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Complete List of Authors:	Valiño, Gonzalo; University of Oviedo, Department of Manufacturing Engineering Rico, J C; University of Oviedo, Department of Manufacturing Engineering MATEOS, SABINO; University of Oviedo, Department of Manufacturing Engineering SUAREZ, CARLOS MANUEL; University of Oviedo, Department of Manufacturing Engineering BLANCO, DAVID; University of Oviedo, Department of Manufacturing Engineering
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A methodology for setup planning automation of turned parts

GONZALO VALIÑO, *J. CARLOS RICO, SABINO MATEOS, CARLOS M. SUAREZ, DAVID BLANCO

Main author: J.Carlos Rico (Full Professor)
University: University of Oviedo
Department: Department of Manufacturing Engineering
Address: Department of Manufacturing Engineering
Campus de Gijón
33203 Gijón – Asturias
SPAIN
Telephone No: +34 985182062
Fax No: +34 985182016
E-mail: jcarlosr@uniovi.es

Abstract

This paper presents an automatic setup planning module integrated in a CAPP system for rotational parts to be machined on a lathe. The developed system determines the possible setup combinations that are necessary for a complete machining of the part as well as the order of each setup and the surfaces to be used for clamping the part. The methodology applied takes into consideration constraints such as the geometry of both the stock and the final part, the geometry and the capacity of the chuck and the part tolerances. In general, these constraints allow the system to obtain several valid solutions for clamping the part. Some criteria based on the clamping force and the value of tolerances, have been considered in order to establish a preference order among these solutions. Finally, the analysis of *linked tolerances* and the tool approach direction to each surface determine the sets of surfaces to be machined in each setup. An example part is used in the course of the paper to conveniently illustrate the methodology used and two additional case studies prove that this methodology is adequate for the solution of real cases.

Keywords: Setup planning, CAPP, Turning, Tolerance Relationship, Clamping Accessibility.

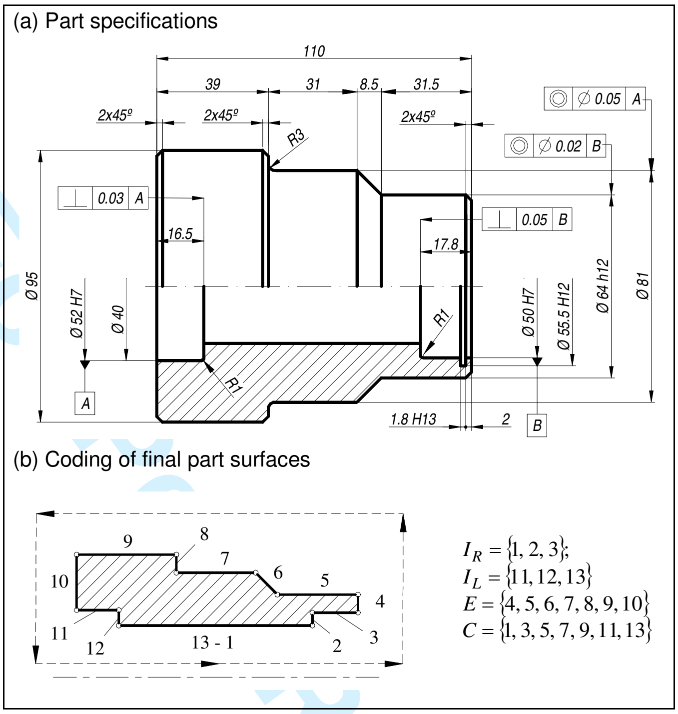

(a) Part specifications
110
39
31
8.5
31.5
2x45º
2x45º
2x45º
R3
0.05 A
0.02 B
0.03 A
16.5
17.8
0.05 B
Ø 95
Ø 52 H7
Ø 40
Ø 50 H7
Ø 55.5 H12
Ø 64 h12
Ø 81
R1
R1
A
B
1.8 H13
2
(b) Coding of final part surfaces
$I_R = \{1, 2, 3\}$;
$I_L = \{11, 12, 13\}$
$E = \{4, 5, 6, 7, 8, 9, 10\}$
$C = \{1, 3, 5, 7, 9, 11, 13\}$

Figure 1

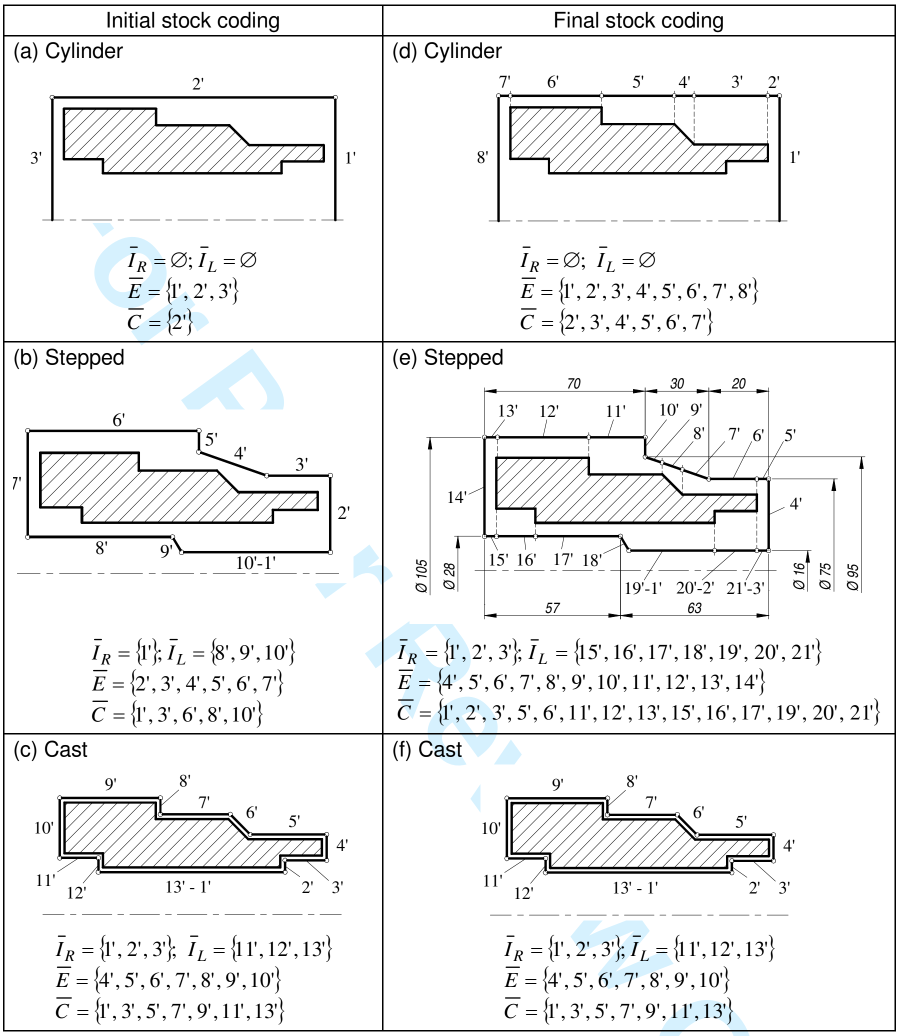

Initial stock coding
Final stock coding
(a) Cylinder
$\bar{I}_R = \varnothing; \bar{I}_L = \varnothing$
$\bar{E} = \{1', 2', 3'\}$
$\bar{C} = \{2'\}$
(d) Cylinder
$\bar{I}_R = \varnothing; \bar{I}_L = \varnothing$
$\bar{E} = \{1', 2', 3', 4', 5', 6', 7', 8'\}$
$\bar{C} = \{2', 3', 4', 5', 6', 7'\}$
(b) Stepped
$\bar{I}_R = \{1'\}; \bar{I}_L = \{8', 9', 10'\}$
$\bar{E} = \{2', 3', 4', 5', 6', 7'\}$
$\bar{C} = \{1', 3', 6', 8', 10'\}$
(e) Stepped
70
30
20
57
63
Ø 105
Ø 28
Ø 16
Ø 75
Ø 95
$\bar{I}_R = \{1', 2', 3'\}; \bar{I}_L = \{15', 16', 17', 18', 19', 20', 21'\}$
$\bar{E} = \{4', 5', 6', 7', 8', 9', 10', 11', 12', 13', 14'\}$
$\bar{C} = \{1', 2', 3', 5', 6', 11', 12', 13', 15', 16', 17', 19', 20', 21'\}$
(c) Cast
$\bar{I}_R = \{1', 2', 3'\}; \bar{I}_L = \{11', 12', 13'\}$
$\bar{E} = \{4', 5', 6', 7', 8', 9', 10'\}$
$\bar{C} = \{1', 3', 5', 7', 9', 11', 13'\}$
(f) Cast
$\bar{I}_R = \{1', 2', 3'\}; \bar{I}_L = \{11', 12', 13'\}$
$\bar{E} = \{4', 5', 6', 7', 8', 9', 10'\}$
$\bar{C} = \{1', 3', 5', 7', 9', 11', 13'\}$

Figure 2

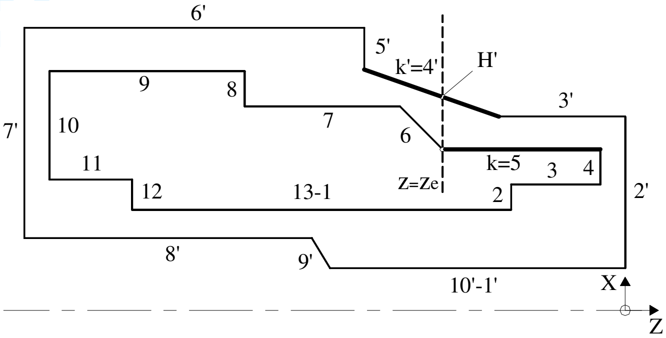
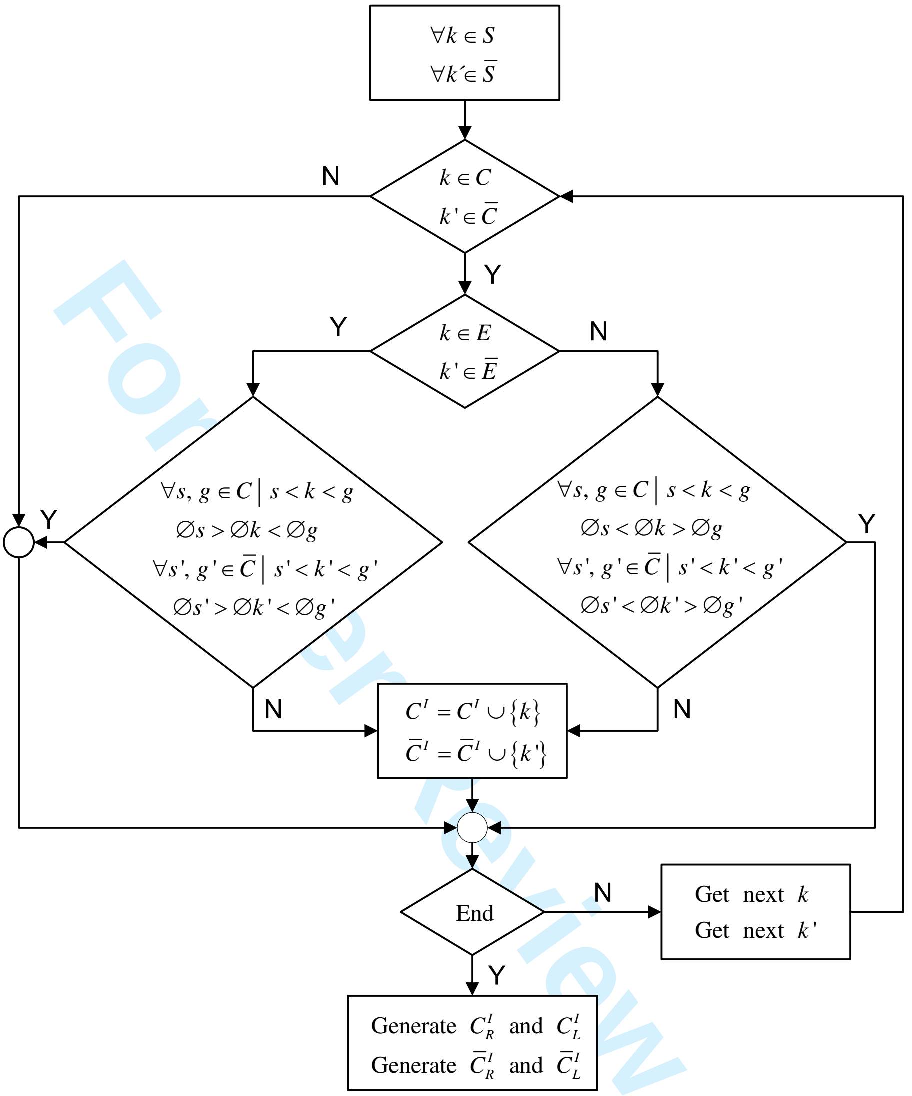


Figure 3



$\forall k \in S$
$\forall k' \in \bar{S}$
$k \in C$
$k' \in \bar{C}$
N
Y
$k \in E$
$k' \in \bar{E}$
Y
N
$\forall s, g \in C \mid s < k < g$
$\varnothing s > \varnothing k < \varnothing g$
$\forall s', g' \in \bar{C} \mid s' < k' < g'$
$\varnothing s' > \varnothing k' < \varnothing g'$
$\forall s, g \in C \mid s < k < g$
$\varnothing s < \varnothing k > \varnothing g$
$\forall s', g' \in \bar{C} \mid s' < k' < g'$
$\varnothing s' < \varnothing k' > \varnothing g'$
Y
Y
N
N
$C^I = C^I \cup \{k\}$
$\bar{C}^I = \bar{C}^I \cup \{k'\}$
End
N
Y
Get next k
Get next k'
Generate C_R^I and C_L^I
Generate $\bar{C}_R^I$ and $\bar{C}_L^I$

Figure 4

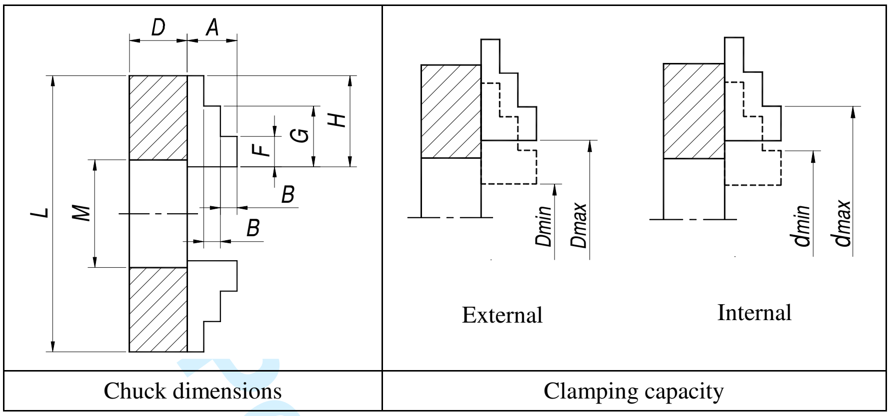

D
A
L
M
F
G
H
B
B
Chuck dimensions
Dmin
Dmax
External
dmin
dmax
Internal
Clamping capacity

Figure 5

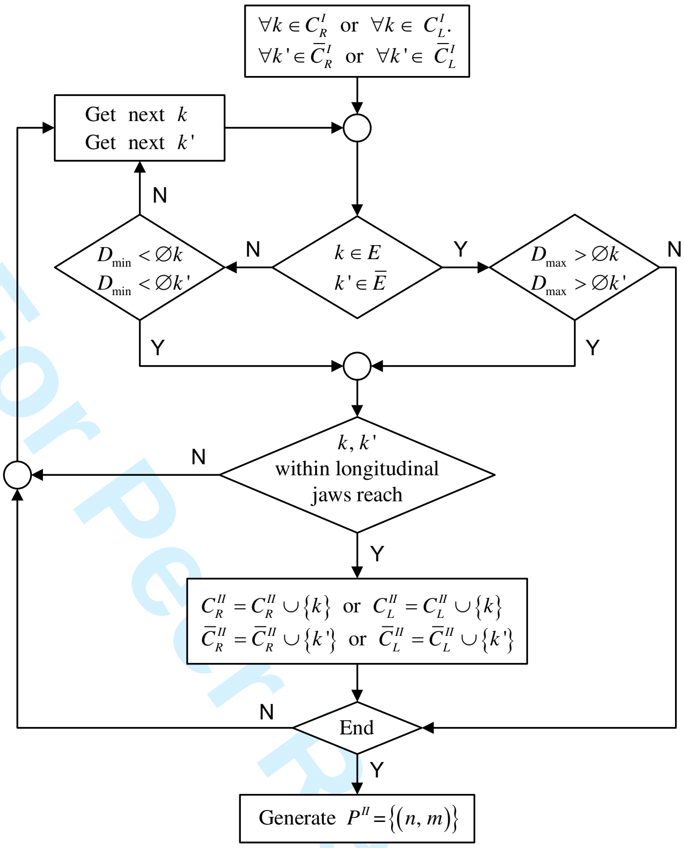

$\forall k \in C_R^I$ or $\forall k \in C_L^I$.
$\forall k' \in \bar{C}_R^I$ or $\forall k' \in \bar{C}_L^I$
Get next k
Get next k'
N
$D_{\min} < \varnothing k$
$D_{\min} < \varnothing k'$
N
$k \in E$
$k' \in \bar{E}$
Y
$D_{\max} > \varnothing k$
$D_{\max} > \varnothing k'$
N
Y
Y
k, k'
within longitudinal
jaws reach
N
Y
$C_R^{II} = C_R^{II} \cup \{k\}$ or $C_L^{II} = C_L^{II} \cup \{k\}$
$\bar{C}_R^{II} = \bar{C}_R^{II} \cup \{k'\}$ or $\bar{C}_L^{II} = \bar{C}_L^{II} \cup \{k'\}$
N
End
Y
Generate $P^{II} = \{(n, m)\}$

Figure 6

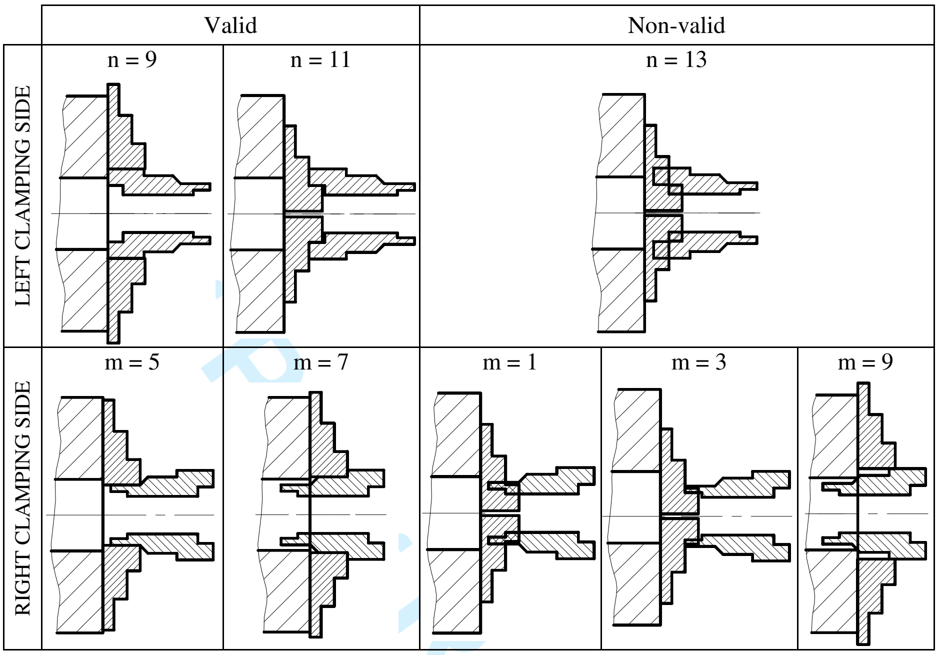

Valid
Non-valid
n = 9
n = 11
n = 13
LEFT CLAMPING SIDE
m = 5
m = 7
m = 1
m = 3
m = 9
RIGHT CLAMPING SIDE

Figure 7

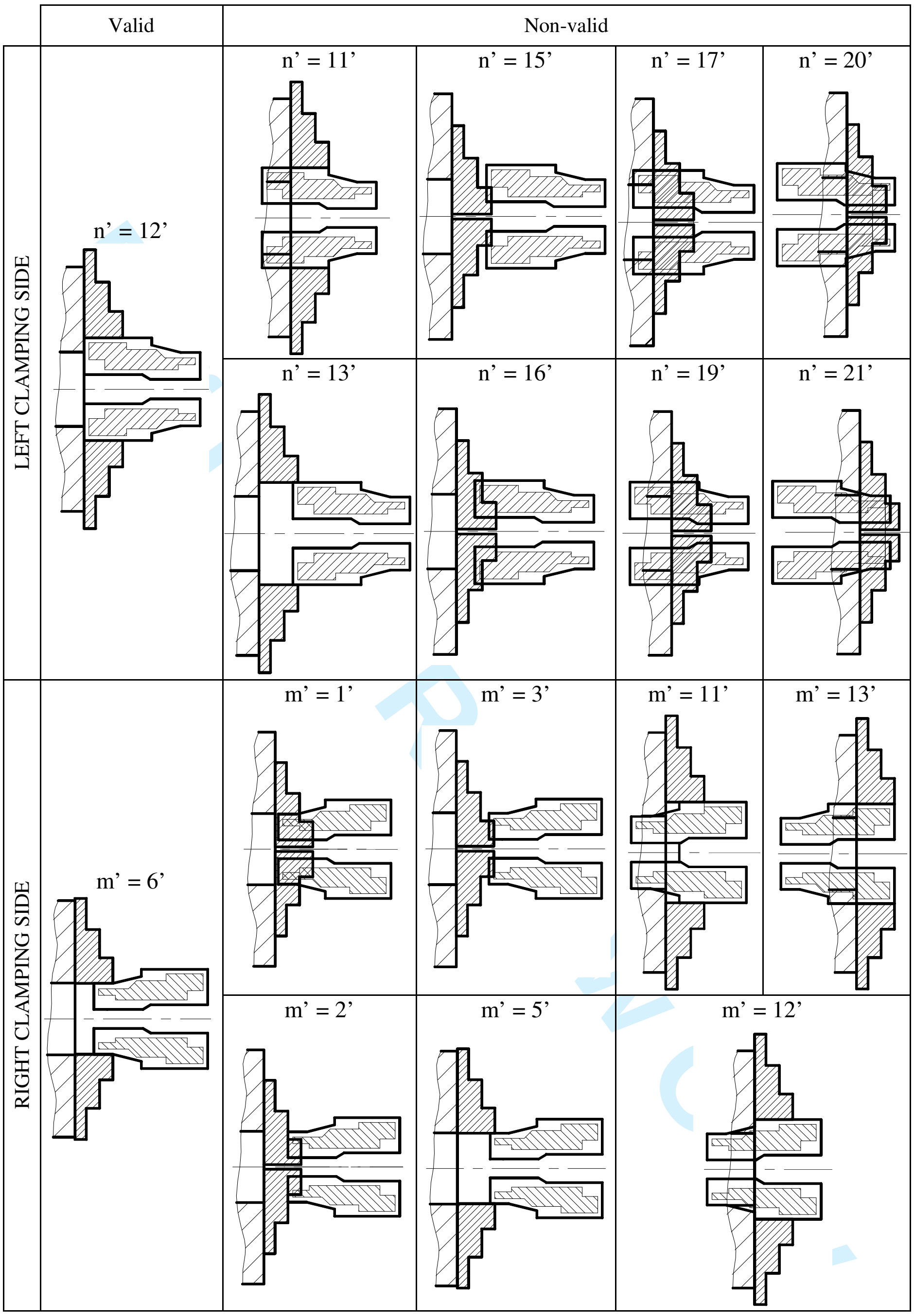

Valid
Non-valid
LEFT CLAMPING SIDE
n’ = 12’
n’ = 11’
n’ = 15’
n’ = 17’
n’ = 20’
n’ = 13’
n’ = 16’
n’ = 19’
n’ = 21’
RIGHT CLAMPING SIDE
m’ = 6’
m’ = 1’
m’ = 3’
m’ = 11’
m’ = 13’
m’ = 2’
m’ = 5’
m’ = 12’

Figure 8

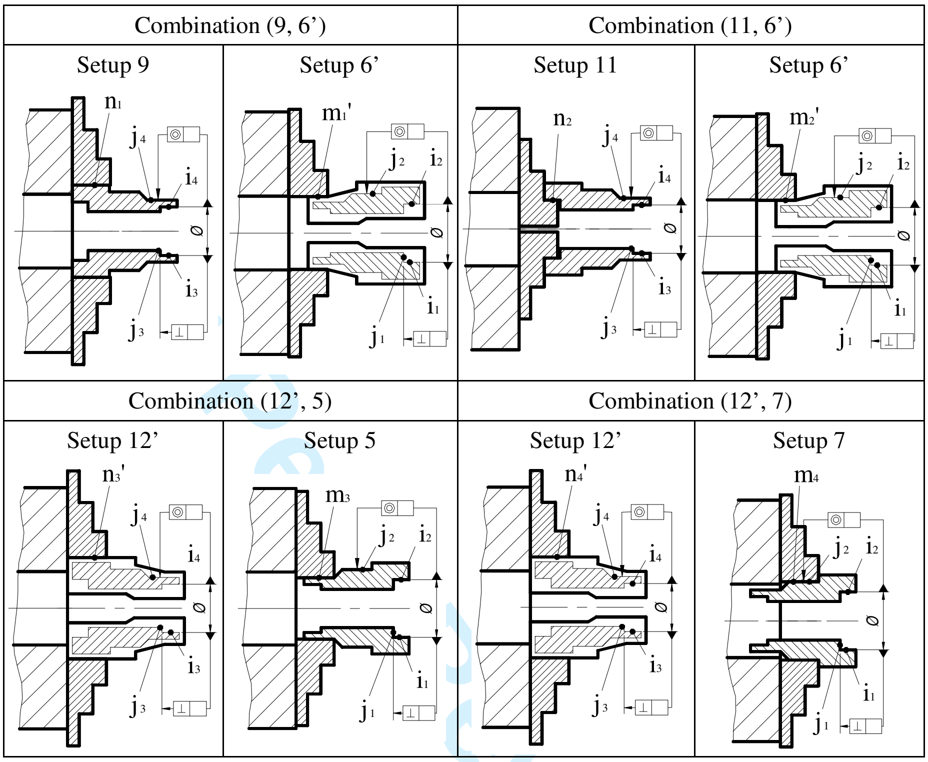

Combination (9, 6’)
Combination (11, 6’)
Setup 9
Setup 6’
Setup 11
Setup 6’
Combination (12’, 5)
Combination (12’, 7)
Setup 12’
Setup 5
Setup 12’
Setup 7

Figure 10

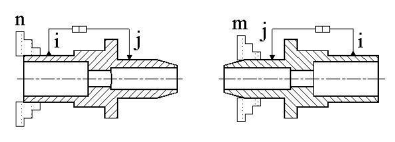
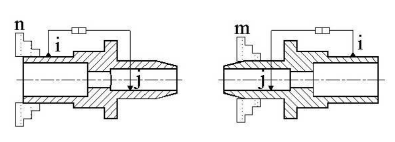
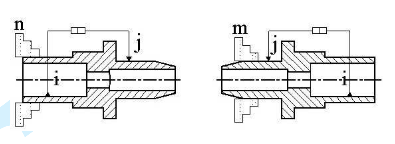
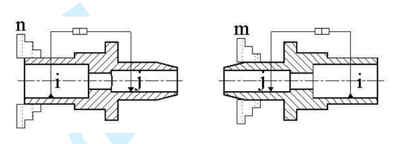
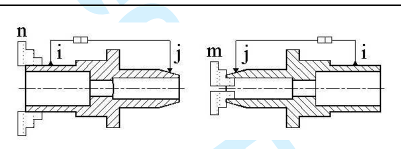
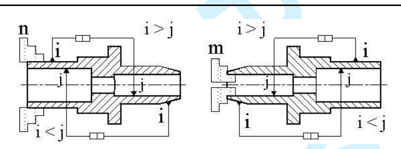
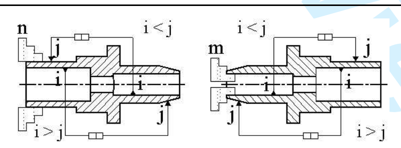
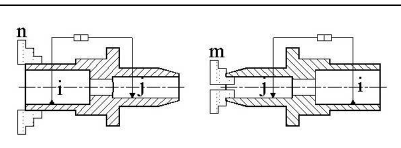
(n, m)	(i, j)	Diagram	Rejection conditions
(n_{ext}, m_{ext})	(i_{ext}, j_{ext})		if min $(i, j) \le n \le$ max (i, j) and min $(i, j) \le m \le$ max (i, j)
	(i_{ext}, j_{int})		
	(i_{int}, j_{ext})		
	(i_{int}, j_{int})		if min $(i, j) \le n \le$ max (i, j) or min $(i, j) \le m \le$ max (i, j)
(n_{ext}, m_{int})	(i_{ext}, j_{ext})		if min $(i, j) \le n \le$ max (i, j) and min (i, j) – min $(k_{ext}) \le 1$
	(i_{ext}, j_{int})		Case $i > j$: if min $(i, j) = j \le n \le i =$ max (i, j) Case $i < j$: if i - min $(k_{ext}) \le 1$
	(i_{int}, j_{ext})		Case $i > j$: if j - min $(k_{ext}) \le 1$ Case $i < j$: if min $(i, j) = i \le n \le j =$ max (i, j)
	(i_{int}, j_{int})		if min $(i, j) \le n \le$ max (i, j)

Figure 11

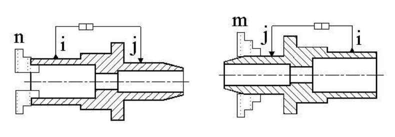
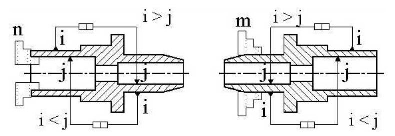
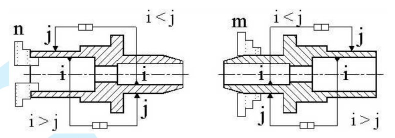
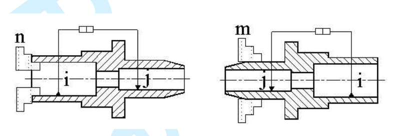
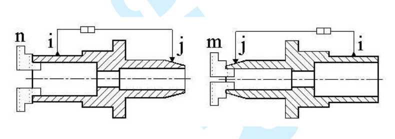
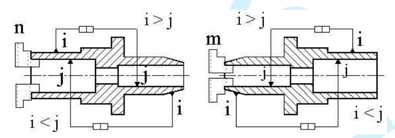
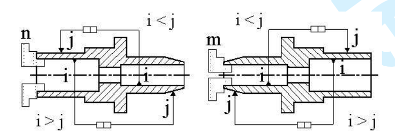
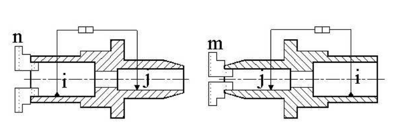
(n, m)	(i, j)	Diagram	Rejection conditions
$(n_{\text{int}}, m_{\text{ext}})$	$(i_{\text{ext}}, j_{\text{ext}})$		if $\min(i, j) \le m \le \max(i, j)$ and $\max(k_{\text{ext}}) - \max(i, j) \le 1$
	$(i_{\text{ext}}, j_{\text{int}})$		Case $i > j$: if $\max(k_{\text{ext}}) - i \le 1$ Case $i < j$: if $\min(i, j) = i \le m \le j = \max(i, j)$
	$(i_{\text{int}}, j_{\text{ext}})$		Case $i > j$: if $\min(i, j) = j \le m \le i = \max(i, j)$ Case $i < j$: if $\max(k_{\text{ext}}) - j \le 1$
	$(i_{\text{int}}, j_{\text{int}})$		if $\min(i, j) \le m \le \max(i, j)$
$(n_{\text{int}}, m_{\text{int}})$	$(i_{\text{ext}}, j_{\text{ext}})$		If $\min(i, j) - \min(k_{\text{ext}}) \le 1$ and $\max(k_{\text{ext}}) - \max(i, j) \le 1$
	$(i_{\text{ext}}, j_{\text{int}})$		Case $i > j$: if $\max(k_{\text{ext}}) - i \le 1$ Case $i < j$: if $i - \min(k_{\text{ext}}) \le 1$
	$(i_{\text{int}}, j_{\text{ext}})$		Case $i > j$: if $j - \min(k_{\text{ext}}) \le 1$ Case $i < j$: if $\max(k_{\text{ext}}) - j \le 1$
	$(i_{\text{int}}, j_{\text{int}})$		if $\min(i, j) \le \min(k_{\text{ext}})$ and $\max(k_{\text{ext}}) < \max(i, j)$

Figure 12

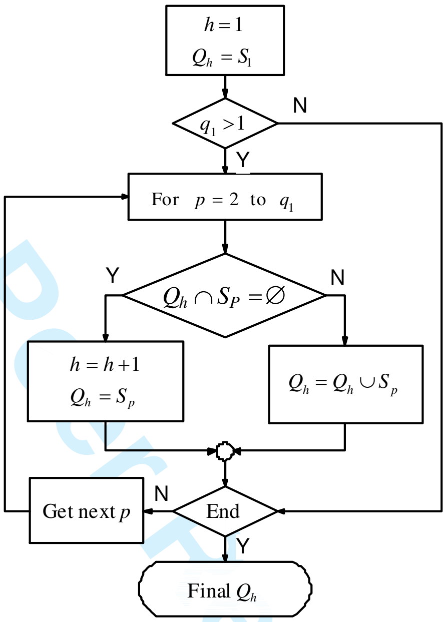

$h = 1$
$Q_h = S_1$
$q_1 > 1$
N
Y
For $p = 2$ to q_1
$Q_h \cap S_P = \varnothing$
Y
N
$h = h + 1$
$Q_h = S_p$
$Q_h = Q_h \cup S_p$
Get next p
N
End
Y
Final Q_h

Figure 13

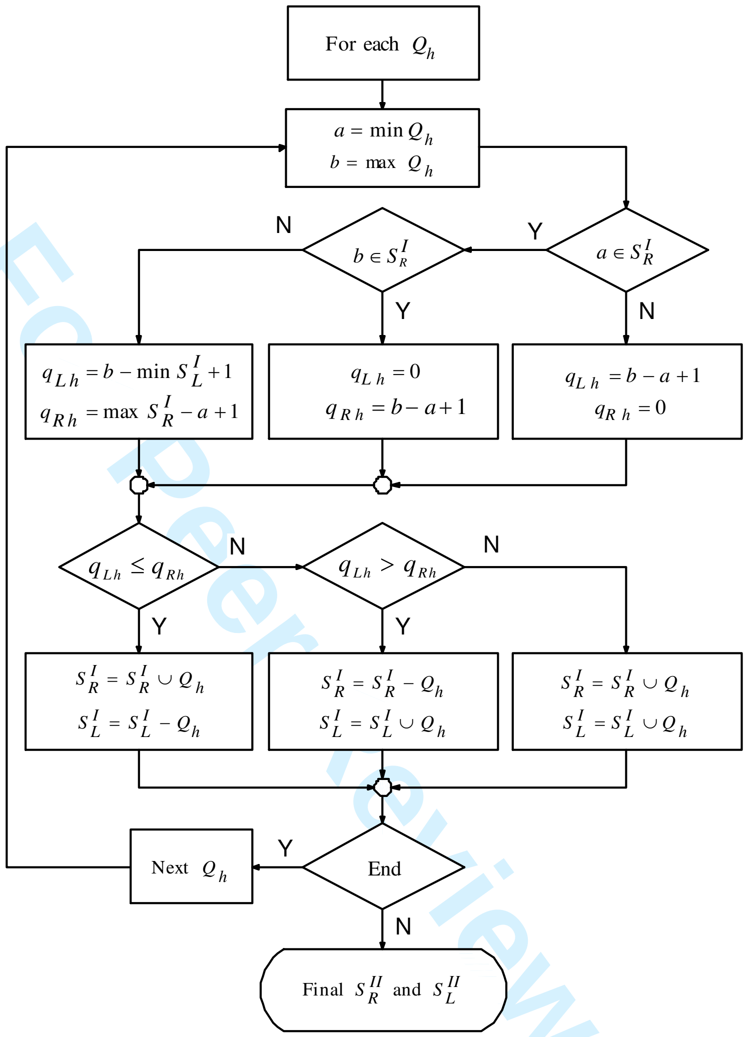
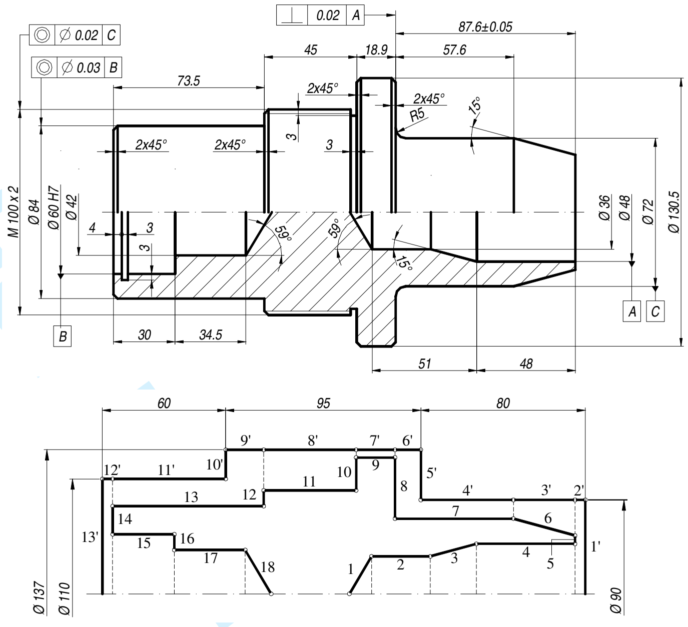

For each Q_h
$a = \min Q_h$
$b = \max Q_h$
$b \in S_R^I$
$a \in S_R^I$
N
Y
Y
N
$q_{Lh} = b - \min S_L^I + 1$
$q_{Rh} = \max S_R^I - a + 1$
$q_{Lh} = 0$
$q_{Rh} = b - a + 1$
$q_{Lh} = b - a + 1$
$q_{Rh} = 0$
$q_{Lh} \le q_{Rh}$
$q_{Lh} > q_{Rh}$
N
N
Y
Y
$S_R^I = S_R^I \cup Q_h$
$S_L^I = S_L^I - Q_h$
$S_R^I = S_R^I - Q_h$
$S_L^I = S_L^I \cup Q_h$
$S_R^I = S_R^I \cup Q_h$
$S_L^I = S_L^I \cup Q_h$
Next Q_h
Y
End
N
Final S_R^{II} and S_L^{II}

Figure 14

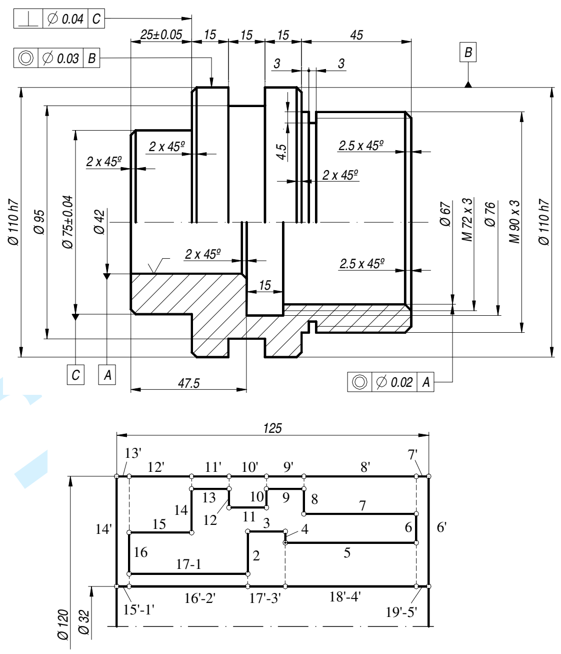
Example 1



Final part coding	Stock coding
$S=\{1,2,3,\ldots,18\}$ $I_R=\{1,2,3,4\}$ $I_L=\{15,16,17,18\}$ $E=\{5,6,7,\ldots,14\}$ $C=\{2,4,7,9,11,13,15,17\}$	$\bar{S}=\{1',2',3',\ldots,13'\}$ $\bar{I}_R=\{\varnothing\}$ $\bar{I}_L=\{\varnothing\}$ $\bar{E}=\{1',2',3',\ldots,13'\}$ $\bar{C}=\{2',3',4',6',7',8',9',11',12'\}$
$C^*=\{(2',0),(3',6),(4',7),(6',7),(7',9),(8',11),(9',13),(11',13),(12',0)\}$	
$C^I=\{2,4,7,9,13,15,17\}$	$\bar{C}^I=\{2',3',4',6',7',8',9',11',12'\}$
$C_R^{II}=\{7\}$; $C_L^{II}=\{13\}$	$\bar{C}_R^{II}=\{3'\}$; $\bar{C}_L^{II}=\{11'\}$
$P^{II}=\{(11',7),(13,3')\}$ $P^{II*}=\{(13,7),(13,6)\}$	
$P^{III*}=\{(13,7),(13,6)\}$ $P^{III}=\{(11',7),(13,3')\}$	
Valid setup combinations: $P^{IV}=\{(13,3'),(11',7)\}$	
Right machining surfaces: $S_R^I=\{1,2,3,\ldots,11\}$	
Left machining surfaces: $S_L^I=\{12,13,14,\ldots,18\}$	

Figure 15

Example 2



Final part coding	Stock coding
$S=\{1,2,3,\ldots,17\}$ $I_R=\{2,3,4,5\}$ $I_L=\{17\}$ $E=\{6,7,8,\ldots,16\}$ $C=\{1,3,5,7,9,11,13,15,17\}$	$\bar{S}=\{1',2',3',\ldots,19'\}$ $\bar{I}_R=\{1',2',3',4',5'\}$ $\bar{I}_L=\{15',16',17',18',19'\}$ $\bar{E}=\{6',7',8',\ldots,14'\}$ $\bar{C}=\left\{\begin{matrix}1',2',3',4',5',7',8',9',10',11',\\12',13',15',16',17',18',19'\end{matrix}\right\}$
$C^*=\left\{\begin{matrix}(1',0),(2',1),(3',3),(4',5),(5',0),(7',0),(8',7),(9',9),(10',11),\\(11',13),(12',15),(13',0),(15',0),(16',17),(17',3),(18',5),(19',0)\end{matrix}\right\}$	
$C^I=\{9,13,15\}$	$\bar{C}^I=\{1',2',3',\ldots,19'\}$
$C_R^{II}=\{\varnothing\}$; $C_L^{II}=\{13,15\}$	$\bar{C}_R^{II}=\{8'\}$; $\bar{C}_L^{II}=\{12'\}$
$P^{II}=\{(13,8'),(15,8')\}$ $P^{II*}=\{(13,7),(15,7)\}$	
$P^{III*}=\{(15,7)\}$ $P^{III}=\{(15,8')\}$	
Valid setup combinations: $P^{IV}=\{(15,8')\}$	
Right machining surfaces: $S_R^I=\{1,2,3,\ldots,13\}$	
Left machining surfaces: $S_L^I=\{14,15,16,17\}$	

Figure 16

Table 1. Equivalent valid and non-valid setup combinations according to the part tolerances

Surfaces related by tolerance $t_p = (i_p, j_p)$	Equivalent setup combination (n^*, m^*) (9, 5)	(11, 5)	(9, 7)
$t_1 = (3, 2)$	✓	✓	✓
$t_2 = (3, 3)$	✓	✓	✓
$t_3 = (3, 5)$	✓	✓	✓
$t_4 = (5, 5)$	✓	✓	✓
$t_5 = (11, 7)$	✓	✓	✗
$t_6 = (11, 11)$	✓	✓	✓
$t_7 = (11, 12)$	✓	✓	✓

Table 2. Preference order among valid setup combinations (P^{III})

Setup combination	Clamping surface: Index	Clamping surface: Diameter 2nd setup (mm)	Tolerance: $t_p = (i_p, j_p)$	Tolerance: Value	Partial precedence order: By clamping force	Partial precedence order: By tolerance value	Final precedence order
(12', 5)	12'		$t_1 = (3, 2)$	0.05	2	2	2
			$t_2 = (3, 3)$	0.025			
			$t_3 = (3, 5)$	0.02			
			$t_4 = (5, 5)$	0.3			
	5	64	$t_5 = (11, 7)$	0.05			
			$t_6 = (11, 11)$	0.03			
			$t_7 = (11, 12)$	0.03			
(9, 6')	6'		$t_5 = (11, 7)$	0.05	1	1	1
			$t_6 = (11, 11)$	0.03			
			$t_7 = (11, 12)$	0.03			
	9	95	$t_1 = (3, 2)$	0.05			
			$t_2 = (3, 3)$	0.025			
			$t_3 = (3, 5)$	0.02			
			$t_4 = (5, 5)$	0.3			
(11, 6')	6'		$t_5 = (11, 7)$	0.05	3	1	3
			$t_6 = (11, 11)$	0.03			
			$t_7 = (11, 12)$	0.03			
	11	60	$t_1 = (3, 2)$	0.05			
			$t_2 = (3, 3)$	0.025			
			$t_3 = (3, 5)$	0.02			
			$t_4 = (5, 5)$	0.3			

Table 3. Surfaces to be machined in the first and second setups

Setup combination P^{IV}	First setup		Second setup	
	Clamping surface	Set of surfaces to be machined	Clamping surface	Set of surfaces to be machined
(9, 6')	6'	$S_L^{II} = \{7, 8, ..., 13\}$	9	$S_R^{II} = \{2, 3, ..., 6\}$
(12', 5)	12'	$S_R^{II} = \{1, 2, ..., 6\}$	5	$S_L^{II} = \{7, 8, ..., 12\}$
(11, 6')	6'	$S_L^{II} = \{7, 8, ..., 13\}$	11	$S_R^{II} = \{2, 3, ..., 6\}$