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-hardiness 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=1or 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 head respectively. Since the vertical spindle head (if it presents) is common for several positions its size (and therefore the cost) depends on the number of positions to be covered. Let $k^h_{\min}$ and $k^h_{\max}$ be the minimal and the maximal position of the common vertical spindle head. Then its cost can be estimated as $C_4+(k^h_{\max}-k^h_{\min})C_5$ where C_5 is the relative cost for covering one additional position by vertical spindle head. If the vertical spindle turret is installed its cost can be estimated by $C_2+C_3b_{k1}$. In the similar way the cost $C(b_{k2})$ for performing set of operations N_{k2} by associated b_{k2} machining modules can be assessed as follows:

$$C(b_{k2}) = \begin{cases} 0 \text{ if } b_{k2}=0, \\ C_4 \text{ if } b_{k2}=1, \\ C_2+C_3b_{k2} \text{ if } b_{k2}>1. \end{cases}$$

The machine cost $Q(P)$ is calculated as the total cost of all equipment used i.e.

$$Q(P) = C_1 m + C_4 sign(|\mathbf{N}_1|)(1-\sum_{k=1}^{m_0} sign(|N_{k12}|)) + \sum_{k=1}^{m_0} sign(|N_{k12}|)(C_2+C_3b_{k1}) + C_5(k^h_{\max}-k^h_{\min}) + \sum_{k=1}^{m_0} C(b_{k2})$$

The studied problem is to determine:

a) orientation of each part to be produced;

b) the assignment of operations from set **N** into subsets N_{kjl}, $k=1,...,m_0$, $j=1,2$, $l=1,\dots,b_{kj}$ to be performed by machining module l of type j at working position k;

c) the feed per minute Γ_{dkjl} applied for each set of operations N_{dkjl}, $d=1,...,d_0$, $k=1,...,m_0$, $j=1,2$, $l=1,\dots,b_{kj}$

in such a way that the machine cost $Q(P)$ is small as possible.

3. MATHEMATICAL MODEL

Mathematical model of the considered design problems can be formulated as follows:

$$Q(P)\to\min \quad (1)$$

$$T(P)\le T_0 \quad (2)$$

$$\bigcup_{k=1}^{m}\bigcup_{j=1}^{2}\bigcup_{l=1}^{b_{kj}} N_{kjl} = \mathbf{N} \quad (3)$$

$$N_{k'j'l'}\cap N_{k''j''l''}=\varnothing;\ k',k''=1,\dots,m_0;\ j',j''=1,2;\ l',l''=1,\dots,b_{kj};\ l'\neq l'' \quad (4)$$

$$H(d)=\bigcap_{j=1}^{2}\ \bigcap_{p\in\mathbf{N}_j\cap\mathbf{N}^d} H(p)\in\mathbf{H}(d),\ d=1,\dots,d_0 \quad (5)$$

$$\mathbf{N}_1\cap(N^d_{s'}\cup N^d_{s''})\in\{\varnothing, N^d_{s'}, N^d_{s''}\},\ d=1,\dots,d_0;\ s',s''=1,\dots,n_d;\ s'\neq s'' \quad (6)$$

$$\mathbf{N}_j\cap N^d_s\in\{\varnothing, N^d_s\},\ j=1,2;\ d=1,\dots,d_0;\ s=1,\dots,n_d \quad (7)$$

$$p\in\bigcup_{k'=1}^{k-1}\bigcup_{j'=1}^{2}\bigcup_{l'=1}^{b_{k'j'}} N_{k'j'l'};\ (p,q)\in D^{OR};\ q\in N_{kjl};\ p\in\mathbf{N}_{3-j};\ q\in\mathbf{N}_j;\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (8)$$

$$p\in\bigcup_{k'=1}^{k-1}\bigcup_{j'=1}^{2}\bigcup_{l'=1}^{b_{k'j'}} N_{k'j'l'}\cup\bigcup_{l'=1}^{l-1} N_{kjl'};\ (p,q)\in D^{OR};\ q\in N_{kjl};\ p,q\in\mathbf{N}_j;\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (9)$$

$$|\bigcup_{j=1}^{2}\bigcup_{l=1}^{b_{kj}} N_{kjl}\cap\{p,q\}|\neq1,\ (p,q)\in E^{SP};\ k=1,\dots,m_0 \quad (10)$$

$$|\bigcup_{l=1}^{b_{kj}} N_{kjl}\cap\{p,q\}|\neq1,\ (p,q)\in E^{ST},\ k=1,\dots,m_0,\ j=1,2 \quad (11)$$

$$|N_{kjl}\cap\{p,q\}|\neq1,\ (p,q)\in E^{SB};\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (12)$$

$$|N_{kjl}\cap\{p,q\}|\neq1,\ (p,q)\in E^{SS};\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (13)$$

$$|\bigcup_{j=1}^{2}\bigcup_{l=1}^{b_{kj}} N_{kjl}\cap\{p,q\}|\neq2,\ (p,q)\in E^{DP};\ k=1,\dots,m_0 \quad (14)$$

$$|\bigcup_{l=1}^{b_{kj}} N_{kjl}\cap\{p,q\}|\neq2 \text{ or } b_{kj}=1,\ (p,q)\in E^{DT};\ k=1,\dots,m_0;\ j=1,2 \quad (15)$$

$$N_{kjl}\cap\{p,q\}|\neq2,\ (p,q)\in E^{DB};\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (16)$$

$$sign(|N_{k11}|)+\sum_{k'=1,k'\neq k}^{m} sign(|N_{k'12}|)\le1,\ sign(|N_{k12}|)+sign(|N_{k21}|)\le1;\ k=1,\dots,m_0 \quad (17)$$

$$\Gamma_{dkjl}\in[\Gamma_1(N_{dkjl}),\Gamma_2(N_{dkjl})];\ d=1,\dots,d_0;\ k=1,\dots,m_0;\ j=1,2;\ l=1,\dots,b_{kj} \quad (18)$$

$$b_{kj}\le b_0 \quad (19)$$

$$m\le m_0. \quad (20)$$

The objective function (1) estimates the final cost of the rotary machine customized. Constraint (2) introduces the productivity constraint. Constraints (3) – (4) ensure that the each operation from **N** is assigned to one working machining module exactly. Constraint (5) obliges to choose feasible orientations of parts. Constraints (6) prohibit assignment of operations for machining elements located at two different sides of the part to vertical spindle head or turret. Constraints (7) ensure that all operations for machining elements located at the same side of the part will be assigned to the same type spindle head or turret. Constraints (8) - (9) provide the precedence constraints for the operations that require the same type of machining module (vertical or horizontal) and different ones, respectively. Inclusion constraints for working positions, turrets, machining modules and spindles are expressed by (10), (11), (12) and (13), respectively. Exclusion constraints for working positions, turrets, and machining modules are introduced by (14), (15) and (16), respectively. Constraint (17) ensures that at most one vertical turret will be chosen for the machine and if it is the case, no horizontal machining units are installed at the same working position. Constraints (18) bound the feasible values of the feed per minute for each machining module. The number of machining modules per turret is limited by constraint (19). The number of working positions on the machine is bounded by (20).

Based on matrices $\mathbf{H}(d)$, d=1, 2, …, d_0, we can build matrix $\mathbf{H}$ of dimension $\prod_{d=1}^{d_0} r_d \times \sum_{d=1}^{d_0} n_d$. It has to be coordinated with inclusion constraints on turrets, machining modules and tools, i.e. we delete row r of $\mathbf{H}$ if $h_{rs'} \neq h_{rs''}$ for $p \in N_{s'}^{d'}$, $q \in N_{s''}^{d''}$ and $(p,q) \in E^{SS} \cup E^{SM} \cup E^{ST}$. Each row of $\mathbf{H}$ defines in one-to-one manner partition of $\mathbf{N}$ to $\mathbf{N}_1$ and $\mathbf{N}_2$. Then the optimal solution of the initial problem can be found as the best partition of corresponding $\mathbf{N}_1$ and $\mathbf{N}_2$ by solution problem (11) – (14) and (18) – (30).

In the next section we present heuristic algorithms for solving such a problem.

4. HEURISTICS

Heuristics are usually confined to a particular problem. For the line balancing problems, priority rules are often used to assign tasks. The most employed are based on task attributes, such as task time or number of followers (Capacho et al. (2009), Pastor et al. (2012)). Composite priority rules, where several rules are considered in lexicographic order, have also been considered (Boctor, 1995).

In multi-pass heuristics different results can be obtained at each pass due to the use of a random criterion and the best solution is returned as output (Andrés et al., 2008, Bock, 2008, Cortés et al., 2010, Guschinskaya and Dolgui 2008, Guschinskaya et al., 2011, Gamberini et al., 2009, Jolai et al., 2009,). The stop criterion may be expressed with a specified number of iterations or a given number of iterations without any solution improvement or/and a pre-specified time to reach a solution.

Since the vertical spindle head has the common feed rate we can determine in advance if it is possible. It cannot be installed if $\max\{\gamma_1(p)|p\in\mathbf{N}_1\} > \min\{\gamma_2(p)|p\in\mathbf{N}_1\}$. The vertical turret cannot be installed if there exist operations $p\in\mathbf{N}_1$ and $q\in\mathbf{N}_2$ such that $(p,q) \in E^{SP}$. If both cases are identified then the problem has no solution.
As a consequence, the solution can be found by solving two independent problems. One of them does not allow installing a vertical turret. The second one consists in finding best partitions of corresponding $\mathbf{N}_1$ and $\mathbf{N}_2$ separately and then combining these partitions appropriately.

The algorithms named SAO (Sequential Assignment of Operations) are modifications of heuristics (Dolgui *et al*, 2005). At each iteration, an algorithm creates machining modules of current position step by step. At the beginning, it builds the list *In* of operations, which are potentially assignable to a current machining module, taking into account precedence constraints as well as exclusion constraints on positions. The list *In* is modified in accordance with inclusion constraints. Then one operation or several operations with regard to inclusion constraints on machining modules and tools is chosen to be assigned to a current machining module. If it is not possible a new machining modules is created. After the assignment, the list *In* is modified and the assignment process is repeated. When the list *In* is empty or b_0 machining modules have been already created, the current position closed and productivity constraint is verified. If it is violated, the algorithm starts from the beginning (creation of the first position). The iteration is considered also unsuccessful if after creation of m_0 positions not all the operations from $\mathbf{N}$ are assigned.

Let TR_{tot} be the current number of trials, TR_{nimp} be the number of trials that do not improve the current solution, C be the cost of the current solution, and C_{min} be the cost of the best solution. The following Algorithm tries to assign operations from $\mathbf{N}_1$ to vertical spindle head common for several positions and operations from $\mathbf{N}_2$ to horizontal spindle heads and turrets.

Algorithm.

Step 1. Let $C_{min} = \infty$, $TR_{tot} = 0$, $TR_{nimp} = 0$.

Step 2. Let C=0, $N^a = \varnothing$, m=0.

Step 3. Let m=m+1. If $m > m_0$ then let C=∞ and go to *Step* 12. Otherwise let $N_{m11} = N_{m21} = \varnothing$, $b_{m1} = b_{m2} = 0$, $N^{na} = \varnothing$.

Step 4. Put in the list *In* all operations *op* from $\mathbf{N} \backslash N^{na} \backslash N^a$ that satisfy precedence constraints for the set N^a, i.e. all the predecessors of operations *op* are in the set N^a. If the list *In* is empty then set C=∞ and go to *Step* 12.

Step 5. Choose operation *op* in the list *In*. Set N={*op*}. Include into N all the operations which are obliged by inclusion constraints on position, turret, machining module or tool and all their predecessors. Save current state of b_{m2}, N_{m11} and N_{m2l} l=1,..,b_{m2}.

Step 6. If set $N \cap \mathbf{N}_1 \cup N_{m11}$ cannot be executed in one machining module then let $N^{na} = N^{na} \cup N$ and go to *Step* 9. Otherwise let $N_{m11} = N_{m11} \cup (N \cap \mathbf{N}_1)$.

Step 7. Divide set $N \cap \mathbf{N}_2$ into subsets N^{2i}, i=1, 2,…,n_2, which should be executed in one machining module or by the same tool. If the set N^{2i} can be executed in one machining module with N_{m2l}, for some $l \in \{1,..,b_{m2}\}$ then let $N_{m2l} = N_{m2l} \cup N^{2i}$ and go to *Step* 8. If $b_{m2} = b_0$ then let $N^{na} = N^{na} \cup N$ and go to *Step* 9. Otherwise let $b_{m2} = b_{m2}+1$ and $N_{m2l} = N_{m2l} \cup N^{2i}$ for $l = b_{m2}$.

Step 8. Compute $T(P)$ for $N_{dkjl} = N_{kjl} \cap \mathbf{N}^d$ and $\Gamma_{dkjl} = [min\{\gamma_2(p)|p \in N_{dkjl}\}$. If $T(P) > T_0$ then restore saved state of b_{m2}, N_{m11} and N_{m2l} l=1,..,b_{m2} as well as let $N^{na} = N^{na} \cup N$. Otherwise let $N^a = N^a \cup N$.

Step 9. Modify the list *In* by including all operations *op* from $\mathbf{N} \backslash N^{na} \backslash N^a$ that satisfy precedence constraints for the set N^a and exclusion constraints for the set $\bigcup_{j=1}^{2} \bigcup_{l=1}^{b_{kj}} N_{mjl}$, i.e. operation *op* can be executed in one position with any operation from $\bigcup_{j=1}^{2} \bigcup_{l=1}^{b_{kj}} N_{mjl}$. If the list *In* is not empty then go to *Step* 5. Otherwise let b_{m1}=1 if $N_{m11} \neq \varnothing$.

Step 10. If N^a dose not include all the operations from $\mathbf{N}$ then go to *Step* 2.

Step 11. Compute $C=Q(P)$.

Step 12. If $C_{min} > C$, then set $C_{min} = C$, $TR_{nimp} = 0$ and keep the current solution as the best, set $TR_{nimp} = TR_{nimp} + 1$ otherwise.

Step 13. Set $TR_{tot} = TR_{tot} + 1$.

Step 14. Stop if one of the following conditions holds:

- a given solution time is exceeded;
- TR_{tot} is greater than the maximum number of iterations authorized;
- TR_{nimp} is greater than a given value;
- C_{min} is lower than a given cost value.

Go to *Step* 2 otherwise.

This algorithm can be applied for assigning operations from $\mathbf{N}_1$ to vertical turret with m_0=1, $\mathbf{N}_1=\varnothing$ and $\mathbf{N}_2=\mathbf{N}_1$. Then this assignment should be combined with the assignment of $\mathbf{N}_2$ only by its corresponding insertion with not violating precedence and productivity constraints.

At *Step* 5, operation *op* can be chosen in different ways, here 9 different algorithms are considered. The proposed algorithms are based on the choice an operation at first:

SAO1 – an operation without inclusion constraints;
SAO2 – an operation with inclusion constraints;
SAO3 – an operation with maximal number of successors;
SAO4 – an operation with minimal number of successors;
SAO5 – an operation with maximal number of operations to be not executed in one machining module;
SAO6 – an operation with minimal number of operations to be not executed in one machining module;
SAO7 – an operation with maximal execution time;
SAO8 – an operation with minimal execution time.

In the case of tie, random choice is done.

5. EXPERIMENTAL STUDY

The purpose of this study is to evaluate the effectiveness of the proposed techniques. There were generated series of 100 test instances for batches of 4, 6 and 8 parts. Their characteristics are presented in Tables 1-3. In these tables |**N**| is the number of operations, OSP is the order strength of precedence constraints, DM, DT, DP, SS, and SM are the densities of graphs G^{DM}, G^{DT}, G^{DP}, G^{SS}, and G^{SM} respectively. Constraints were generated using tools (Dolgui *et al*, 2008). Experiments were carried out on ASUS notebook (1.86 Ghz, 4 Gb RAM).

In Table 4 we compare results for SAO1 and SAO2 with NIT=10000, NIIT=5000 with results for SA3 – SAO8 with NIT=200, NIIT=100 where NIT is the maximal number of iterations, NIIT is the maximal number of non-improved iterations, SB is the number of parts to be machined, NSOL is the number of solved problems, NOPT is the number of solved problems with the best value of the objective function, AVED, MIND and MAXD are average, minimal and maximal deviations (in percents) the found value of the objective function from the best known respectively.

Table 1. Parameters of problems for 4 parts

Parameters of problems	|N|	OSP	DM	DT	DP	SS	SM
Min value	44	0.034	0.064	0.026	0	0.027	0
Max value	95	0.525	0.659	0.659	0.242	0.051	0.016
Av. value	69	0.106	0.373	0.348	0.024	0.036	0.004

Table 2. Parameters of problems for 6 parts

Parameters of problems	|N|	OSP	DM	DT	DP	SS	SM
Min value	89	0.029	0.003	0.002	0	0.024	0
Max value	159	0.471	0.462	0.462	0.205	0.031	0.057
Av. value	124	0.29	0.228	0.197	0.027	0.027	0.016

Table 3. Parameters of problems for 8 parts

Parameters of problems	|N|	OSP	DM	DT	DP	SS	SM
Min value	118	0.023	0.003	0.002	0	0.024	0
Max value	216	0.456	0.438	0.417	0.214	0.033	0.057
Av. value	165	0.288	0.197	0.168	0.025	0.028	0.017

Table 4. Calculation results

SB	METH	NSOL	NOPT	AVED	MIND	MAXD
4	SAO1	99	84	0.85	0.00	12.61
	SAO2	98	79	0.86	0.00	11.24
	SAO3	97	80	0.75	0.00	12.61
	SAO4	98	87	0.49	0.00	13.48
	SAO5	97	85	0.51	0.00	13.48
	SAO6	97	83	0.60	0.00	12.61
	SAO7	98	86	0.59	0.00	13.48
	SAO8	97	83	0.55	0.00	9.01
6	SAO1	99	71	1.32	0.00	14.91
	SAO2	99	62	1.69	0.00	13.13
	SAO3	97	57	2.06	0.00	13.64
	SAO4	96	63	1.78	0.00	9.57
	SAO5	95	61	1.67	0.00	19.15
	SAO6	94	56	2.31	0.00	19.15
	SAO7	95	49	2.43	0.00	19.15
	SAO8	95	70	1.47	0.00	14.04
8	SAO1	99	73	1.37	0.00	17.54
	SAO2	97	57	2.23	0.00	17.54
	SAO3	97	57	2.20	0.00	22.35
	SAO4	96	58	2.62	0.00	21.28
	SAO5	90	67	1.66	0.00	31.76
	SAO6	95	56	2.26	0.00	21.28
	SAO7	92	54	1.94	0.00	22.35
	SAO8	97	70	1.38	0.00	14.88

6. CONCLUSION

A problem of design of rotary transfer machines with turrets has been studied for batch machining of multiple parts. The goal is to choose the orientation of parts and to assign the manufacturing operations to positions in order to minimize the equipment cost. The design problem is formulated as a special partition set problem. Then it is decomposed in a number of problems for fixed orientations of parts. Heuristics algorithms have been developed to solve such a problem.

They are based on sequential assignment of operations to machining modules. Several rules of choice of an operation to be assigned have been proposed. Experiments show that the heuristic choice of the operation with minimal execution time is preferable in the most cases. The further research will concern combining several rules in one algorithm as well as developing MIP-based heurictics.

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