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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 \( m_0 \) \((1, 2, \ldots, m_0)\) 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; Battaia 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 (Battaia et al., 2012c). MIP models for parallel and sequential machining of multiple parts were considered in (Battaia et al., 2013) and (Battaia 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
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 \( \pi = (\pi_1, \pi_2, \ldots, \pi_{n_p}) \) where \( \pi_i \in \{0, 1, 2, \ldots, d_0\}, i = 1, 2, \ldots, m_0, \mu_d \) is multiple to \( m_0 + 1 \) and \( \pi_0 = 0 \) means that no part is loaded. Using sequence \( \pi \) 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 \( N^d \) 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 operations for machining of elements of the \( s \)-th side of the part. The part \( d \) can be located at zero position in different orientations \( H(d) \) 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. \( H(d) \) can be represented by matrix of dimension \( r_min,d \times 1 \), where \( h_{ij}(d) \) is equal \( j=1, 2 \) if the elements of the \( s \)-th of the part \( d \) can be machined by spindle head or turret of type \( j \).

Let \( N = \bigcup_{d=1}^{d_0} N^d \). All operations \( p \in N \) are characterized by the following parameters:
- length \( \delta(p) \) of the working stroke for operation \( p \in N \), i.e. the distance to be run by the tool in order to execute operation \( p \);
- range \( \{\gamma(p), \gamma(p)\} \) of feasible values of feed rate which characterizes the machining speed;
- set \( H(p) \) of feasible orientations of the part (indexes \( r \in \{1, 2, \ldots, r_j\} \) of rows of matrix \( H(d) \)) for execution of operation \( p \in N^d \) by spindle head or turret of type \( j \) (vertical if \( h_{ij}(d) = 1 \) and horizontal if \( h_{ij}(d) = 2 \)).

Let subset \( N_{dij} \) be the grouping of operations from set \( N \) assigned to \( k \)-th working position.

Let sets \( N_{d1} \) and \( N_{d2} \) be the sets of operations assigned to working position \( k \) that are concerned by vertical and horizontal machining, respectively.

Finally, let \( b_{ij} \) be the number of machining modules (not more than \( b_{ij} \)) of type \( j \) (vertical if \( j = 1 \) or horizontal if \( j = 2 \)) installed at \( k \)-th working position and respectively subsets \( N_{dij} \), \( l = 1, \ldots, b_{ij} \) contain the operations from set \( N_{dij} \) 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 \( N \), which defines possible sequences of operations. These precedence constraints can be specified by a directed graph \( G^{OR} = (N, D^{OR}) \) 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 \( N \) 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 \( G^{SP} = (N, E^{SP}) \), \( G^{ST} = (N, E^{ST}) \), \( G^{SM} = (N, E^{SM}) \), and \( G^{SS} = (N, E^{SS}) \), where the edge \((p,q) \in E^{SS} \) 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 \( N \) 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 \( G^{OM} = (N, E^{OM}) \), \( G^{OS} = (N, E^{OS}) \), and \( G^{OP} = (N, E^{OP}) \) where the edge \((p,q) \in E^{OP} \) if and only if the operations \( p \) and \( q \) cannot be executed in the same machining module (turret, position).

Let \( P = \{P_1, \ldots, P_{d_0}, \ldots, P_{d_0}\} \) is a design decision with \( P_1 = \{P_{1k1}, P_{2k1}, \ldots, P_{d_0k1}, P_{1k1b_1}, P_{2k1b_1}, \ldots, P_{d_0k1b_1}, \ldots, P_{1k2b_1}, P_{2k2b_1}, \ldots, P_{d_0k2b_1}\} \).

The execution time \( \hat{T}(P_{dij}) \) of operations from \( N_{dij} \) with the feed per minute \( \gamma(p) \in \{\max(\gamma(p)) \in N_{dij}\} \), \( min(\gamma(p)) \in N_{dij}\} \) is equal to \( \hat{T}(P_{dij}) = \hat{T}(N_{dij}) / \gamma(p) \), where \( L(N_{dij}) = \max(\lambda(p) \in N_{dij}) \), and \( T' \) 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 \( N_{dij} \) is equal to \( \hat{T}(P_{dij}) = T'_{h_{ij}} + \sum_{l=1}^{b_{ij}} \hat{T}(P_{dij}), \text{ if } j = 1, 2 \), where \( T' \) is an additional time for one rotation of turret. If the spindle head is installed then \( \hat{T}(P_{dij}) = \hat{T}(P_{dij}), \text{ if } j = 1, 2 \). If all \( N_{dij} \) are empty then \( \hat{T}(P_{dij}) = 0 \).

The execution time \( \hat{T}(P_{dij}) \) is defined as \( \hat{T}(P_{dij}) = T' + max(\hat{T}(P_{dij})j = 1, 2) \), where \( T' \) is an additional time for table rotation. Then time \( T(P) \) of execution of all corresponding operations after \( \mu_0 \) turns of rotary table is equal to \( T(P) = \sum_{i=1}^{m_0} max(\hat{T}(P_{dij})) \).

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 \( k_{\min}^h \) and \( k_{\max}^h \) be the minimal and the maximal position of the common vertical spindle head. Then its cost can be estimated as \( C_3 + (k_{\max}^h - k_{\min}^h)C_3 \) where \( C_3 \) 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 \( C_2 + C_3 b_{k1} \). In the similar way the cost \( C(b_{l2}) \) for performing set of operations \( N_{l2} \) by associated \( b_{l2} \) machining modules can be assessed as follows:

\[
C(b_{l2}) = \begin{cases} 
  0 & \text{if } b_{k2} = 0, \\
  C_4 & \text{if } b_{k2} = 1, \\
  C_2 + C_3 b_{k2} & \text{if } b_{k2} > 1.
\end{cases}
\]

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

\[
Q(P) = C_1 m + C_4 \sum_{k=1}^{m_0} \text{sign}(\lfloor \frac{N_{l1}}{k} \rfloor) (1 - \sum_{k=1}^{m_0} \text{sign}(\lfloor \frac{N_{l12}}{k} \rfloor)) + \\
\sum_{k=1}^{m_0} \text{sign}(\lfloor \frac{N_{l12}}{k} \rfloor) (C_2 + C_3 b_{k1}) + C_3 (k_{\max}^h - k_{\min}^h) + \sum_{k=1}^{C} C(b_{k2})
\]

The studied problem is to determine:

a) orientation of each part to be produced;

b) the assignment of operations from set \( P \) into subsets \( N_{l1j} \), \( k=1,...,m_0; j=1,2 \), \( l=1,...,b_{lj} \) to be performed by machining module \( l \) of type \( j \) at working position \( k \);

c) the feed per minute \( \Gamma_{djl} \) applied for each set of operations \( N_{djl} \), \( d=1,...,d_0 \), \( k=1,...,m_0; j=1,2 \), \( l=1,...,b_{lj} \).

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:

\[
Q(P) \rightarrow \min
\]

\[
T(P) \leq T_0
\]

\[
m \sum_{k=1}^{b_{l1}} N_{l1j} = N
\]

\[
N_{l1j} \cap N_{l1j'} = \emptyset; k^1, k^2 = 1, \ldots, m_0; j^1, j^2 = 1,2; l^1, l^2 = 1, \ldots, b_{lj}; l^1 \neq l^2
\]

\[
H(d) = \bigoplus_{j=1}^{m} \bigcap_{p \in P} H(p) \cap N_d
\]

\[
N(l) \cap (N_d \cup N_s) = \{ \emptyset, N_s, N_d \}, d=1,...,d_0;
\]

\[
s_l = 1, \ldots, d_0; s_l \neq s_l;
\]

\[
N(l) \cap N_s \emptyset(s \cup N_s \emptyset), j=1,2; d=1,...,d_0; s=1,...,n_d
\]

The objective function (1) estimates the final cost of the rotary table 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 \(H(d), d=1, 2, \ldots, d_0\), we can build matrix \(H\) of dimension \(d_0 \times \sum d_d\). It has to be coordinated with inclusion constraints on turrets, machining modules and tools, i.e. we delete row \(r\) of \(H\) if \(h_{r\alpha} \neq \sum h_{r\alpha}\) for \(p \in N_{d_{s}}\), \(q \in N_{d_{s}}^*\) and \((p,q) \in E^{SS} \cup E^{SM} \cup E^{ST}\). Each row of \(H\) defines in one-to-one manner partition of \(N\) to \(N_1\) and \(N_2\). Then the optimal solution of the initial problem can be found as the best partition of corresponding \(N_1\) and \(N_2\) 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., 2005). At each iteration, an algorithm creates machining module. If it is not possible a new machining module is created. After the assignment, the list \(In\) is modified and the assignment process is repeated. When the list \(In\) is empty or \(b_p\) machining modules have already been 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 \(m_j\) positions not all the operations from \(N\) are assigned.

Let \(TR_{tot}\) be the current number of trials, \(TR_{simp}\) be the number of trials that do not improve the current solution, \(C\) be the cost of the current solution, and \(C_{max}\) be the cost of the best solution. The following Algorithm tries to assign operations from \(N_i\) to vertical spindle head common for several positions and operations from \(N_j\) to horizontal spindle heads and turrets.

Algorithm.

Step 1. Let \(C_{min} = \infty\). \(TR_{tot} = 0\), \(TR_{simp} = 0\).

Step 2. Let \(C=0\), \(N'=\emptyset\), \(m=0\).

Step 3. Let \(m=m+1\). If \(m > m_0\) then let \(C=\infty\) and go to Step 12. Otherwise let \(N_{n11} = N_{m2}=\emptyset\), \(b_{n1} = b_{n2} = 0\), \(N'=\emptyset\).

Step 4. Put in the list \(In\) all operations \(o_p\) from \(N'\subseteq N\) that satisfy precedence constraints for the set \(N'\), i.e. all the predecesors of operations \(o_p\) are in the set \(N'\). If the list \(In\) is empty then set \(C=\infty\) and go to Step 12.

Step 5. Choose operation \(o_p\) in the list \(In\). Set \(N^*\{o_p\}\). 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 \(b_{n2}, N_{m11}\) and \(N_{m2} \{\l=1, \ldots, b_{n2}\}\).

Step 6. If set \(N'=N_1\cup N_{m11}\) cannot be executed in one machining module then let \(N'=N_{m11}\cup N\) and go to Step 9. Otherwise let \(N_{m11}=N_{m11}\cup (N\cap N_1)\).

Step 7. Divide set \(N_1\cap N_2\) into subsets \(N_{2i}, i=1, 2, \ldots, n_2\), 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 \(N_{m2}\), for some \(l \in \{1, \ldots, b_{n2}\}\) then let \(N'=N_{m2}\cup N_{2i}\) and go to Step 8. If \(b_{n2}=b_{n2}\) then let \(N'=N_{m2}\cup N\) and go to Step 9. Otherwise let \(b_{n2}=b_{n2}+1\) and \(N_{m2} \{\l=1, \ldots, b_{n2}\}\) as well as let \(N'=N_{m2}\cup N\). Otherwise let \(N'=N_{m2}\cup N\).

Step 8. Compute \(T(P)\) for \(N_{m2}=N_{m2}\cap N_{2i}\) and \(F_m = \min \{\gamma(p)|p \in N_{m2}\}\). If \(T(P) > T_m\), then restore saved state of \(b_{n2}, N_{m11}\) and \(N_{m2} \{\l=1, \ldots, b_{n2}\}\) as well as let \(N'=N_{m2}\cup N\).

Step 9. Modify the list \(In\) by including all operations \(o_p\) from \(N'\subseteq N\) that satisfy precedence constraints for the set \(N'\) and exclusion constraints for the set \(\cup \cup N_{m2j}\), i.e. operation \(o_p\) can be executed in one position with any operation from \(2 \cup \cup N_{m2}\). If the list \(In\) is not empty then go to Step 5.

Otherwise let \(b_{n1}=1\) if \(N_{m11}\neq \emptyset\).
Step 10. If \( N \) dose not include all the operations from \( N \) then go to Step 2.

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

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

Step 13. Set \( TR_{\text{tot}} = TR_{\text{tot}} + 1 \).

Step 14. Stop if one of the following conditions holds:
- a given solution time is exceeded;
- \( TR_{\text{tot}} \) is greater than the maximum number of iterations authorized;
- \( TR_{\text{nimp}} \) is greater than a given value;
- \( C_{\text{min}} \) is lower than a given cost value.

Go to Step 2 otherwise.

This algorithm can be applied for assigning operations from \( N \) to vertical turret with \( m_0=1, N_i=\emptyset \) and \( N_i=N_i \). Then this assignment should be combined with the assignment of \( N_2 \) 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

<table>
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<tr>
<th>Parameters of problems</th>
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<tr>
<td>(</td>
<td>N</td>
<td>)</td>
<td>OSP</td>
<td>DM</td>
<td>DT</td>
<td>DP</td>
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<tr>
<td>Min value</td>
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<td>0.027</td>
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<tr>
<td>Max value</td>
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<td>0.659</td>
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<tr>
<td>Av. value</td>
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<td>0.106</td>
<td>0.373</td>
<td>0.348</td>
<td>0.024</td>
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### Table 2. Parameters of problems for 6 parts

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<td>(</td>
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<td>)</td>
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<tr>
<td>Min value</td>
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<td>0.024</td>
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<tr>
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<tr>
<td>Av. value</td>
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### Table 3. Parameters of problems for 8 parts

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<td>(</td>
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<tr>
<td>Min value</td>
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<td>0.003</td>
<td>0.002</td>
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<td>0.024</td>
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<tr>
<td>Max value</td>
<td>216</td>
<td>0.456</td>
<td>0.438</td>
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<tr>
<td>Av. value</td>
<td>165</td>
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### Table 4. Calculation results

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<th>NSOL</th>
<th>NOPT</th>
<th>AVED</th>
<th>MIND</th>
<th>MAXD</th>
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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.
REFERENCES


