Variety-oriented design of rotary production systems

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A B S T R A C T

The variety oriented design problem for rotary production systems is considered. Given the multiple parts to be produced, the problem is to determine the feasible configurations of the machining system with minimum cost. This problem is modelled as a combinatorial optimization problem. Constraints related to the design of machining units as well as to the precedence and compatibility of operations are taken into account. The optimization methods developed to solve the problem are based on its MIP formulation. An industrial example is presented.

1. Introduction

Managing variety is a great challenge facing industry today. In order to reduce the expenses related to the initial setup of the system capacities required by related but different items, such as variants of a product family, variety-oriented planning of capabilities and capacities is needed on the manufacturing-side. Therefore, the manufacturing system should be designed to fit the product variety to be produced [1]. Several approaches for variety-oriented design of manufacturing systems were proposed in the literature, mostly for assembly systems [2–5].

This paper studies variety-oriented design of rotary production systems used for machining parts. In such a production system, parts are sequentially machined on m (1, 2, . . ., m) working positions. An example of such a position is provided in Fig. 1. A circular transfer is realized from the zero position where the billet is loaded through all working positions. Each finished part is unloaded at the zero position before the loading of the next billet to be processed.

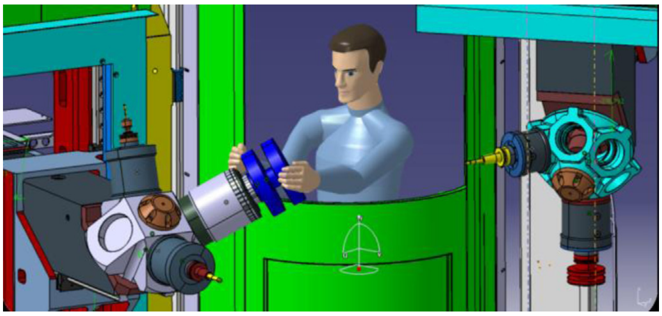

Fig. 1. A rotary machining system.

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At each working position, several machining modules (spindle heads) can be installed to process the operations assigned to this position. The machining modules can work sequentially or simultaneously on the same part. Sequential machining is realized by the use of turrets. Simultaneous machining is possible if machining modules applied to different sides of the part work in parallel. Such production systems can use horizontal and vertical spindle heads and turrets to access to different sides of parts at a working position.

Such production systems are modular and can be adapted according to the parts to be produced [6], i.e. the fixtures of parts are changed and some spindles are mounted or dismounted if necessary. However, few studies published in the literature on the design of rotary production systems were mostly dedicated to the mass production case [7–12]. In difference to that previous work, this paper considers the case of the production of different variants of a product family. Therefore, the production system has to be adapted for producing different product models. The design objective is to choose the equipment to be used by the rotary production system such as – turrets (a turret has several machining modules) and spindle heads – to be installed at all working positions. The goal is to minimize the cost of the equipment required for producing all given product variants. The following decisions must be also made: the choice of orientations of parts, the partitioning of the given set of operations into positions and assignments them to the equipment, and the choice of cutting modes for each spindle head and turret.

The developed design approach offers a mathematical model for the description of the part parameters and operations, constraints between operations and machining modules and technological constraints for rotary productions systems (Section 2). With the use of this model, the design problem is formulated as a combinatorial optimization problem. A mixed integer programming (MIP) approach is used to find the optimal solutions. An industrial example is presented in Section 3.

2. Problem statement

In this section, the mathematical model for variety-oriented design problem for rotary production systems is presented. Let us consider the case where d_0 product variants have to be produced with required output O_d, $d = 1, 2, \ldots, d_0$.

Let $\mathbf{N}^d$ be the set of operations needed for machining dth part, $d = 1, 2, \ldots, d_0$, with n_d sides to be machined; N_s^d, $s = 1, 2, \ldots, n_d$, is a subset of operations to be realized on sth side of part d.

The part d can be located at zero position in different orientations $\mathbf{H}(d)$ which define the initial part exposure.

The set of all different operations to be performed is defined as $\mathbf{N} = \bigcup_{d=1}^{d_0} \mathbf{N}^d$. All operations $p \in \mathbf{N}$ are characterized by the following parameters:

- The 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 complete operation p;
- Range $[\gamma_1(p), \gamma_2(p)]$ of feasible values of feed rate which characterizes the machining speed;
- Set $H(p,j)$ of feasible orientations of the part for operation $p \in \mathbf{N}$ if operation p can be assigned to spindle head or turret of type j ($j = 1$ for vertical and $j = 2$ for horizontal).

It should be noted that no solution exists if $\bigcap_{p \in N_s^d} H(p, j) = \varnothing$ for each $j \in \{1, 2\}$ and some $d \in \{1, 2, \ldots, d_0\}$, $s \in \{1, 2, \ldots, n_d\}$.

Let subset N_k, $k = 1, \ldots, m$ contain the operations from set $\mathbf{N}$ assigned to the kth 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 installed at the kth 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. In the considered case, only one vertical turret or spindle head can be used to perform vertical operations at any working position. In addition, each position can be equipped with one horizontal turret or spindle head.

The assignment of operations to machining modules has to respect the technological constraints that emanate from the machining process. First, precedence constraints specified by a directed graph $G^{OR} = (\mathbf{N}, D^{OR})$ have to be respected. An arc $(p, q) \in D^{OR}$ if and only if operation p has to be executed before operation q. It should be noted that if such operations p and q belong to different sides of the part, then they cannot be assigned to the same working position.

Tolerance constraints require 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 different parts and for each pair of operations). Such inclusion constraints are modelled 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 operations p and q must be executed by the same spindle, at the same machining position (or turret).

Because of unfeasible tool location or technological incompatibility, some operations cannot be performed by the same spindle head, turret, etc. These exclusion constraints are modelled 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 operations p and q cannot be executed by the same machining module, turret or at the same position. It should be noted that some operations can be assigned to the same spindle head but not to the same turret.

Let $P = \langle P_1, \ldots, P_k, \ldots, P_m \rangle$ 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 $t^b(P_{dkjl}) = L(N_{dkjl})/\Gamma_{dkjl} + \tau^a$ of operations from N_{dkjl} where $\Gamma_{dkjl} \in [max\{\gamma_1(p)|p \in N_{dkjl}\}, min\{\gamma_2(p)|p \in N_{dkjl}\}]$ and $L(N_{dkjl}) = max\{\lambda(p)\ |p \in N_{dkjl}\}$, τ^a is an additional time for advance and disengagement of tools.

We assume that only time needed for rotation of the turret between nonempty sets N_{dkjl} is taken into account and the execution time is equal to:

$$t^h(P_{dkj}) = \tau^g(l^d_{\max}(P_{dkj}) - l^d_{\min}(P_{dkj})) + \sum_{l=1}^{b_{kj}} t^b(P_{dkjl}), \quad j = 1, 2,$$

where τ^g is an additional time for one rotation of turret, $l^d_{\max}(P_{dkj}) = \max\{l = 1, 2, \ldots, b_{kj} | N_{dkjl \neq \varnothing}\}$

and $l^d_{\min}(P_{dkj}) = \min\{l = 1, 2, \ldots, b_{kj} | N_{dkjl} \neq \varnothing\}$, respectively.

The execution time at a working position $t^p(P_{dk})$ 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 the time t_d for machining all the elements of dth part is equal to $t^d(P) = max\{t^p(P_{dk})|\ k = 1, \ldots, m_0\}$.

We assume that the given productivity is provided, if the total time $T(P)$ for machining O_d parts does not exceed the available time T_0, i.e. $T(P) = \sum_{d=1}^{d_0} t^d(P) O^d \leq T_0$.

The constraint on the productivity is respected if and only if it is satisfied for $\Gamma_{dkjl} = min\{\gamma_2(p)|p \in N_{dkjl}\}$, $d = 1, \ldots, d_0$, $k = 1, \ldots, m$, $j = 1, 2$, $l = 1, \ldots, b_{kj}$.

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 installed) 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 numbers for a 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 a vertical spindle head. If the vertical spindle turret is installed, its cost can be estimated by $C_2 + C_3 b_{k1}$. In a 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:

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

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

$$\begin{aligned} Q(P) = {} & C_1 m + C_4 sign(|N_1|) \left(1 - \sum_{k=1}^{m} sign(|N_{k12}|) \right) \\ & + \sum_{k=1}^{m} sign(|N_{k12}|)(C_2 + C_3 b_{k1}) + C_5(k^h_{\max} - k^h_{\min}) \\ & + \sum_{k=1}^{m} C(b_{k2}) \to \min \end{aligned} \tag{1}$$

where $sign(a) = 1$ if $a > 0$, and $sign(a) = 0$ if $a \leq 0$.

If a vertical turret is installed, then the second and the forth sum elements are equal to 0 since $N_{k12} \neq \varnothing$ for some $k \in \{1, \ldots, m\}$ and $k^h_{\max} = k^h_{\min} = 0$. If a vertical spindle head is installed, then the second sum element is equal to C_4 and the third sum element is equal to 0, since $sign(|\mathbf{N}_1|) = 1$ and $\sum_{k=1}^{m} sign(|N_{k12}|) = 0$. If there is no vertical machining in the design decision, then the second, third and fourth summands are equal to 0, since $\mathbf{N}_1 = \varnothing$, $N_{k12} = \varnothing$, $k = 1, \ldots, m$, and $k^h_{\max} = k^h_{\min} = 0$.

Thus, the problem is to determine:

(1) The number of positions m;
(2) The orientations of parts $H(d)$;
(3) The number b_{kj} of machining modules of type j ($j = 1$ for vertical and $j = 2$ for horizontal) installed at the kth position, $k = 1, \ldots, m$;
(4) Subsets N_{dkjl} of operations from $\mathbf{N}^d$ assigned to the lth machining module of type j at the kth position, $d = 1, 2, \ldots, d_0$, $k = 1, \ldots, m$, $l = 1, \ldots, b_{kj}$;

(5) The feed per minute Γ_{dkjl} for each subset N_{dkjl}, $d = 1, 2, \ldots, d_0$, $k = 1, \ldots, m$, $j = 1, 2$, $l = 1, \ldots, b_{kj}$.

The goal is to minimize the machine cost while respecting all constraints.

$$T(P) \le T_0; \tag{2}$$

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

$$N_{k'j'l'} \cap N_{k''j''l''} = \varnothing; \quad k', k'' = 1, \ldots, m; j', j'' = 1, 2; l', l'' = 1, \ldots, b_{kj}; l' \ne l'' \tag{4}$$

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

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

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

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

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

$$\left| \bigcup_{j=1}^{2}\bigcup_{l=1}^{b_{kj}} N_{kjl} \cap \{p, q\} \right| \ne 1, (p, q) \in E^{SP};\ k = 1, \ldots, m; \tag{10}$$

$$\left| \bigcup_{l=1}^{b_{kj}} N_{kjl} \cap \{p, q\} \right| \ne 1,\ (p, q) \in E^{ST}, k = 1, \ldots, m, j = 1, 2 \tag{11}$$

$$|N_{kjl} \cap \{p, q\}| \ne 1,\ (p, q) \in E^{SB}, k = 1, \ldots, m, j = 1, 2; l = 1, \ldots, b_{kj} \tag{12}$$

$$|N_{kjl} \cap \{p, q\}| \ne 1,\ (p, q) \in E^{SS}, k = 1, \ldots, m, j = 1, 2; l = 1, \ldots, b_{kj} \tag{13}$$

$$\left| \bigcup_{j=1}^{2}\bigcup_{l=1}^{b_{kj}} N_{kjl} \cap \{p, q\} \right| \ne 2, (p, q) \in E^{DP};\ k = 1, \ldots, m \tag{14}$$

$$\left| \bigcup_{l=1}^{b_{kj}} N_{kjl} \cap \{p, q\} \right| \ne 2 \text{ or } b_{kj} = 1, (p, q) \in E^{DT};\ k = 1, \ldots, m;\ j = 1, 2 \tag{15}$$

$$N_{kjl} \cap \{p, q\} \ne 2, (p, q) \in E^{DB};\ k = 1, \ldots, m;\ j = 1, 2;\ l = 1, \ldots, b_{kj}$$
$$sign(|N_{k11}|) + \sum_{k'=1, k' \ne k}^{m} sign(|N_{k'12}|) \le 1, \tag{16}$$

$$sign(|N_{k12}|) + sign(|N_{k21}|) \le 1;\ k = 1, \ldots, m \tag{17}$$

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

$$b_{kj} \le b_0 \tag{19}$$

$$m \le m_0. \tag{20}$$

where $\Gamma_1(N) = \max\{\gamma_1(p) | p \in N\}$ and $\Gamma_2(N) = \min\{\gamma_2(p) | p \in N\}$.

Constraint (2) introduces the productivity requirement. Constraints (3)–(4) ensure that each operation from **N** is assigned to one machining module exactly. Constraint (5) obliges to choose feasible orientations of parts. Constraints (6) prohibit assignments of operations for machining elements located at two different sides of the part to a 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 of spindle head or turret. Constraints (8)–(9) provide the precedence relations for the operations that require either the same type of machining module (vertical or horizontal) or different ones, respectively. Inclusion constraints for working positions, turrets, machining modules and spindle heads 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 this 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).

The developed model can be implemented using mixed integer programming (MIP) approach.

3. Industrial example

The following 6 parts are to be machined on a rotary transfer machine (Fig. 2). The available production time T_0 = 360 min. The required outputs of the parts are (24, 24, 24, 24, 48, 48) units, respectively. Other parameters are: $\tau^a = \tau^g = \tau^r = 0.1$ min. The possible orientations of the parts are: $\mathbf{H}(1) = \mathbf{H}(3) = \{(H4\text{–}H9), (H18\text{–}H21)\}$, $\mathbf{H}(5) = \{(H4\text{–}H9), (–)\}$, $\mathbf{H}(2) = \mathbf{H}(4) = \mathbf{H}(6) = \{(H10\text{–}H15), (H16)\}$. Here orientation $(H4\text{–}H9)$ means that holes $H4\text{–}H9$ are to be assigned to vertical machining modules and (–) means that there is no vertical machining. Each operation p can be assigned either to vertical or horizontal machining modules. The parameters of the operations are given in Table 1.

Table 1
Parameters of operations.

p	Hole	Part	$\lambda(p)$, mm	$\gamma_1(p)$, mm/min	$\gamma_2(p)$, mm/min	p	Hole	Part	$\lambda(p)$, mm	$\gamma_1(p)$, mm/min	$\gamma_2(p)$, mm/min
1	H4	1	48	39.2	62.9	46	H9	3	75	44	86.5
2	H4	1	34	27.2	248	47	H18	3	29	22.3	87.6
3	H5	1	48	39.2	62.9	48	H18	3	10	28.3	106.3
4	H5	1	34	27.2	248	49	H18	3	26	59	102.9
5	H6	1	107	22.8	81.3	50	H19	3	29	22.3	87.6
6	H6	1	105	44	86.5	51	H19	3	10	28.3	106.3
7	H7	1	107	22.8	81.3	52	H19	3	26	59	102.9
8	H7	1	105	44	86.5	53	H20	3	29	22.3	87.6
9	H8	1	107	22.8	81.3	54	H20	3	10	28.3	106.3
10	H8	1	105	44	86.5	55	H20	3	26	59	102.9
11	H9	1	91	22.8	81.3	56	H21	3	29	22.3	87.6
12	H9	1	89	44	86.5	57	H21	3	10	28.3	106.3
13	H18	1	29	22.3	87.6	58	H21	3	26	59	102.9
14	H18	1	10	28.3	106.3	59	H16	4	30	54.6	68.9
15	H18	1	26	59	102.9	60	H16	4	19	31.9	197.1
16	H19	1	29	22.3	87.6	61	H16	4	19	26.9	161.6
17	H19	1	10	28.3	106.3	62	H16	4	18	26.7	160.2
18	H19	1	26	59	102.9	63	H10	4	7	35.2	105.6
19	H20	1	29	22.3	87.6	64	H11	4	7	35.2	105.6
20	H20	1	10	28.3	106.3	65	H12	4	7	35.2	105.6
21	H20	1	26	59	102.9	66	H13	4	7	35.2	105.6
22	H21	1	29	22.3	87.6	67	H14	4	7	35.2	105.6
23	H21	1	10	28.3	106.3	68	H15	4	6	35.2	105.6
24	H21	1	26	59	102.9	69	H4	5	53	39.2	62.9
25	H16	2	30	54.6	68.9	70	H4	5	34	27.2	248
26	H16	2	19	31.9	197.1	71	H5	5	53	39.2	62.9
27	H16	2	19	26.9	161.6	72	H5	5	34	27.2	248
28	H16	2	18	26.7	160.2	73	H6	5	94	22.8	81.3
29	H10	2	6	35.2	105.6	74	H6	5	92	44	86.5
30	H11	2	7	35.2	105.6	75	H7	5	94	22.8	81.3
31	H12	2	7	35.2	105.6	76	H7	5	92	44	86.5
32	H13	2	7	35.2	105.6	77	H8	5	39	22.8	81.3
33	H14	2	6	35.2	105.6	78	H8	5	37	44	86.5
34	H15	2	6	35.2	105.6	79	H9	5	94	22.8	81.3
35	H4	3	103	39.2	62.9	80	H9	5	92	44	86.5
36	H4	3	18	27.2	248	81	H16	6	30	54.6	68.9
37	H5	3	48	39.2	62.9	82	H16	6	19	31.9	197.1
38	H5	3	34	27.2	248	83	H16	6	19	26.9	161.6
39	H6	3	92	22.8	81.3	84	H16	6	18	26.7	160.2
40	H6	3	90	44	86.5	85	H10	6	6	35.2	105.6
41	H7	3	92	22.8	81.3	86	H11	6	6	35.2	105.6
42	H7	3	90	44	86.5	87	H12	6	6	35.2	105.6
43	H8	3	77	22.8	81.3	88	H13	6	6	35.2	105.6
44	H8	3	75	44	86.5	89	H14	6	6	35.2	105.6
45	H9	3	77	22.8	81.3	90	H15	6	6	35.2	105.6

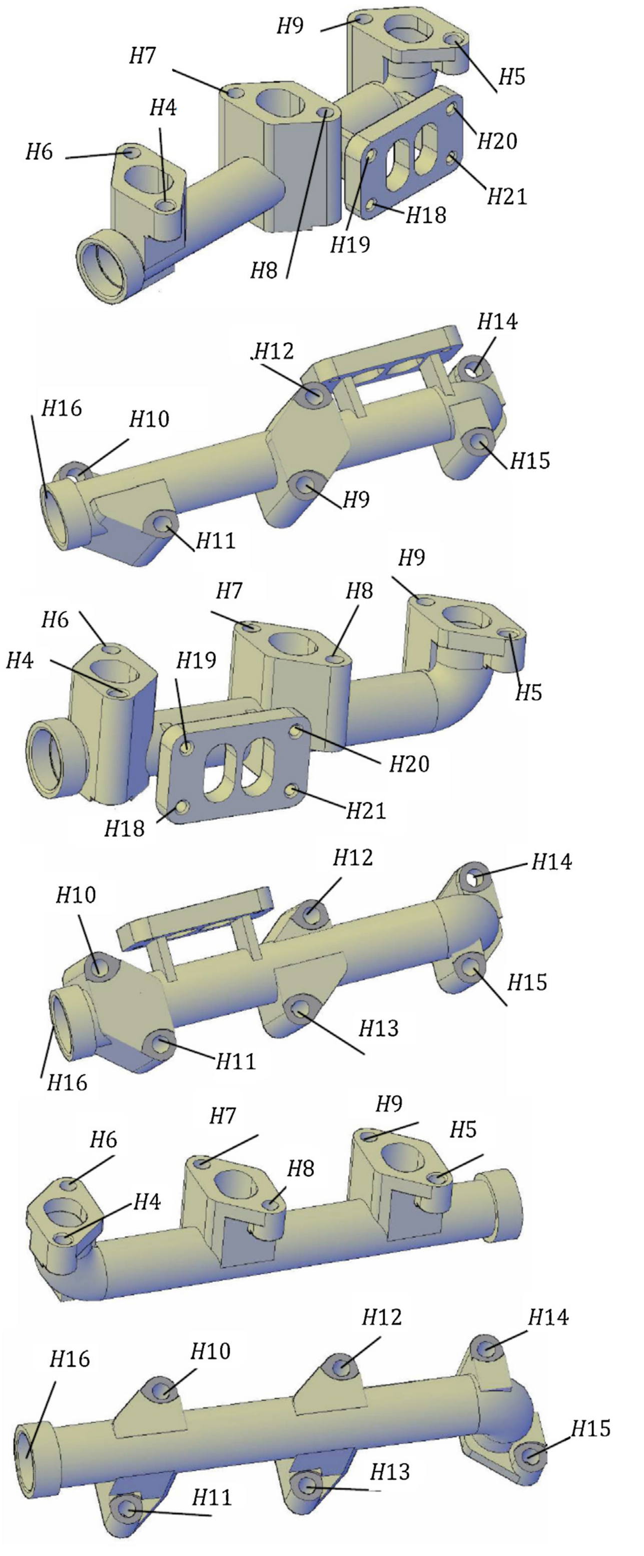

Fig. 2. The six parts to be machined.

Precedence and compatibility constraints are numerous and can be provided on demand by the corresponding author. The optimization problem was solved for $m_0 = 5$ using CPLEX 12.2. The obtained optimal solution is presented in Table 2. After preprocessing, the model contained 1488 variables and 4295 constraints. The total solution time was 21.6 s. This solution was validated and implemented by our industrial partner.

Table 2
Characteristics of the optimal solution.

Set N_{dkjl}	Operations of N_{dkjl}	$L(N_{dkjl})$	Γ_{dkjl}	$t^b(P_{dkjl})$	N_{dkjl}	Operations of N_{dkjl}	$L(N_{dkjl})$	Γ_{dkjl}	$t^b(P_{dkjl})$
N_{1111}	13 16 19 22	29	87.6	0.43	N_{1211}	14 17 20 23	10	87.6	0.22
N_{3111}	47 50 53 56	29	87.6	0.43	N_{2211}	29 30 31 32 33 34	7	87.6	0.18
N_{2121}	25	30	62.9	0.58	N_{3211}	48 51 54 57	10	87.6	0.22
N_{4121}	59	30	62.9	0.58	N_{4211}	63 64 65 66 67 68	7	87.6	0.18
N_{6121}	81	30	62.9	0.58	N_{6211}	85 86 87 88 89 90	6	87.6	0.17
N_{2122}	26	19	62.9	0.4	N_{1311}	15 18 21 24	26	87.6	0.4
N_{4122}	60	19	62.9	0.4	N_{3311}	49 52 55 58	26	87.6	0.4
N_{6122}	82	19	62.9	0.4	N_{1321}	2 4 6 8 10 12	105	86.5	1.32
N_{1123}	1 3 5 7 9 11	107	62.9	1.8	N_{2321}	28	18	86.5	0.31
N_{2123}	27	19	62.9	0.4	N_{3321}	36 38 40 42 44 46	90	86.5	1.14
N_{3123}	35 37 39 41 43 45	103	62.9	1.74	N_{4321}	62	18	86.5	0.31
N_{4123}	61	19	62.9	0.4	N_{5321}	70 72 74 76 78 80	92	86.5	1.17
N_{5123}	69 71 73 75 77 79	94	62.9	1.59	N_{6321}	84	18	86.5	0.31
N_{6123}	83	19	62.9	0.4					

4. Conclusions

A problem of variety-oriented design of rotary production systems has been studied. A mathematical model for this optimization problem has been developed where constraints between operations and machining modules and technological constraints for rotary production systems were integrated. The configuration of such systems is optimized using mixed integer programming (MIP) techniques. The configuration module has been implemented in a decision support system. This system can detect the conflicts in the constraints and guide the designer through the optimization process. The model and the module have been validated in practice. The future research work will concern the reconfiguration techniques for rotary production systems to be adapted to new manufacturing conditions.

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