be installed to process the operations assigned to this position. They are activated sequentially or simultaneously. Sequential activation is realized by the use of turrets. Simultaneous activation is possible if machining modules are related to the different sides of the part and work in parallel. Horizontal and vertical spindle heads and turrets can be used to access to different sides of parts on a working position.

We consider the case where only one vertical turret can be mounted at the machine or one spindle head common for all working positions. Several horizontal spindle heads and turrets can be used. However, there is only one horizontal spindle head or turret per position. Different parts are loaded in a given sequence and they are processed simultaneously by corresponding machining modules. When machining at all working positions is finished, the rotary table turns and the machining modules of turrets are changed (if necessary) in accordance with the part to be machined on that position. Since different parts are located at the rotary table the time between turns may vary.

At the preliminary design stage, the following decisions must be made: the choice of orientations of parts, the partitioning of the given set of operations into positions and machining modules, and the choice of cutting modes for each spindle head and turret.

Only few studies on rotary transfer machines exist in the literature. The machines without turrets were more frequently considered. Configuration of semi-automated systems with multi-turn rotary table was discussed in (Battini *et al.*, 2007). Productivity of production lines with rotary transfer was evaluated by Usubamatov *et al.*, (2008). Mathematical models of transfer machines with rotary or mobile table were proposed in (Dolgui *et al.*, 2009; Battaïa *et al.*, 2012a,b, 2014a,b) where the NP-hardness of these problems was also shown. The first mathematical model for the design of rotary transfer machines with turrets for machining a single part was presented in (Battaïa *et al.*, 2012c). MIP models for parallel and sequential machining of multiple parts were considered in (Battaïa *et al.*, 2013) and (Battaïa *et al.*, 2015) respectively

The paper is organized as follows. Sections 2 and 3 presents the statement of the problem and its mathematical formulation; Section 4 gives in detail heuristics for solving the considered problem. Results of experimental study of

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heuristics are presented in Section 5, and concluding remarks are given in Section 6.

2. PROBLEM STATEMENT

We consider the problem of design of a rotary transfer machine with m_0 working positions for machining d_0 different parts. The parts are loaded in sequence $\pi=(\pi_1, \pi_2, \ldots,\pi_{\mu_0})$ where $\pi_i\in\{0, 1, 2, \ldots, d_0\}$, $i=1, 2, \ldots, \mu_0$, μ_0 is multiple to m_0+1 and $\pi_i=0$ means that no part is loaded. Using sequence π we can define in one-to-one manner function $\pi(i,k)$ of part number on the k-th working position after i turns of the rotary table.

Let $\mathbf{N}^d$ be the set of machining operations needed for machining of elements of the d-th part $d=1, 2, \ldots, d_0$, located on n_d sides and N_s^d, $s=1, 2, \ldots, n_d$, is a subset of opertations for machining of elements of the s-th side of the part. The part d can be located at zero position in different orientations $\mathbf{H}(d)$ but elements of no more than one side can be machined by vertical spindle head or turret. All elements of other sides of the part have to be assigned to horizontal spindle heads or turrets. $\mathbf{H}(d)$ can be represented by matrix of dimension $r_d x n_d$ where $h_{rs}(d)$ is equal j, $j=1,2$ if the elements of the s-th of the part d can be machined by spindle head or turret of type j.

Let $\mathbf{N}=\bigcup_{d=1}^{d_0}\mathbf{N}^d$. All operations $p\in\mathbf{N}$ are characterized by the following parameters:

- length $\lambda(p)$ of the working stroke for operation $p\in\mathbf{N}$, i.e. the distance to be run by the tool in order to execute operation p;
- range $[\gamma_1(p), \gamma_2(p)]$ of feasible values of feed rate which characterizes the machining speed;
- set $H(p)$ of feasible orientations of the part (indexes $r\in\{1, 2, \ldots, r_d\}$ of rows of matrix $\mathbf{H}(d)$) for execution of operation $p\in N_s^d$ by spindle head or turret of type j (vertical if $h_{rs}(d)=1$ and horizontal if $h_{rs}(d)=2$).

Let subset N_k, $k=1,\ldots,m_0$ contain the operations from set $\mathbf{N}$ assigned to k-th working position.

Let sets N_{k1} and N_{k2} be the sets of operations assigned to working position k that are concerned by vertical and horizontal machining, respectively.

Finally, let b_{kj} be the number of machining modules (not more than b_0) of type j (vertical if $j=1$or horizontal if $j=2$) installed at k-th working position and respectively subsets N_{kjl}, $l=1,\ldots,b_{kj}$ contain the operations from set N_{kj} assigned to the same machining module.

This assignment has to respect the technological constraints that emanate from the machining process required. They can be grouped in three following families.

A number of known technological factors determines an order relation on the set $\mathbf{N}$, which defines possible sequences of operations. These precedence constraints can be specified by a directed graph $G^{OR}=(\mathbf{N},D^{OR})$ where an arc $(p,q)\in D^{OR}$ if and only if the operation p has to be executed before the operation q. Let $Pred(p)$ be the set of immediate predecessors of the operation p in the graph G^{OR}.

The required tolerance of mutual disposition of machined part elements as well as a number of additional factors imply the necessity to perform some pairs of operations from $\mathbf{N}$ at the same working position, by the same turret, by the same spindle head or even by the same spindle for each pair. Such inclusion constraints can be given by undirected graphs $G^{SP}=(\mathbf{N},E^{SP})$, $G^{ST}=(\mathbf{N},E^{ST})$, $G^{SM}=(\mathbf{N},E^{SM})$ and $G^{SS}=(\mathbf{N},E^{SS})$ where the edge $(p,q)\in E^{SS}$ ($(p,q)\in E^{SM}$, $(p,q)\in E^{ST}$, $(p,q)\in E^{SP}$) if and only if the operations p and q must be executed by the same spindle, in the same machining module (turret, position).

At the same time, the possibility to perform operations from $\mathbf{N}$ at the same working position, by the same turret or by the same spindle head is also defined by a number of technological constraints, for instance, mutual influence of combining operations, possibility of tool location in spindle head, turret, etc. These exclusion constraints can also be defined by undirected graphs $G^{DM}=(\mathbf{N},E^{DM})$, $G^{DT}=(\mathbf{N},E^{DT})$, and $G^{DP}=(\mathbf{N},E^{DP})$ where the edge $(p,q)\in E^{DM}$ ($(p,q)\in E^{DT}$, $(p,q)\in E^{DP}$)) if and only if the operations p and q cannot be executed in the same machining module (turret, position).

Let $P=<P_1,\ldots,P_k,\ldots,P_m>$ is a design decision with $P_k=(P_{1k11}, P_{2k11}, \ldots, P_{d_0k11}, \ldots, P_{1k1b_{k1}}, P_{2k1b_{k1}}, \ldots, P_{d_0k1b_{k1}}, P_{1k21}, P_{2k21}, \ldots, P_{d_0k21}, \ldots, P_{1k2b_{k1}}, P_{2k2b_{k1}}, \ldots, P_{d_0k2b_{k1}})$, $P_{dkjl}=(N_{dkjl},\Gamma_{dkjl})$, and $\mathbf{N}_j=\bigcup_{d=1}^{d_0}\bigcup_{k=1}^{m}\bigcup_{l=1}^{b_{kj}} N_{dkjl}$, $j=1,2$.

The execution time $t^b(P_{dkjl})$ of operations from N_{dkjl} with the feed per minute $\Gamma_{dkjl}\in[max\{\gamma_1(p)|p\in N_{dkjl}\}, min\{\gamma_2(p)|p\in N_{dkjl}\}]$ is equal to $t^b(P_{dkjl})=L(N_{dkjl})/\Gamma_{dkjl}+\tau^a$, where $L(N_{dkjl})=max\{\lambda(p)|p\in N_{dkjl}\}$, and τ^a is an additional time for advance and disengagement of tools.

We assume that if the turret of type j is installed at the k-th position then the execution time of operations from N_{dkjl} is equal to $t^h(P_{dkj})=\tau^g b_{kj}+\sum_{l=1}^{b_{kj}} t^b(P_{dkjl})$, $|j=1, 2$, where τ^g is an additional time for one rotation of turret. If the spindle head is installed then $t^h(P_{dkj})= t^b(P_{dkjl})$, $|j=1,2$. If all N_{dkjl} are empty then $t^h(P_{dkj})=0$.

The execution time $t^p(P_{dk})$ is defined as $t^p(P_{dk})=\tau^r+max\{t^h(P_{dkj})|j=1,2\}$, where τ^r is an additional time for table rotation. Then time $T(P)$ of execution of all corresponding operations after μ_0 turns of rotary table is equal to

$$T(P)=\sum_{i=1}^{\mu_0} max\{t^p(P_{\pi(i,k)k})\,|k=1,\ldots,m_0\}.$$

We assume that the given productivity is provided, if the total time $T(P)$ does not exceed the available time T_0.

Let C_1, C_2, C_3, and C_4 be the relative costs for one position, one turret, one machining module of a turret, and one spindle