



TECHNICAL UNIVERSITY – GABROVO

**Faculty: "Mechanical Engineering and
Instrumentation"**

**Department: "Mechanical Engineering Equipment
and Technologies"**

mag. eng. NIKOLAY PENKOV KOLEV

**OPTIMIZATION OF TECHNOLOGICAL PROCESSES
FOR PART PROCESSING ON CNC MACHINES WITH
ROBOTIC FEEDING**

AUTOREFERAT

to acquire an educational and scientific degree

DOCTOR

Field of higher education: 5. Technical science

Professional field: 5.1. Mechanical Engineering

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Research supervisors: **Prof. Dr. eng. Irina Stefanova Alexandrova**
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The dissertation was discussed and directed for official defense at a meeting of the Extended Department Council of the Department of Mechanical Engineering and Technologies at the Faculty of Mechanical Engineering and Instrumentation of the Technical University - Gabrovo, held on 16.03.2026.

The dissertation work contains 114 pages and an appendix. The scientific content is presented in an introduction, 4 chapters and a conclusion and includes 41 figures, 21 tables and 1 appendix. 126 literary sources are cited. The numbering of the figures, tables and formulas in the abstract is in accordance with that in the dissertation.

The development/research of the dissertation work was/are carried out in the Department of Mechanical Engineering and Technologies at the Faculty of Mechanical Engineering and Instrumentation of the Technical University - Gabrovo and in the company "ADTECH" EOOD, Gabrovo.

The official defense of the dissertation will take place on 09. 07. 2026 at 14:30 in the Conference Hall, Rectorate building of the Technical University - Gabrovo.

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GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

Despite their advantages, CNC machines have one serious drawback - their high productivity is often not used effectively due to the need for manual operation. Feeding and unloading of parts, changing pallets and handling of blanks are usually performed by operators, which leads to unpredictable downtime and limited production capacity. According to a number of studies, auxiliary operations account for 25÷40% of the total production cycle time. This means that even the most modern CNC machine cannot reach its full potential without an integrated automated feeding system.

In addition to purely economic, the implementation of robotic systems also has social dimensions. Through automation, operators are freed from heavy and repetitive operations, which improves work ergonomics and safety in the production environment. The likelihood of accidents related to the manipulation of heavy workpieces is reduced, as well as injuries caused by close contact with rotating machine parts.

All these factors clearly demonstrate the relevance of the issue of optimizing technological processes in machining parts on CNC machines using robotic feeding. The topic is strategic for the development of Bulgarian industry in the context of its integration into the European production network and achieving the goals of Industry 4.0 and Industry 5.0.

Purpose and tasks of the dissertation work

The purpose of the dissertation work is to optimize the CNC turning process with robotic feeding according to the criteria of productivity, durability of cutting tools and roughness of the machined surfaces and to ensure a continuous work cycle when processing heat-treated (hardened and high-temperature tempered) steel 42CrMo4.

To achieve the set goal, it is necessary to solve the following main tasks:

1. Development of a methodology for research, modeling and optimization of the turning process on CNC machines with robotic feed.
2. Research and modeling of the productivity, durability of cutting tools and roughness of the machined surfaces when processing heat-treated (hardened and high-temperature annealed) steel 42CrMo4 in CNC turning with robotic feed.
3. Multi-objective optimization of the CNC turning process with robotic feed and determination of the optimal cutting modes when processing 42CrMo4 steel.
4. Ensuring a continuous work cycle of CNC machines with robotic feed.

Research methods

The research presented in the work has been carried out using modern and adequate methods and technical means for solving the tasks set. Methods for modeling, statistical processing and analysis of experimental results, planning of experiments and optimization using specialized software have been applied.

Scientific novelty

The scientific novelty is concluded in:

- Regression models of the parameter Ra of roughness, productivity and durability of cutting tools when machining on CNC turning machines with two types of robotic feeding stations.
- Methodology for multi-objective compromise optimization of the CNC turning process with robotic feeding.
- Methodology for determining the number of cutting tools to ensure a continuous work process depending on the durability of the tools, the capacity of the tool magazine and the feeding mechanism and the volume of the production program

Applicability

- Optimal cutting modes when turning improved steel 42CrMo4 on CNC lathes with robotic stations.
- Algorithm for a software product for controlling the operation of CNC lathes with robotic feeding.

Approbation of the dissertation work

The dissertation work was reported and discussed at an extended meeting of the Department of Mechanical Engineering and Technologies at the Technical University of Gabrovo.

Stages of the dissertation work were discussed and published in:

- 16th International Scientific and Practical Conference on Environment. Technology. Resources. Rezekne, Latvia, 2025;
- International Conference "Automatics and Informatics", Varna, Bulgaria, 2025;
- International Scientific Conference UNITECH 2023, 2024, Gabrovo, Bulgaria.

Structure and volume of the dissertation work

The dissertation work consists of: table of contents, accepted notations and abbreviations, introduction, 4 chapters, conclusion, classification of contributions, list of publications on the dissertation, used literature and appendix, in a total volume of 114 pages, which contain text, formulas, 41 figures and graphs and 21 tables.

The literature includes 92 titles (articles, reports, books, textbooks, dissertations, reference books and catalogs, standards) and 34 Internet sites. Of the literary sources, 84 are in Latin.

CONTENTS OF THE DISSERTATION WORK

Chapter One: Robotization of CNC machines – state of the problem

The literature analysis clearly shows that although the problem of CNC production robotization is well studied worldwide, the Bulgarian scientific and technical literature still lacks sufficiently in-depth studies that combine the technological, economic and organizational aspects of the topic. This in turn determines the need for research aimed at optimizing CNC processes through robotic feeding, based on both a theoretical model and experimental data.

Based on the literature review, the following important conclusions can be formulated:

- Robotic stations for setting up parts on CNC machines, especially those with six-axis robots, are a key element in the modern manufacturing industry. They offer high flexibility, precision and efficiency, which significantly improves production processes. Despite the high initial investments and complex integration, these systems represent a strategic investment that increases productivity and reduces human errors.

- The analysis of the technological capabilities, advantages and disadvantages of the considered robot designs shows that the most suitable for automating complex operations performed on CNC machines are six-axis robots. The choice of a six-axis robot design is specific, depends on the type of machine and requires research to optimize the technological process.

- It has been established that in order to reduce the cycle time, it is necessary to know the durability of the tools in order to set a “life” with a duration that is a multiple of the capacity of the robotic station. This will allow to combine the moment of tool change with the moment of loading the magazine with parts and ensure a continuous work cycle of the machine.

- To ensure high productivity and quality of the processed surfaces on CNC lathes with robotic feeding, it is necessary to know the optimal processing conditions for materials with different physical and mechanical properties.

- For the manufacture of critical parts in mechanical engineering, operating in conditions requiring a combination of high static strength and hardness with high impact toughness, such as parts of compressors, turbines, working elements of heavy ground and underground equipment, parts for agricultural machinery, etc., heat-treated (hardened and high-temperature annealed) steel 42CrMo4

is used. The optimal cutting modes for its processing specified and recommended in the literature are valid only for certain cutting tools and metal-cutting machines. However, there is no information on the machinability of this steel on CNC lathes in conditions of robotic feeding.

Based on the conclusions drawn, the goal of the dissertation and the tasks, the solution of which will achieve the goal, are defined.

Chapter Two: Research and modeling of the technological parameters of the turning process on CNC turning machines with robotic feeding.

2.1. Purpose of the study

The purpose is an experimental study and modeling of the influence of the cutting mode on the productivity, durability of cutting tools and the roughness of the machined surfaces when machining 42CrMo4 steel on CNC lathes with robotic feeding.

2.2 Materials, equipment and supplies

2.2.1 Machined parts

The studies were conducted in real production conditions at ADTECH Ltd. - Gabrovo during the machining of two parts with the shape and dimensions shown in Fig. 2.1. The machined material is hardened and high-temperature tempered steel 42CrMo4 with a hardness of 33.8 HRC and a yield strength $f_y \geq 850$ MPa. The chemical composition of the steel according to BDS EN ISO 683-2:2018 is presented in Table 2.1.

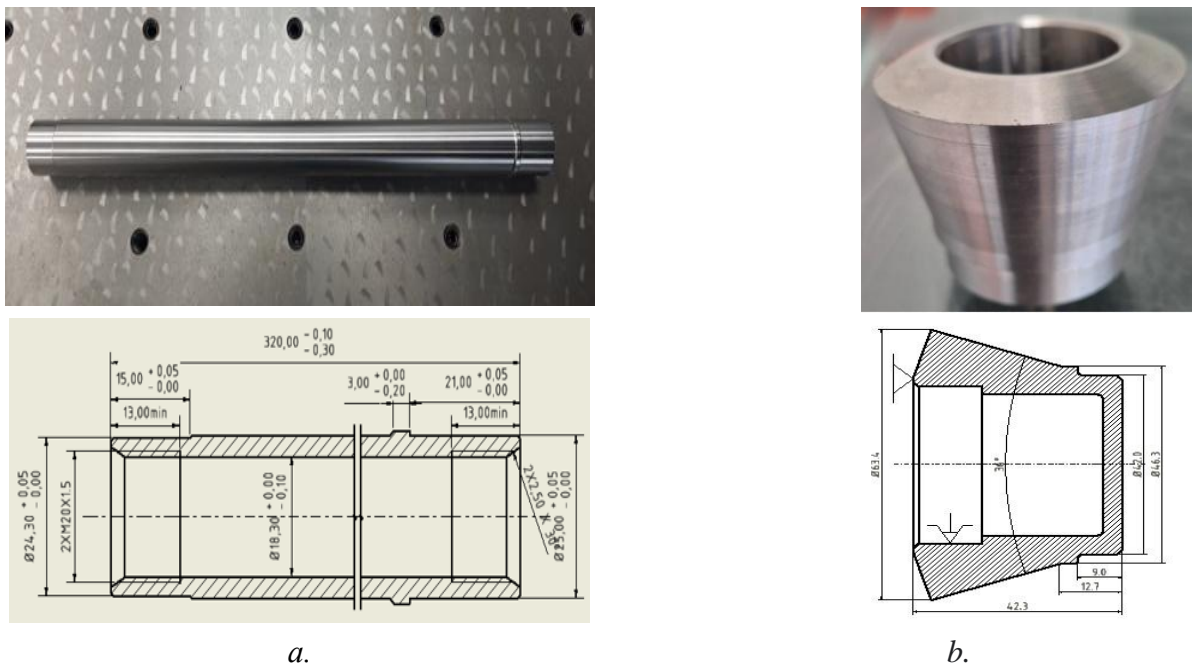


Fig. 2.1. Machined parts: a – part 1; b – part 2

Table 2.1. Chemical composition of steel 42CrMo4, %

C	Si	Mn	Ni	Cr	Mo	P	Cu
0,38-0.45	0.17-0.37	0.50-0.80	≤0.3	0.9-1.2	0.15-0.25	≤0.035	≤0.3

2.2.2. Equipment

The experiments were conducted on a HARRIS C400 CNC lathe – Fig. 2.2. with two types of robotic feeding stations:

- Fanuc LR Mate 200iD/7L with BOXY Raptor Auto Loader automation system (Fig. 2.3). On this robotic station, a surface machining operation with a diameter of $\varnothing 24.3$ mm and a length of $l = 15.0$ mm is performed on a workpiece with the shape and dimensions shown in Fig. 2.1 a.:

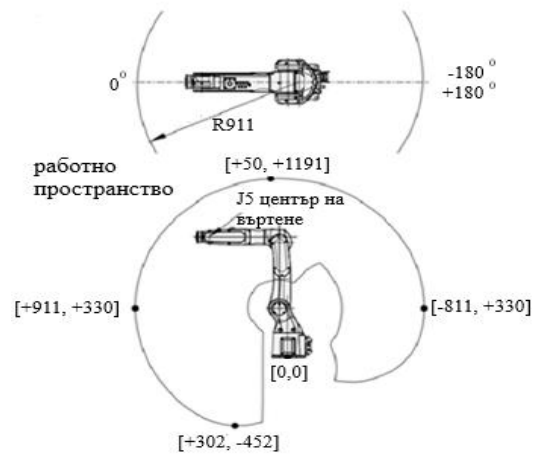
- Mitsubishi RV-8CRL with RoboPro DR800 automation system (Fig. 2.4). This robotic station performs an operation for machining a cylindrical surface with a diameter of $\varnothing 42.0$ mm and a conical surface with an angle of 36° with diameters from $\varnothing 46.3$ mm to $\varnothing 63.4$ mm, with a total length $l = 42.3$ mm on a workpiece with the shape and dimensions shown in Fig. 2.1 b.



Fig.2.2. CNC lathe HARRIS C400K



a.

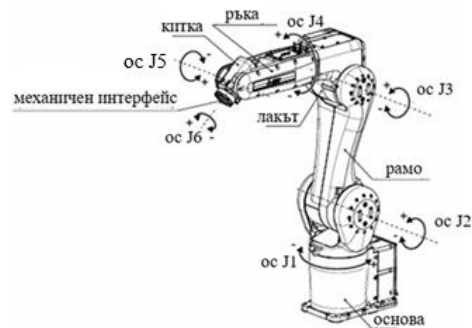


b.

Fig. 2.3. Fanuc LR Mate 200iD/7L robotic feeding station (a) and robot working range (b)



a.



b.





Fig. 2.4 Mitsubishi RV-8CRL robotic feeding station (a) and schematic diagram of the robot (b)

A 6% solution of FUCHS ECOCOOL MACH 300 was used as a lubricating and cooling fluid during the work process. It was supplied to the cutting zone at a pressure of 6 Bar.

2.2.3 Cutting tools

Turning knives with metal-ceramic indexable inserts with coatings providing high wear resistance were used as cutting tools. The designations of the tools and the type of inserts used are presented in Table 2.2.

Table 2.2. Turning tool and cermet inserts

Lathe knife		Plates			
Designation	Geometry	№	Plates	Manufacturer	Coating
SCACR 1616K-09S	main setting angle $\kappa_r = 95^\circ$ auxiliary setting angle $\kappa'_r = 5^\circ$ back angle $\alpha = 7^\circ$ tool tip radius $r_\xi = 0.4$ mm	1	CCMT09T304-F1 TP2501 	SECO	CVD: TiN+ Al ₂ O ₃
		2	CCMT09T304-MP 	PALBIT	CVD: TiN+ Al ₂ O ₃ +TiCN
		3	CCMT09T304-F3M IC807 	ISCAR	PVD: TiAlN+TiN
PCLXR 2525M- 12X-JHP	main setting angle $\kappa_r = 95^\circ$ auxiliary setting angle $\kappa'_r = 5^\circ$ back angle $\alpha_0 = 6^\circ$ tool tip radius $r_\xi = 0.8$ mm	4	CXMG 12T508 M3P IC8150 	ISCAR	CVD: TiCN+ Al ₂ O ₃ +TiCN+TiN

2.3. Research and modeling of the influence of cutting mode elements on the output parameters of the turning process under robotic feeding conditions

2.3.1. Research and modeling of the output parameters of the CNC turning process using a robotic loading station FANUC BOXY Raptor AutoLoader

The machined parts have the shape and dimensions shown in Fig. 2.1.a.

The experimental studies were conducted with a turning knife SCACR 1616K-09S with the following cutting inserts (table 2.2):

- CCMT09T304-F1 TP2501- фирма SECO;
- CCMT09T304-MP- фирма PALBIT;
- CCMT09T304-F3M IC807- фирма ISCAR.

2.3.1.1. Study of the roughness of the machined surfaces

The task of the study is to establish the influence of the number of machined parts on the roughness of the machined surfaces.

The cutting speed V_c , m/min, the feed f , mm/rev and the number of machined parts n were selected as the controlling factors of the process. The cutting depth is constant $a_p = 1.5$ mm.

Based on preliminary information, the following type of model was adopted:

$$Y_g = b_0 + \sum_{i=1}^3 b_i x_i + \sum_{i=1}^3 b_{ii} x_i^2 + \sum_{\substack{i=1 \\ j < i}}^3 b_{ij} x_i x_j, \quad (2.1)$$

where: $Y_g = R_{ag}$ – index corresponding to the type of tool used ($g = 1, 2, 3$);

$X_1 = V_c$, m/min;

$X_2 = f$, mm/rev;

$X_3 = n$, 6p.

A planned experiment with three factors was conducted under an optimal orthogonal centrally designed design of type 2.2:

$$N = 2^3 + 2.3 + 1. \quad (2.2)$$

The levels of variation of the control factors ensuring the operability of the cutting tools are indicated in Table 2.3.

Table 2.3. Levels of driving factors

Governing factors		Levels of variation of factors		
coded	natural	-1	0	+1
X_1	f, mm/rev	0.12	0.15	0.18
X_2	V_c , m/min	130	150	170
X_3	n, 6p.	50	275	500

The roughness of the treated surface was measured with a TESA Rugosurf 20 profilometer using the criterion “arithmetic mean deviation from the profile midline” R_a , which is the most commonly used parameter in practice.

The experimental design and experimental data for roughness are presented in Table 2.4.

Table 2.4. Experimental design and experimental data

№	X_1	X_2	X_3	V_c , m/min	f, mm/rev	n, 6p.	Plate SECO		Plate PALBIT		Plate ISCAR	
							R_{a1} , μm	\hat{R}_{a1} , μm	R_{a2} , μm	\hat{R}_{a2} , μm	R_{a3} , μm	\hat{R}_{a3} , μm
1.	-1	-1	-1	130	0.12	50	1.028	0,993	1.179	1,094	1.168	1,080
2.	+1	-1	-1	170	0.12	50	1.179	1,195	1.183	1,248	1.189	1,146
3.	-1	+1	-1	130	0.18	50	1.039	1,107	1.254	1,238	1.235	1,237
4.	+1	+1	-1	170	0.18	50	1.264	1,309	1.543	1,436	1.389	1,304
5.	-1	-1	+1	130	0.12	500	2.929	2,926	2.998	2,989	3.022	3,018
6.	+1	-1	+1	170	0.12	500	3.487	3,495	3.641	3,725	3.605	3,680
7.	-1	+1	+1	130	0.18	500	3.062	3,039	3.114	3,133	3.182	3,175
8.	+1	+1	+1	170	0.18	500	3.615	3,609	3.952	3,914	3.927	3,838
9.	-1	0	0	130	0.15	275	1.834	1,895	2.124	2,114	2.214	2,128
10.	+1	0	0	170	0.15	275	2.276	2,280	2.518	2,581	2.351	2,492
11.	0	-1	0	150	0.12	275	2.139	2,152	2.398	2,264	2.265	2,231
12.	0	+1	0	150	0.18	275	2.352	2,266	2.426	2,430	2.305	2,389
13.	0	0	-1	150	0.15	50	1.127	1,029	1.087	1,254	1.062	1,192
14.	0	0	+1	150	0.15	500	3.124	3,145	3.495	3,440	3.523	3,428
15.	0	0	0	150	0.15	275	2.076	2,087	2.295	2,347	2.209	2,310

The roughness values for each trial were determined based on single-factor experiments conducted to determine the influence of the number of machined parts n on R_a for combinations of cutting speed and feed values presented in Table 2.4. (Fig. 2.7).

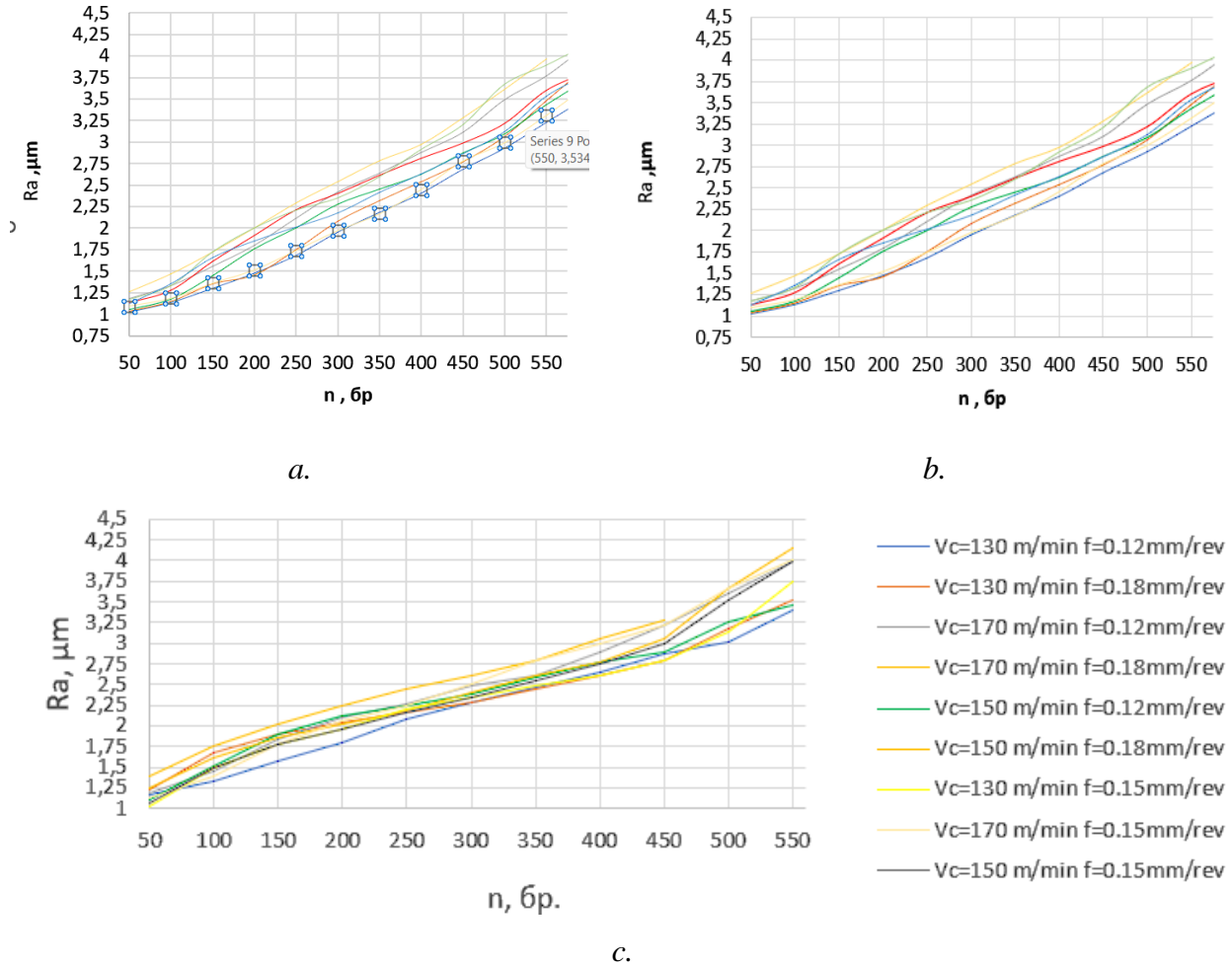


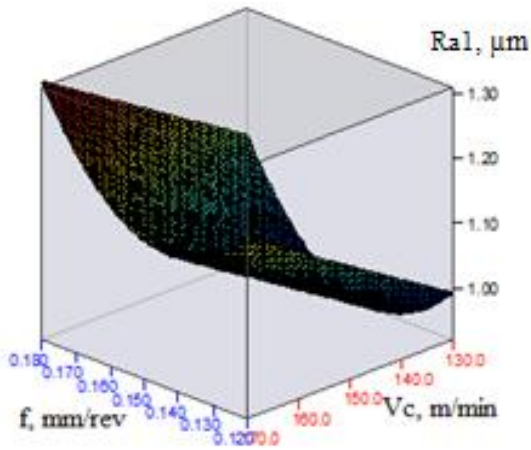
Fig. 2.7. Change in roughness values depending on the number of processed parts when turning with replaceable cermet inserts:
 a - CCMT09T304-F1 TP2501- company SECO; b - CCMT09T304-MP- company PALBIT;
 c - CCMT09T304-F3M IC807- company ISCAR

The results of the research were processed with the QstatLab software and experimental models were obtained, presented in Table 2.5. They create the possibility of predicting with sufficient accuracy the roughness of machined parts made of 42CrMo4 steel.

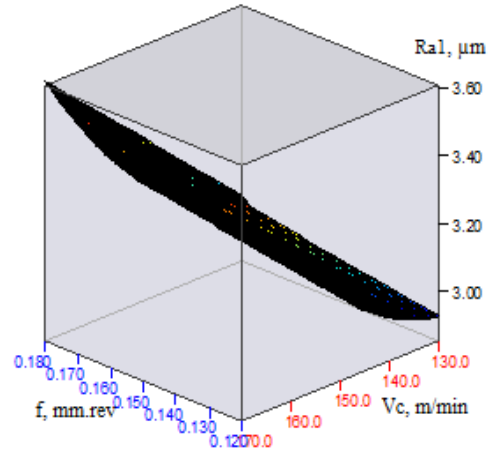
Table 2.5. Experimental models for roughness and statistical analysis

Plate	Experimental models	$t_{\alpha/2, \nu}$	$\hat{F} \geq F^T$		\hat{R}^2
			\hat{F}	F^T	
CCMT09T304-F1 TP2501	$Ra_1 = 2,95 + 0,004Vc - 38,77f + 0,002n + 135,56f^2 + 2,042E-5Vc.n$	2,262	700,13657	3,48166	0,99601
CCMT09T304-MP	$Ra_2 = 0,596 + 0,02Vc.f + 3,24E-5Vc.n$	2,179	870,98507	3,88529	0,99202
CCMT09T304- F3M IC807	$Ra_3 = 0,549 + 2,63f + 3,313E-5Vc.n$	2,179	768,18043	3,88529	0,99096

The results obtained are presented graphically in Figures 2.8, 2.9 and 2.10.

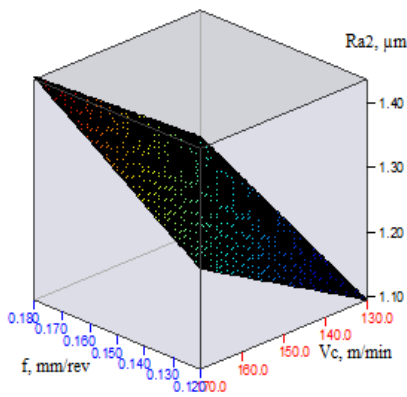


$n=50$

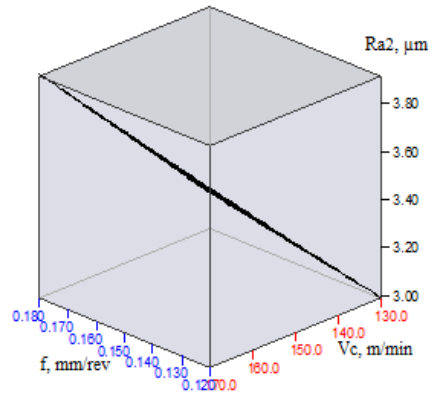


$n=500$

Fig. 2.8. Graphical dependences of roughness of machined surfaces depending on cutting speed V_c , m/min; feed f , mm/rev and number of machined parts n for cutting inserts CCMT09T304-F1 TP2501 from SECO

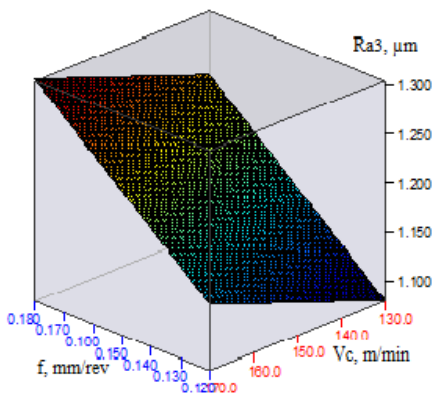


$n=50$

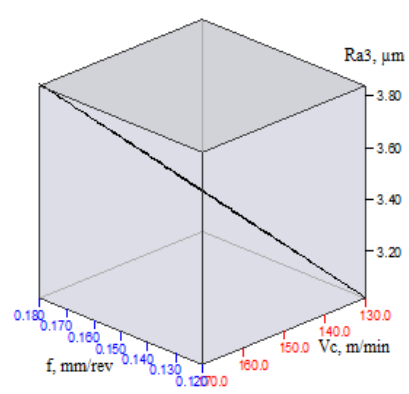


$n=500$

Fig. 2.9. Graphical dependences of roughness of machined surfaces depending on cutting speed V_c , m/min; feed f , mm/rev and number of machined parts n for cutting inserts CCMT09T304-MP from PALBIT



$n=50$



$n=500$

Fig. 2.10. Graphical dependences of roughness of machined surfaces depending on cutting speed V_c , m/min; feed f , mm/rev and number of machined parts n for cutting inserts CCMT09T304-F3M IC807 of ISCAR

To determine the influence of the controlling factors on the roughness, an analysis of variance (ANOVA) was performed. The analysis of variance showed that the greatest influence on the roughness was exerted by the number of processed parts n , followed by the cutting speed V_c . It was found that the greatest influence on the roughness was exerted by the cutting speed when turning with mineral ceramic inserts CCMT09T304-MP from PALBIT.

2.3.1.2. Study of the machinability of 42CrMo4 steel in turning with tools with metal-ceramic prefabricated inserts

The machinability of 42CrMo4 steel, as the main technological characteristic of the turning process, was studied according to the criteria of roughness of the machined surface, durability of cutting tools and productivity of the process.

The conditions for conducting the experiment are similar to those described in point 2.3.1.1. Based on preliminary information, the type of model - 2.3 was adopted:

$$Y_i = B_0 + \sum B_i \cdot X_i + \sum B_{ii} \cdot X_i^2 + B_{12} X_1 X_2, \quad (2.3)$$

where: $X_1 = f$, mm/rev; $X_2 = V_c$, m/min.

A planned experiment with two factors was conducted according to an optimal orthogonal central compositional design of the type:

$$N = 2^2 + 2 \cdot 2 + 1. \quad (2.4)$$

The experimental design and experimental data are presented in Table 2.6.

The processing of the experimental results was carried out in the sequence described in section 2.3.1.1.

Table 2.6. Experimental design and experimental data

№	f mm/rev	V _c m/min	Durability-T, number of details			Durability – L, mm			Processing time t,s			Roughness, Ra,µm		
			T ₁	T ₂	T ₃	L ₁	L ₂	L ₃	t ₁	t ₂	t ₃	Ra ₁	Ra ₂	Ra ₃
1	0.12	130	510	500	490	18661	18295	17929	5610	5500	5390	1,028	1,179	1,168
2	0.18	130	490	475	475	17929	17380	15380	3430	3325	3325	1,039	1,254	1,235
3	0.12	170	425	400	420	15551	14360	15368	3400	3200	3360	1,176	1,183	1,189
4	0.18	170	405	355	390	14819	12989	14270	2430	2130	2340	1,264	1,543	1,389
5	0.12	150	480	455	465	17563	16648	17014	4800	4550	4650	1,057	1,087	1,109
6	0.18	150	455	420	440	16648	15368	16099	2730	2520	2640	1,132	1,387	1,253
7	0.15	130	505	490	480	18478	17929	17563	4545	4410	4320	1,095	1,085	1,032
8	0.15	170	415	380	405	15185	13904	14819	2905	2660	2835	1,172	1,243	1,131
9	0.15	150	470	440	450	17197	16099	16466	3760	3520	3600	1,127	1,087	1,062

The results of the research were processed with the QstatLab software, and the resulting models and the statistical analysis of the experimental results are presented in Table 2.7.

The constructed models are adequate, since the condition $F^{\wedge} > F(\alpha, v_1, v_2)$ is fulfilled with a 95% confidence probability. The calculated F^{\wedge} and tabulated $F(\alpha, v_1, v_2)$ values of the Fisher criterion ($\alpha=0.05$; $v_1 = k - 1$ and $v_2 = N - k$ - degrees of freedom) for each of the regression models are presented in Table 2.7. The experimental models describe with high accuracy the dependencies between the technological parameters and the control factors. The values of the coefficients of determination R^2 are $0.82264 \div 1.00000$ (Table 2.7).

The graphical interpretation of the obtained models is shown in Figures 2.12 ÷ 2.15.

To determine the influence of the controlling factors on the studied parameters, an analysis of variance (ANOVA) was conducted.

Table 2.7. Experimental models and statistical analysis

Plate	Experimental models	$\alpha/2 \cdot v$	$\hat{F} \geq F^T$		\hat{R}^2
			\hat{F}	F^T	
CCMT09T304-F1 TP2501	$T_1 = 285 - 361,111f + 5,333V_c - 0,025V_c^2$	2,57	695,476	5,409	0,99727
	$Ra_1 = 0,976 - 2,8109f + 0,02518 f \cdot V_c$	2,447	19,553	5,143	0,82264
	$L_1 = 9489,9797 + 194,85 \cdot V_c - 44246,955 \cdot f^2 - 0,9138 \cdot V_c^2$	2,5706	981.561	5.4095	0.9973
	$t_1 = 25490,694 - 104625 \cdot f - 116,0417 \cdot V_c + 504,1667 \cdot f \cdot V_c$	2.5706	171.221	5.4095	0.9846
CCMT09T304-MP	$T_2 = 469,583 + 666,667f + 2,25V_c - 0,0125V_c^2 - 8,333f \cdot V_c$	2,776	1611,0	6,388	0,99876
	$Ra_2 = 9,3611 - 58,340f - 0,0597V_c + 148,704f^2 + 0,00015V_c^2 + 0,119f \cdot V_c$	3,182	43,6955	9,013	0,96388
	$L_2 = 14964,431 + 54850 \cdot f^2 + 82,25 \cdot V_c - 101481 \cdot f^2 - 0,4571 \cdot V_c^2 - 305 \cdot f \cdot V_c$	3.1825	364.178 1.10 ⁵	9.0135	1.0000
	$t_2 = 24846,468 - 98368,056 \cdot f - 112,7708 \cdot V_c + 460,4167 \cdot f \cdot V_c$	2.5706	285.4256	5.4095	0.9907
CCMT09T304-F3M IC807	$T_3 = 188,125 + 548,611f + 5,271 V_c - 0,0208V_c^2 - 6,25f V_c$	2,776	943,53338	6,388	0,99788
	$Ra_3 = 8,099 - 55,64f - 0,043V_c + 165,37f^2 + 0,00012V_c^2 + 0,0554f \cdot V_c$	3,182	58,25263	9,013	0,97281
	$L_3 = 8349,67221 + 192,8438 \cdot V_c + 67036,196 \cdot f^2 - 0,7621 \cdot V_c^2 - 228,9588 \cdot f \cdot V_c$	2.777	2034,1388	6.3882	0.9990
	$t_3 = 23274,375 - 93618,056 \cdot f - 102,8125 \cdot V_c + 435,4167 \cdot f \cdot V_c$	2.5706	170.9663	5.4095	0.9846

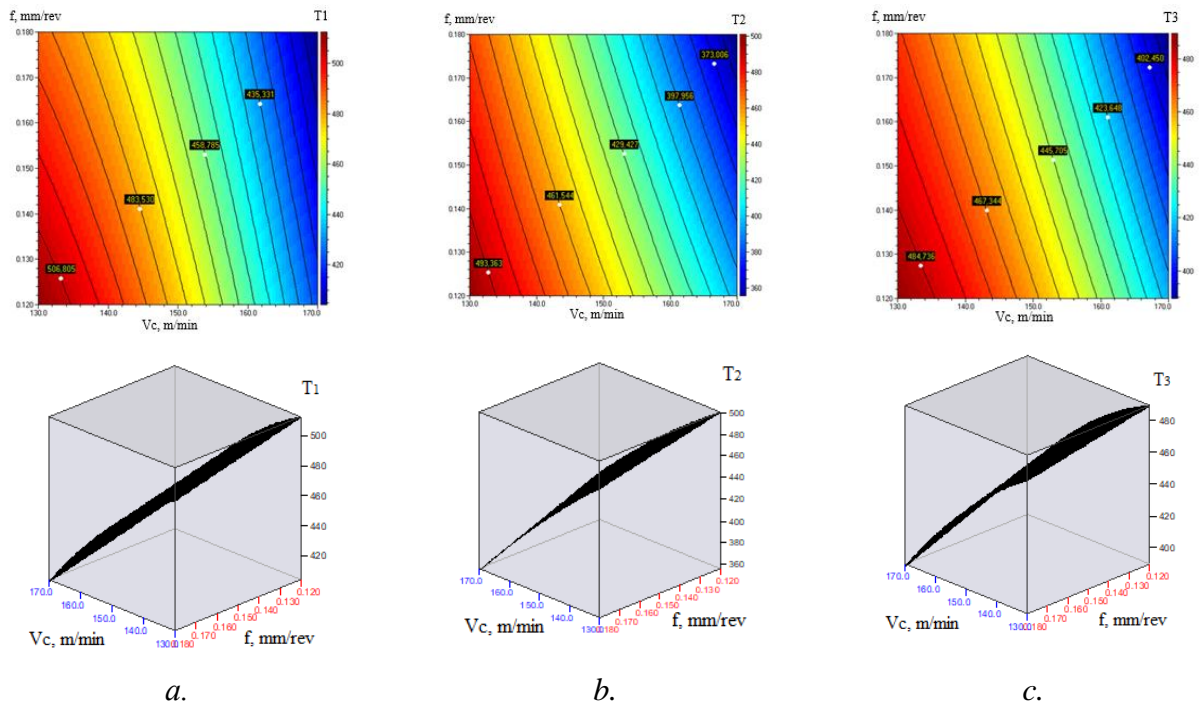


Fig. 2.12. Influence of cutting conditions on the durability of cutting tools, assessed by the criterion of the number of processed parts when machining with cutting tools of different manufacturers:

- a - CCMT09T304-F1 TP2501- company SECO;
- b - CCMT09T304-MP- company PALBIT;
- c - CCMT09T304-F3M IC807- company ISCAR.

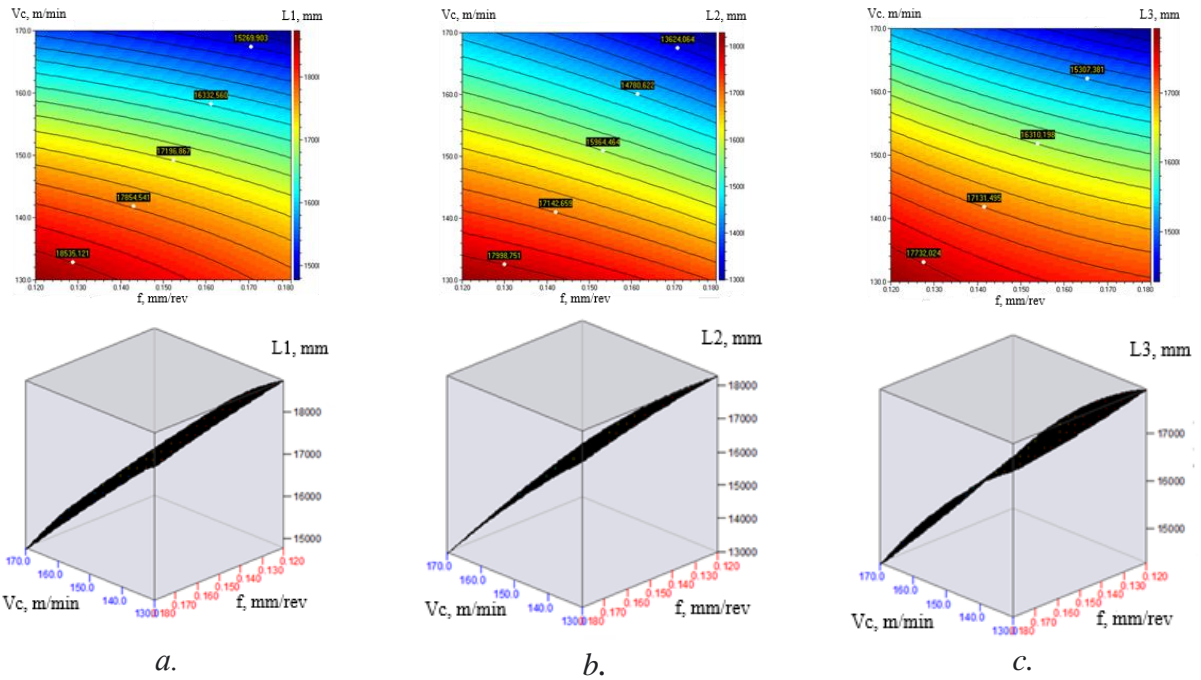


Fig. 2.13. Influence of cutting conditions on the durability of cutting tools, assessed by the criterion of distance traveled during machining with cutting tools of different manufacturers:
a - CCMT09T304-F1 TP2501- company SECO;
b - CCMT09T304-MP- company PALBIT;
c - CCMT09T304-F3M IC807- company ISCAR.

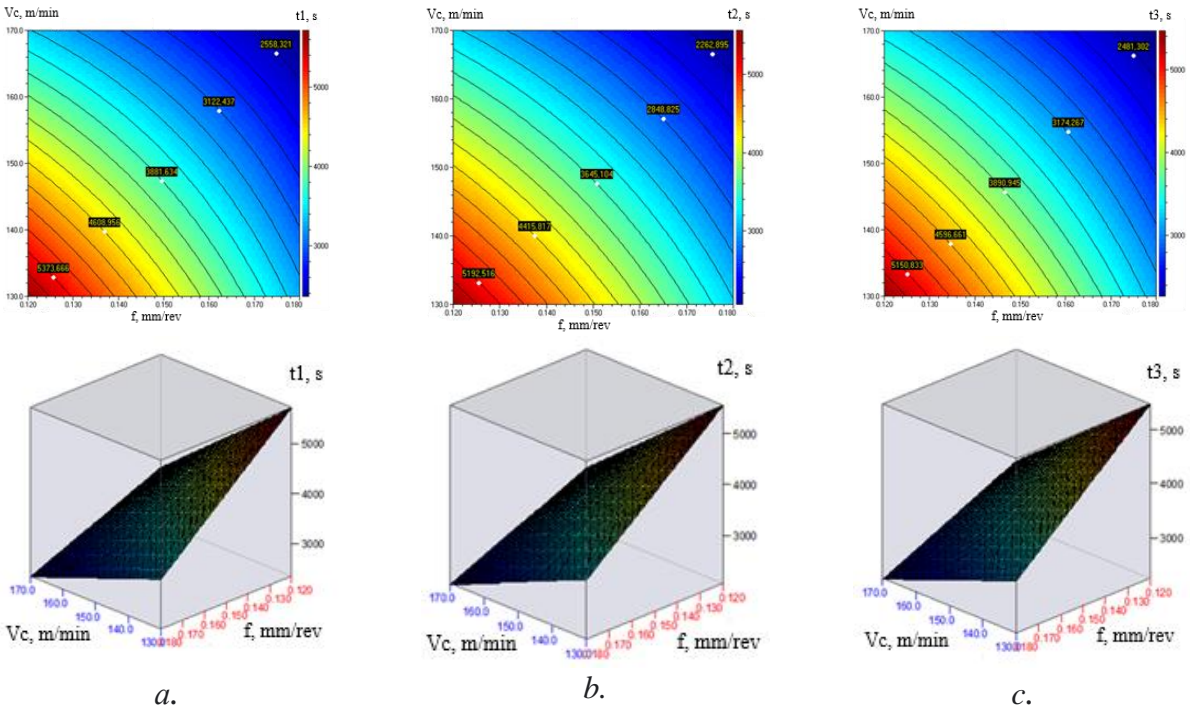


Fig. 2.14. Influence of cutting conditions on the productivity of the CNC turning process when machining with cutting tools of different manufacturers:
a - CCMT09T304-F1 TP2501- company SECO;
b - CCMT09T304-MP- company PALBIT;
c - CCMT09T304-F3M IC807- company ISCAR.

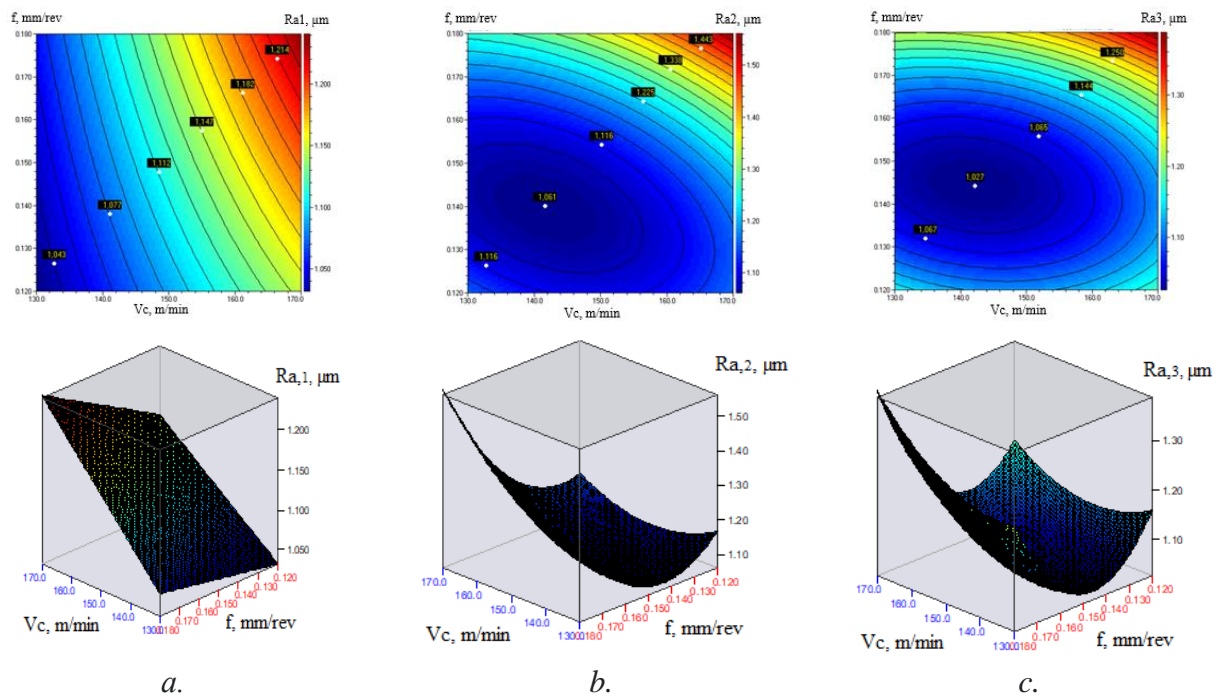


Fig. 2.15. Influence of cutting conditions on the roughness of the machined surfaces when machining with cutting tools of different manufacturers:
a - CCMT09T304-F1 TP2501- company SECO;
b - CCMT09T304-MP- company PALBIT;
c - CCMT09T304-F3M IC807- company ISCAR

The analysis of the obtained experimental models and the graphical dependencies built on their basis shows that the machinability of 42CrMo4 steel, evaluated by the criteria of durability, productivity and roughness, depends on the elements of the cutting mode, as follows:

- With increasing V_c and f , a decrease in durability is observed according to the criteria of number of processed parts and distance traveled by the tool, i.e. deterioration of machinability according to this criterion (table 2.9). The influence of the cutting speed is stronger, as its change in the studied range leads to a decrease in durability according to the criteria of number of parts and distance traveled by 29% and 25.2%, respectively, for the individual inserts (table 2.10). With increasing feed, durability decreases according to the criterion of number of processed parts from 4.9 to 8.4%, and according to the criterion of distance traveled by the tool – from 5.2 to 11.2% (table 2.10). The influence of V_c and f is strongest when turning with inserts from PALBIT. The greatest durability according to both criteria, respectively the best machinability, is obtained when machining with SECO inserts with feed $f_{min}=0.12\text{mm/rev}$ and cutting speed $V_{c,min}=130\text{m/min}$ (table 2.9).

- The feed and cutting speed have approximately the same effect on the productivity of the process, estimated by the machining time. This effect is most pronounced when machining with metal-ceramic inserts CCMT09T304-MP from PALBIT, as with an increase in V_c and f the machining time decreases to 48.8%. The highest productivity, respectively the best machinability and according to this criterion is obtained when machining with inserts CCMT09T304-MP from PALBIT with feed $f_{max}=0.18\text{mm/rev}$ and cutting speed $V_{c,max}=170\text{m/min}$ (table 2.9).

- The machinability of the processed steel according to the roughness criterion deteriorates with increasing V_c and f (table 2.9). The influence of speed is strongest when processing with inserts CCMT09T304-F1 TP2501 from SECO, as with an increase in V_c in the studied range the roughness increases by 14.4% (table 2.9). The increase in feed leads to an increase in roughness in the range from 5.3 to 21.2%, with the change in roughness being most pronounced when processing with inserts CCMT09T304-MP from PALBIT (table 2.10). The smallest roughness is obtained when processing with inserts CCMT09T304-F1 TP2501 from SECO at a feed $f_{min}=0.12\text{mm/rev}$ and a cutting speed $V_{c,min}=130\text{m/min}$. (table 2.9).

Table 2.9. Limits of change of the criteria in the studied range of cutting modes

Plate	$f_{\min}=0,12$ mm/rev $V_{c,\min} = 130$ m/min				$f_{\max}=0,18$ mm/rev $V_{c,\max}=170$ m/min			
	T,6p.	L,mm	t, s	$R_a, \mu\text{m}$	T,6p.	L,mm	t, s	$R_a, \mu\text{m}$
CCMT09T304-F1 TP2501	512	18661	5610	1,032	404	14819	2430	1,241
CCMT09T304-MP	501	18295	5500	1,166	356	12989	2130	1,561
CCMT09T304-F3M IC807	490	17929	5390	1,159	390	14270	2340	1,388

Table 2.10. Influence of cutting mode elements on machinability criteria,%

Plate	$f_{\min}=0,12$ mm/rev, $f_{\max}=0,18$ mm/rev				$V_{c,\min}=130$ m/min, $V_{c,\max}=170$ m/min			
	ΔT	ΔL	Δt	ΔR_a	ΔT	ΔL	Δt	ΔR_a
CCMT09T304-F1 TP2501	4,9	5,2	43,1	5,3	20,9	17,8	39,4	14,4
CCMT09T304-MP	8,4	11,2	44,6	21,2	29,1	25,2	48,8	12,9
CCMT09T304-F3M IC807	5,3	7,1	43,2	11,9	19,0	17,9	37,7	7,9

2.3.2. Research and modeling of technological parameters in turning using a robotic loading station Mitsubishi RV-8CRL

As technological parameters, the durability of cutting tools and the productivity of the turning process in the processing of 42CrMo4 steel on CNC turning machines with robotic feeding were studied.

The experimental studies were carried out with cutting inserts CXMG 12T508 M3P IC8150 from ISCAR, installed in a prismatic holder PCLXL 2525 – 12M (table 2.2).

The machined parts have the shape and dimensions shown in Fig. 2.1.b.

The cutting speed V_c , m/min, the feed f , mm/rev and the cutting depth a_p mm were selected as the control factors. The levels of variation of the control factors are indicated in table 2.11 and take into account the increased wear resistance of the inserts used.

Table 2.11. Levels of driving factors

Governing factors		Levels of variation of factors		
coded	natural	-1	0	+1
x_1	V_c , m/min	180	230	280
x_2	f , mm/rev	0.15	0.20	0,25
x_3	a_p , mm	2.0	2.5	3,0

Based on preliminary information, the following model was adopted:

$$Y_{g(g=1,2)}=b_0+\sum_{i=1}^3 b_i X_i+\sum_{i<j}^3 b_{ij} \cdot X_i X_j+\sum_{i=1}^3 b_{ii} X_i^2+b_{123} \cdot X_1 X_2 X_3, \quad (2.5)$$

where: $Y_1=L$, mm; $Y_2=T$, s; $X_1 = V_c$, m/min; $X_2=f$, mm/rev; $X_3= a_p$, mm.

A planned experiment with three factors was conducted under an optimal orthogonal central - compositional design of type 2.6:

$$N=2^3 + 3 \cdot 2 + 1. \quad (2.6)$$

Durability is defined as the length of the working stroke L (mm) when processing surfaces in a specific cutting mode, with the roughness of the processed surface - $R_a=2.0 \mu\text{m}$, which is measured with a TESA Rugosurf 20 profilometer, being adopted as the wear criterion.

The total time (main and auxiliary) t (s) for traveling the path L (mm) until reaching the specified roughness is adopted as a performance criterion.

The experimentally determined durability and performance values are presented in Table 2.12.

Table 2.12. Experimental design and experimental data

№	Governing factors			Durability, mm		Productivity, min	
	Vc m/min	a _p mm	f mm/rev	L	Ĥ	t	ĥ
1	180	2	0,15	67742	67043	427.92	419,2
2	280	2	0,15	65170	65208	266,00	266,5
3	180	3	0,15	47547	47883	295.17	295,4
4	280	3	0,15	46312	46049	187.50	184,2
5	180	2	0,25	61740	61671	234,00	234,8
6	280	2	0,25	61225	61544	148.75	146,0
7	180	3	0,25	42237	42511	159.60	156,5
8	280	3	0,25	42360	42384	102.90	109,1
9	180	2,5	0,2	52170	52294	246.67	257,5
10	280	2,5	0,2	51465	51313	158.17	157,5
11	230	2	0,2	63455	63866	234.33	233,0
12	230	3	0,2	45077	44707	164.25	152,7
13	230	2,5	0,15	53439	54063	265.30	276,6
14	230	2,5	0,25	50055	49544	147.92	146,9
15	230	2,5	0,2	51888	51803	190.13	192,8

The results of the research were processed with the QstatLab software, and the obtained experimental models and the values of the Student's t-test, Fisher's exact test and the coefficient of determination are presented in Table 2.12. The regression models (Table 2.13) include only the significant regression coefficients determined in accordance with the condition $t > t_{\alpha/2, \nu}$. ($\alpha=0.05$, $\nu = N - k$).

Table 2.13. Experimental models for durability and performance and statistical analysis

Experimental models	$t_{\alpha/2, \nu}$	$\hat{F} \geq F^T$		\hat{R}^2
		\hat{F}	F^T	
$L=180927.94-43.958.V_c-68821.8a_p-84458.5f+9932.4a_p^2+170.75V_c f$	2,262	963,03220	3,48166	0,9971
$T=135369.7-361.156V_c-15992,2a_p-415683.f+0,3532V_c^2+453800f^2+382.9V_c f+27300a_p f+24.84V_c a_p$	2,447	125,81918	4,14680	0,98617

The constructed models are adequate, since the condition $\hat{F} > F^T (\alpha, \nu_1, \nu_2)$ is fulfilled with a 95% confidence probability (table 2.12).

The values determined by the models are presented in table 2.11.

The graphical interpretation of the resulting models is shown in Fig. 2.21 and Fig. 2.22.

To determine the influence of the controlling factors on the durability and performance of the studied instrument, an analysis of variance (ANOVA) was conducted.

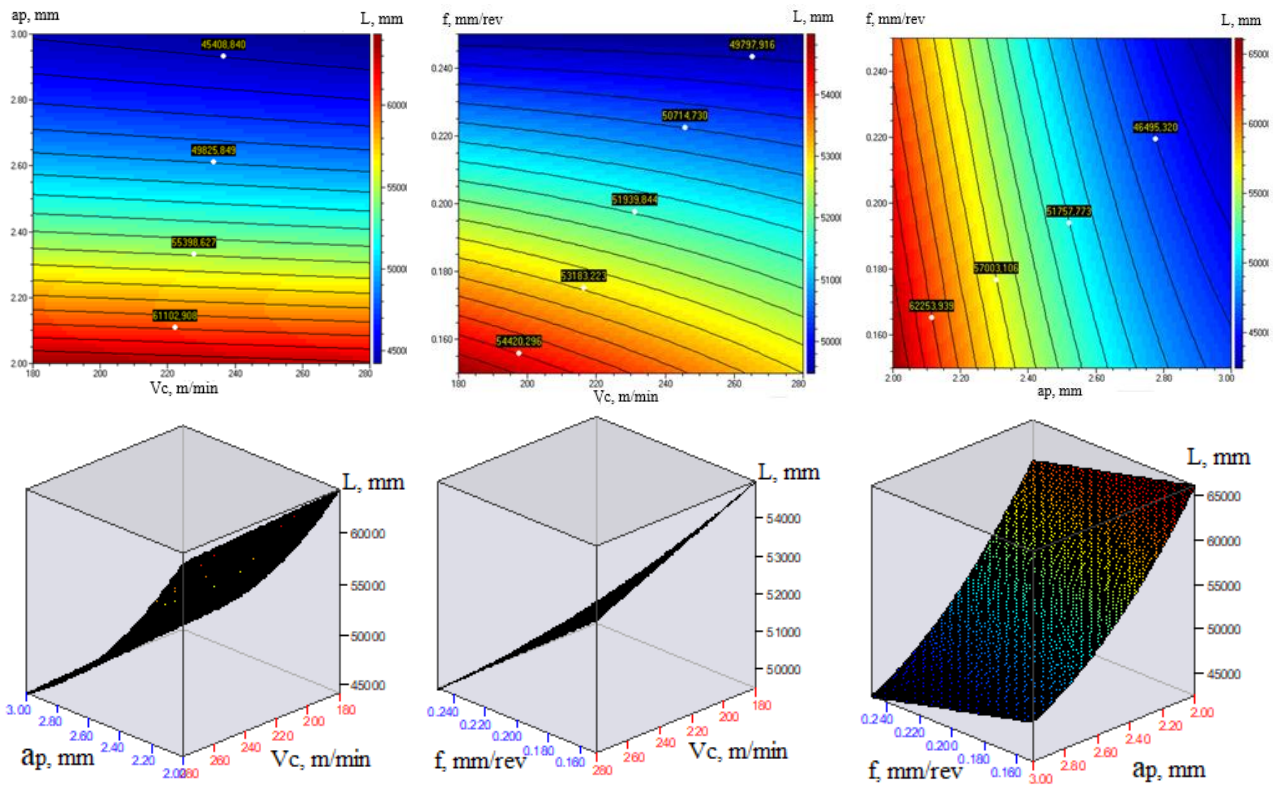


Fig. 2.21. Durability as a function of cutting speed V_c , feed f , and cutting depth a_p

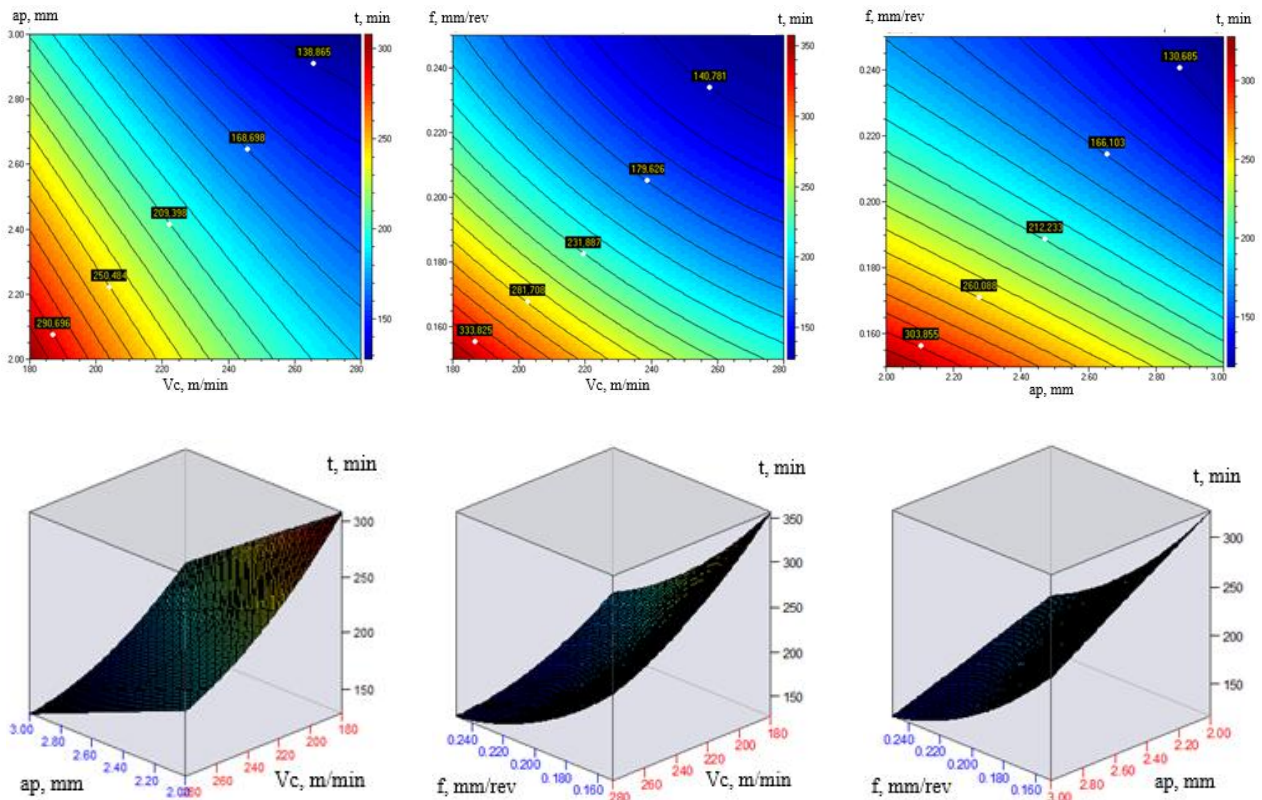


Fig. 2.22. Productivity depending on cutting speed V_c , feed f , and cutting depth a_p

The analysis of the obtained experimental models (table 2.13) shows that:

- With increasing a_p , f and V_c , a decrease in durability and an increase in productivity are observed (table 2.14);

Table 2.14. Limits of change of the criteria in the studied range of cutting modes

Plate	$a_{p,\min} = 2,0$ mm $f_{\min}=0,15$ mm/rev $V_{c,\min} = 180$ m/min		$a_{p,\max} = 3,0$ mm $f_{\max}=0,25$ mm/rev $V_{c,\max}=280$ m/min	
	L,mm	t, s	L,mm	t, min
CXMG 12T508 M3P IC8150	67742	25675	42360	102,9

- The cutting depth a_p has a stronger influence on productivity than on durability, as its increase increases productivity by 45.9%, and durability decreases by 11.2% (table 2.15);

Table 2.15. Influence of cutting mode elements on machinability criteria, %

Plate	$a_{p,\min} = 2,0$ mm $a_{p,\max} = 3,0$ mm		$f_{\min}=0,15$ mm/rev $f_{\max}=0,25$ mm/rev		$V_{c,\min}=180$,m/min $V_{c,\max}=280$, m/min	
	ΔL	Δt	ΔL	Δt	ΔL	Δt
CXMG 12T508 M3P IC8150	11,2	45,9	31,6	31,8	3,8	37,4

- The feed f has approximately the same effect on the tool life and the process productivity, as its increase decreases the tool life by about 32% (table 2.15);
- The cutting speed V_c has a stronger effect on the productivity, as its increase increases it to 37.4%. The decrease in tool life with increasing speed in the studied range is minimal - up to 3.8% (table 2.15).

Chapter Three: Multi-objective optimization of the turning process on CNC machines with robotic feeding

3.1. Research objective

The research objective is to determine the cutting mode that provides the best combination of CNC turning process parameters with robotic feeding (maximum productivity; maximum tool life and minimum surface roughness)..

3.2. Selection of method and methodology for conducting the study

The analysis of multi-objective optimization methods shows that a greater amount of information for making a reasoned decision for choosing optimal cutting conditions is offered by the following two methods, which were applied to achieve the set goal:

- Determination of a compromise optimal region, as the solution of the optimization problem is reduced to determining Pareto-optimal solutions for the elements of the cutting mode.
- Scalarization of the vector optimization criterion, using the generalized utility objective function

The methodology for multi-objective process optimization and its specific implementation in machining on CNC lathes with robotic feeding proceeds in two phases:

- Modeling using experimental design and statistical regression of technological parameters (productivity, durability of cutting tools and roughness of machined surfaces) of the CNC turning process with robotic feeding, presented in chapter two;
- Multi-objective trade-off optimization, based on a genetic algorithm, to determine the optimal conditions for the implementation of the process.

3.2.1 Determination of the compromise optimal region

To determine the optimal cutting mode by this method, it is necessary to solve the following system of inequalities, which includes functional and factor constraints necessary to determine the pareto front:

$$\left\{ \begin{array}{l} Y(X_1^*, X_2^*, X_3^*) = Y_{max} > Y(X_1, X_2, X_3) \\ Z(X_1^*, X_2^*, X_3^*) = Z_{min} < Z(X_1, X_2, X_3) \\ X_{1,min} \leq X_1 \leq X_{1,max} \\ X_{2,min} \leq X_2 \leq X_{2,max} \\ X_{3,min} \leq X_3 \leq X_{3,max} \end{array} \right. , \quad (3.2)$$

where: $Y \equiv L$ (mm);

T (number of details);

$Z \equiv t$ (s, min); R_a (μm);

X_1, X_2, X_3 - cutting mode elements;

X_1^*, X_2^*, X_3^* - optimal elements of the cutting mode.

The models for the durability and productivity of turning with the Fanuc LR Mate 200iD/7L and Mitsubishi RV-8CRL robotic stations are presented in Tables 2.7 and 2.12, respectively, and the areas of variation of the elements of the cutting mode in Tables 2.3 and 2.10, respectively.

The task is reduced to determining Pareto-optimal solutions satisfying the system of inequalities (3.2), using a genetic algorithm and the QStatLab software product.

3.2.2 Multi-objective optimization by generalized utility function

The generalized utility function has many advantages over other combinatory methods mainly due to its flexibility, as it allows to simultaneously maximize some of the output quantities and minimize others.

The optimization problem is solved in the following sequence:

1. Experimental models are constructed for the generalized utility function with weighting coefficients depending on the controlling factors of the turning process, the general form of which is:

$$\Phi_{Ai} = A_0 + \sum_{j=1}^k A_j X_j + \sum_{j=1}^k A_{jj} X_j^2 + \sum \sum_{j < l} A_{jl} X_j X_l . \quad (3.3)$$

The generalized arithmetic mean utility function with weighting coefficients is determined for each trial in accordance with dependence 3.4:

$$\Phi_{Ai} = \sum_{i=1}^m w_i \eta_i ; \quad (3.4)$$

where: m – number of technological parameters studied Q_i ($Q_i \equiv Y_i ; Z_i$;

η_i - utility coefficients;

w_i - weighting coefficients for the studied parameters Q_i .

The utility coefficients η_i are determined by dependence 3.5:

$$\eta_i = \frac{k_i(Q_i - Q_{imin})}{(Q_{imax} - Q_{imin})} \quad (3.5)$$

where: Q_{imax} и Q_{imin} - limits of utility of the studied parameters Q_i ;

- Q_{iu} - the most useless results of the studied parameters obtained within the limits of the factor space;
- $k_i = \pm 1$ - coefficients taking into account the utility of the increase in the studied parameter.

2. Combinations of values of the controlling factors in the studied factor space are determined, in which the generalized arithmetic mean utility functions with weighting coefficients Φ_{Ai} have a maximum value:

$$\Phi_{Ai}(X_1^*, X_2^*, X_3^*) = (\Phi_{Ai})_{\max} > \Phi_{Ai}(X_1, X_2, X_3) . \quad (3.6)$$

3. Using a genetic algorithm and the QStatLab software product, Pareto-optimal conditions are determined that guarantee the best combination of the studied technological parameters of the process.

3.3. Multi-objective optimization of the turning process using a robotic loading station Fanuc BOXY Raptor Auto Loader

3.3.1. Determination of the compromise optimal region

Using the obtained experimental models (table 2.7) and a genetic algorithm, optimization of the elements of the cutting mode was carried out according to the durability criteria, estimated with the parameters number of machined parts T and roughness Ra. A combination of feed f, mm/rev and cutting speed Vc, m/min was determined, at which maximum durability of the cutting inserts and minimum roughness of the machined surfaces is achieved (table 3.1). A visualization of the method used to search for the optimal solution for each of the used carbide inserts is presented in Fig. 3.1.

Table 3.1. Optimal cutting modes

Cutting tools	Optimal cutting modes		Technological parameters			
	f*, mm/rev	Vc*, m/min	t(s) / t, min	T, бр	L, mm	Ra, μm
CCMT09T304-F1 TP2501 SECO	0,122	130,5	5622,4/93,71	511	18701,2	1,034
CCMT09T304-MPPALBIT	0,140	141,7	4248,6/70,81	466	17093,1	1,061
CCMT09T304-F3M IC807 ISCAR	0,145	141,9	4083,5/68,06	468	17074,7	1,027

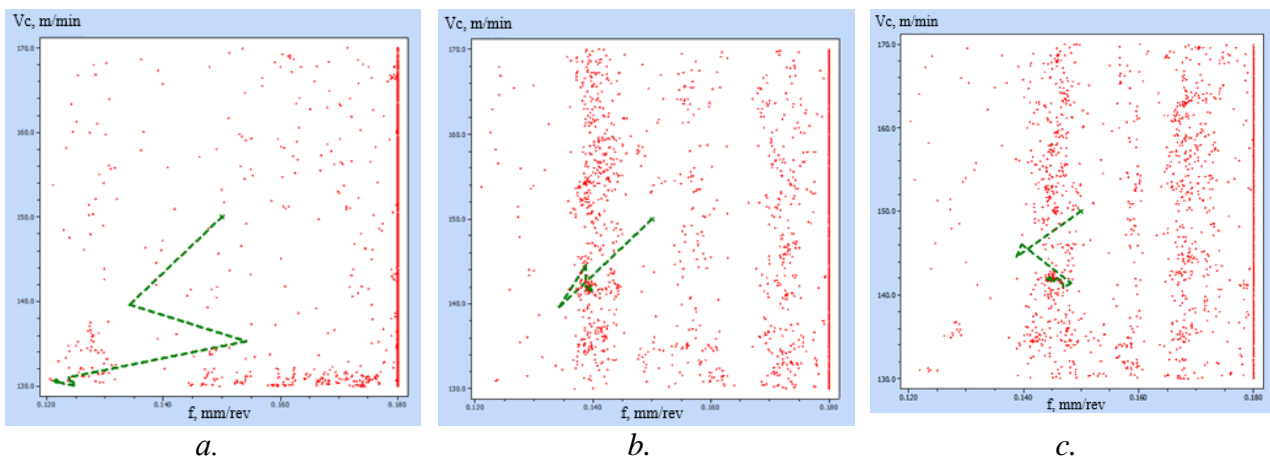


Fig. 3.1 Visualization of determining the optimal cutting mode:

- a - CCMT09T304-F1 TP2501 from SECO;
- b - CCMT09T304-MP from PALBIT;
- c - CCMT09T304-F3M IC807 from ISCAR

A combination of cutting speed and feed values (V_c^*, f^*) was determined, which resulted in the best combination of technological parameters for the three types of cutting inserts used (table 3.2, fig. 3.2). The results obtained show that with the determined optimal cutting mode, the lowest roughness and the highest durability are obtained when machining with SECO cutting inserts, and the highest productivity - when machining with ISCAR cutting inserts.

Table 3.2. Cutting modes providing maximum durability and minimum roughness

Plate	Cutting mode			t, min	\hat{t} , min	T, σ_p .	\hat{T} , σ_p .	L, mm	\hat{L} , mm	R _a , μ m	\hat{R}_a , μ m
	f, mm/rev	V _c , m/min	a _p , mm								
CCMT09T304-F1TP2501 ECO	0,12	130	1,5	93,5	5715	510	512	18661	18740,9	1,028	1,032
CCMT09T304-MPPALBIT	0,12	130	1,5	91,7	5565	500	501	18295	18294,9	1,179	1,166
CCMT09T304-F3MIC807ISCAR	0,12	130	1,5	89,8	5467	490	490	17929	17933,7	1,168	1,159

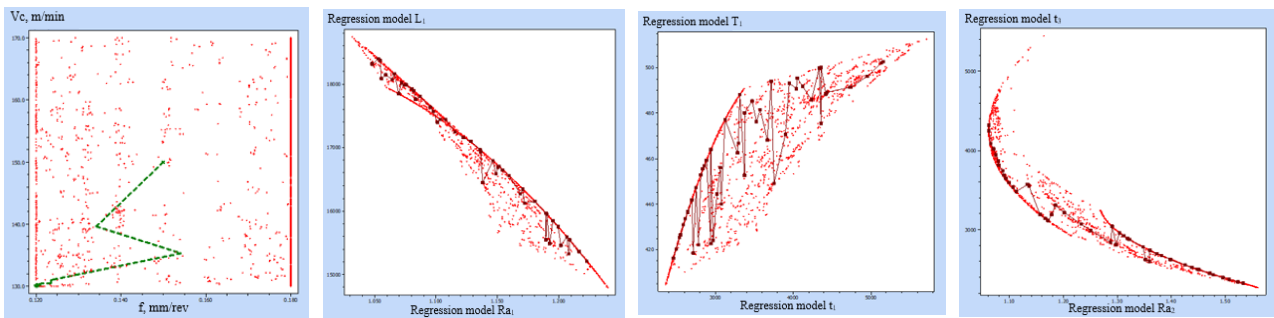


Fig. 3.2 Visualization of determining the optimal cutting mode with the best combination of technological parameters

3.3.2. Multi-objective process optimization using the generalized utility function method

3.3.2.1 Modeling a generalized utility function

The generalized arithmetic mean utility function with weighting coefficients is a complex indicator characterizing the technological parameters Q_i of the turning process (processing time t , durability, determined by the distance traveled to reach a given technological criterion L and roughness of the machined surface R_a) ($Q_1 = t_j$, $Q_2 = L_j$ and $Q_3 = R_{aj}$) and is determined in accordance with dependencies (3.4) and (3.5):

$$\Phi_{A_i} = \sum_{i=1}^3 w_i k_i (Q_i - Q_{iu}) / (Q_{imax} - Q_{imin}), \quad (3.7)$$

where: $Q_{1u} = t_{jmax}$, $Q_{2u} = L_{jmin}$ и $Q_{3u} = R_{ajmax}$ (Table 2.6).

The solution of the optimization problem is reduced to determining combinations of values of the control factors of the CNC turning process with robotic feeding (f^* , V_c^*), at which the generalized arithmetic mean utility function with weighting coefficients has a maximum. The problem is solved for each of the cutting tools used (table 2.2), with the values of the weighting coefficients being as follows: $w_{1j} = 0.5$ for the target parameter $Q_1 = t_j$; $w_{2j} = 0.3$ for the target parameter $Q_2 = L_j$; $w_{3j} = 0.2$ for the target parameter $Q_3 = R_{aj}$.

The general form of the models reflecting the influence of cutting speed and feed on process productivity, cutting tool life and surface roughness is:

$$\Phi_{A_i} = B_0 + B_1 f + B_2 V_c + B_{11} f^2 + B_{22} V_c^2 + B_{12} f V_c. \quad (3.8)$$

The models (3.8) are built based on the experimentally determined values of durability, productivity and roughness (table 2.8) and the results of numerical experiments, according to an orthogonal central compositional plan - table 3.3.

Table 3.3. Experimental design and summary utility functions

№	Governing factors		Utility coefficients									Generalized utility function		
	f (mm/rev)	Vc (m/min)	η_{11}	η_{12}	η_{13}	η_{21}	η_{22}	η_{23}	η_{31}	η_{32}	η_{33}	Φ_1	Φ_2	Φ_3
1	0,12	130	1	0,707	0,728	1	0,935	0,871	0	0,032	0,063	0,5	0,438	0,438
2	0,18	130	0,979	0,561	0,598	0,871	0,774	0,774	0,626	0,657	0,657	0,77	0,673	0,680
3	0,12	170	0,713	0,699	0,687	0,452	0,290	0,419	0,635	0,693	0,647	0,596	0,573	0,587
4	0,18	170	0,542	0	0,299	0,323	0	0,226	0,914	1	0,940	0,662	0,5	0,598
5	0,12	150	0,944	0,885	0,843	0,806	0,645	0,710	0,232	0,304	0,276	0,545	0,523	0,520
6	0,18	150	0,798	0,303	0,563	0,645	0,419	0,548	0,828	0,888	0,853	0,767	0,630	0,704
7	0,15	130	0,870	0,889	0,992	0,968	0,871	0,806	0,306	0,345	0,371	0,617	0,612	0,626
8	0,15	170	0,720	0,583	0,8	0,387	0,161	0,323	0,777	0,848	0,797	0,649	0,589	0,655
9	0,15	150	0,808	0,885	0,934	0,742	0,548	0,613	0,532	0,601	0,578	0,650	0,642	0,660

In each experiment, the generalized arithmetic mean functions Φ_{A1} , Φ_{A2} and Φ_{A3} are determined in accordance with dependence (3.6). After statistical analysis of the experimental results using the regression analysis method and by applying the Qstat Lab software product, regression models for Φ_{A1} , Φ_{A2} and Φ_{A3} in CNC turning with cutting tools from SECO, PALBIT and ISCAR companies were created (table 3.4).

Table 3.4. Experimental models of the generalized utility function and statistical analysis of the models

Experimental models	Student's criterion	Fisher's criterion		Coefficient of determination
	$t_{\alpha/2, \nu}$	\hat{F}	F_{α, ν_1, ν_2}	\hat{R}^2
$\Phi_1 = -2,9673 - 15,85 \cdot f + 0,0292 \cdot V_c - 5,41 \cdot 10^{-5} \cdot V_c^2 - 0,085 \cdot f \cdot V_c$	2.7765	42.8112	6.3882	0.9544
$\Phi_2 = -5,7743 + 40,1333 \cdot f + 0,0444 \cdot V_c - 64,629 \cdot f^2 - 8,54 \cdot 10^{-5} \cdot V_c^2 - 0,1283 \cdot f \cdot V_c$	3.1825	95.9719	9.0135	0.9834
$\Phi_3 = -5,1865 + 36,5875 \cdot f + 0,03824 \cdot V_c - 65,7470 \cdot f^2 - 7,667 \cdot 10^{-5} \cdot V_c^2 - 0,0963 \cdot f \cdot V_c$	3.1825	27.0379	9.0135	0.9421

They include only the significant regression coefficients determined according to the condition $t > t_{\alpha/2, \nu}$. The regression models are adequate ($F > F_{\alpha, \nu_1, \nu_2}$ with 95% confidence probability) and describe with high accuracy the dependencies between the generalized utility functions Φ_{A1} , Φ_{A2} and Φ_{A3} and the controlling factors. The values of the determination coefficients are $R^2 = 0.9421 \div 0.9834$ (table 3.4). The influence of the cutting conditions on the generalized arithmetic mean utility functions in accordance with the created models (table 3.4) is presented graphically in Fig. 3.3. In order to determine the degree of influence of the controlling factors on Φ_{A1} , Φ_{A2} and Φ_{A3} , an analysis of variance (ANOVA) was conducted.

The analysis of the experimental models (table 3.4) and the graphical dependencies built on their basis (Fig. 3.3), as well as the interpretation of the ANOVA results (Fig. 3.4) show that the feed and cutting speed have a different impact on the generalized arithmetic mean utility functions Φ_{A1} , Φ_{A2} and Φ_{A3} :

- The feed has a greater influence, as its increase increases Φ_{A1} , Φ_{A2} and Φ_{A3} within the range of 11 ÷ 61%. The influence of the feed is most pronounced when turning with ISCAR cutting tools and increases with decreasing cutting speed.

- The influence of cutting speed on Φ_{A1} , Φ_{A2} and Φ_{A3} is different depending on the feed rate. When turning with $f = 0.12$ mm/rev with increasing V_c the generalized arithmetic mean utility functions increase in the range from 22% to 34%. When machining with $f \geq 0.15$ mm/rev the increase in cutting speed leads to a decrease in Φ_{A1} , Φ_{A2} and Φ_{A3} in the range from 12 ÷ 26%. The influence of cutting speed is most pronounced when turning with ISCAR cutting tools and increases with decreasing feed.

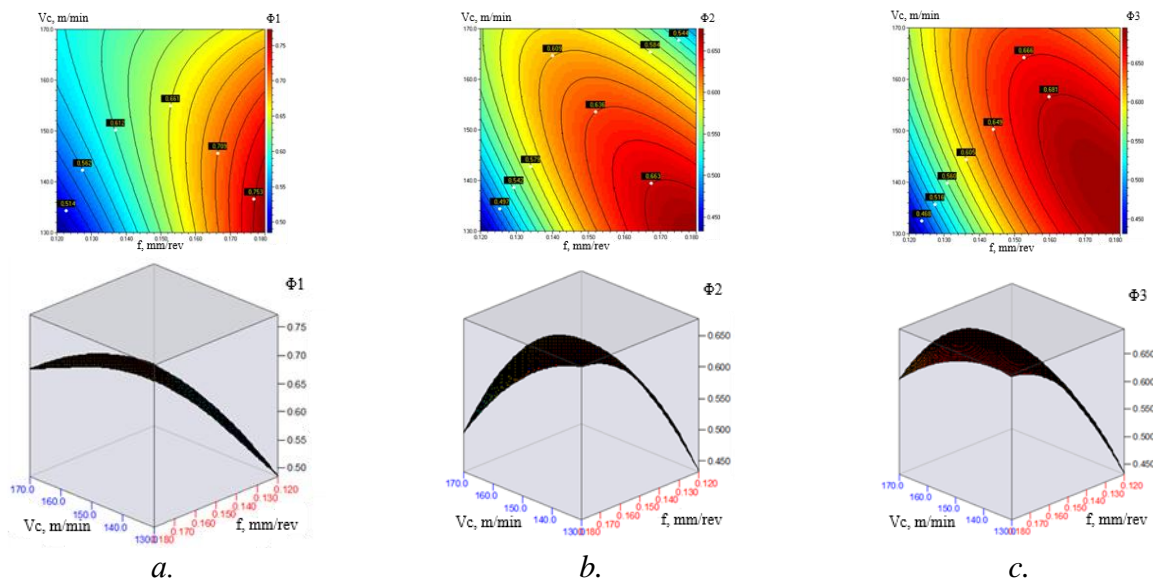


Fig. 3.3. Graphical dependences of the models of the generalized utility function in CNC turning with cutting tools of the companies: a - SECO; b - PALBIT; c – ISCAR.

3.3.2.2. Determination of the optimal cutting modes

The optimal cutting modes (feed f^* and cutting speed Vc^*) when turning 42CrMo4 steel on a CNC lathe with robotic feed were determined by applying a genetic algorithm and using the QStatLab software product (table 3.5). These conditions guarantee the main advantages of the CNC turning process with robotic feed - maximum productivity (processing time $t \leq 3370$ s (56.2 min)) combined with production continuity (cutting tool life, estimated by the distance traveled to reach a set technological wear criterion - $L \geq 16\,940$ mm) and quality of the machined surfaces (roughness $Ra \leq 1.3 \mu\text{m}$) (table 3.5).

A visualization of the method for searching for the optimal solution for each of the used carbide inserts is presented in Fig. 3.5.

Table 3.5. Optimal cutting modes

Cutting tool	Optimal cutting modes		Technological parameters			Generalized utility function		
	f^* , mm/rev	Vc^* , m/min	t (s)/ t (min)	L , mm	Ra , μm	Φ_{A1}	Φ_{A2}	Φ_{A1}
SECO	0.18	130	3370/56,2	17 941	1.059	0.768	-	-
PALBIT	0.18	130	3254/54,2	17 380	1.269	-	0.677	-
ISCAR	0.177	138.2	3143/52,4	16 944	1.115	-	-	0.696

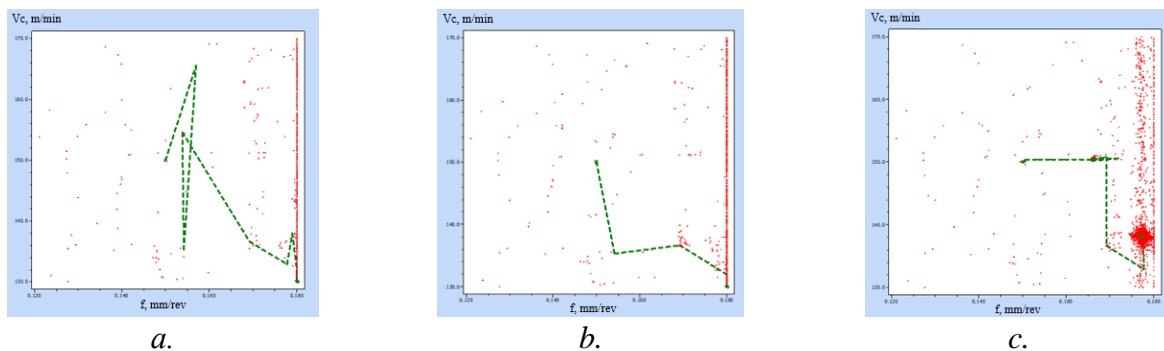


Fig. 3.5 Visualization of determining the optimal cutting mode:
a - CCMT09T304-F1 TP2501 from SECO;
b - CCMT09T304-MP from PALBIT;
c - CCMT09T304-F3M IC807 from ISCAR.

3.3.3. Comparative analysis of the technological parameters of the turning process at the optimal cutting modes determined by the two optimization methods

The comparison of the technological parameters of the turning process at the optimal values of the cutting mode elements determined by the two multi-objective optimization methods (table 3.6) shows:

- higher productivity when working with the modes determined by the generalized utility function method, with the largest difference when processing with SECO inserts – up to 40%;
- comparable durability of cutting tools at the optimal cutting modes determined by both methods, with the difference ranging from 0.77 to 4%;
- lower roughness when working with the cutting mode determined by the compromise optimal region method, with the largest difference when processing with PALBIT inserts – up to 16.4%.

Table 3.6. Comparison of the determined optimal cutting modes and technological parameters

Cutting tool	Compromise optimal region					Generalized utility function					Δt %	ΔL %	ΔRa %
	Optimal cutting modes		Technological parameters			Optimal cutting modes		Technological parameters					
	f^* (mm/rev)	V_c^* (m/min)	t (min)	L (mm)	Ra (μm)	f^* (mm/rev)	V_c^* (m/min)	t (min)	L (mm)	Ra (μm)			
SECO	0.122	130,5	93,71	18701,2	1,034	0.18	130	56,2	17 941	1.059	40,03	-4,06	2,36
PALBIT	0.14	141,7	70,81	17093,1	1,061	0.18	130	54,2	17 380	1.269	23,5	1,65	16,4
ISCAR	0.145	141,9	68,06	17074,7	1,027	0.177	138.2	52,4	16 944	1.115	23,0	-0,77	7,9

3.4. Optimization of the turning process using a Mitsubishi RV-8CRL robotic loading station

3.4.1. Determination of the compromise optimal area

The analysis of the obtained results (table 2.12, fig. 2.21 ÷ 2.24) shows that maximum tool life is obtained at a cutting speed $V_c = 192$ m/min, feed $f = 0.17$ mm/rev and cutting depth $a_p = 2$ mm, and maximum productivity - at a cutting speed $V_c = 275$ m/min, feed $f = 0.24$ mm/rev and cutting depth $a_p = 2.8$ mm.

Using the obtained experimental models (table 2.12) and a genetic algorithm, a compromise optimization of the elements of the cutting mode was carried out, determining the cutting speed V_c , m/min, the feed f mm/rev and the cutting depth a_p , mm, at which a combination of maximum durability and maximum productivity is achieved (table 3.7).

Table 3.7. Optimal cutting mode and technological parameters

Optimal cutting modes			Technological parameters	
V_c^* , m/min	a_p^* , mm	f^* , mm/rev	L , mm	t , min
180	2,0	0,16	66360,1	387,4

The durability of cutting tools and the productivity of the process in the optimal cutting mode are presented graphically in Fig. 3.6.

The graphical dependencies allow to select combinations of values of V_c , f and a_p , providing a given durability or productivity (Fig. 3.7).

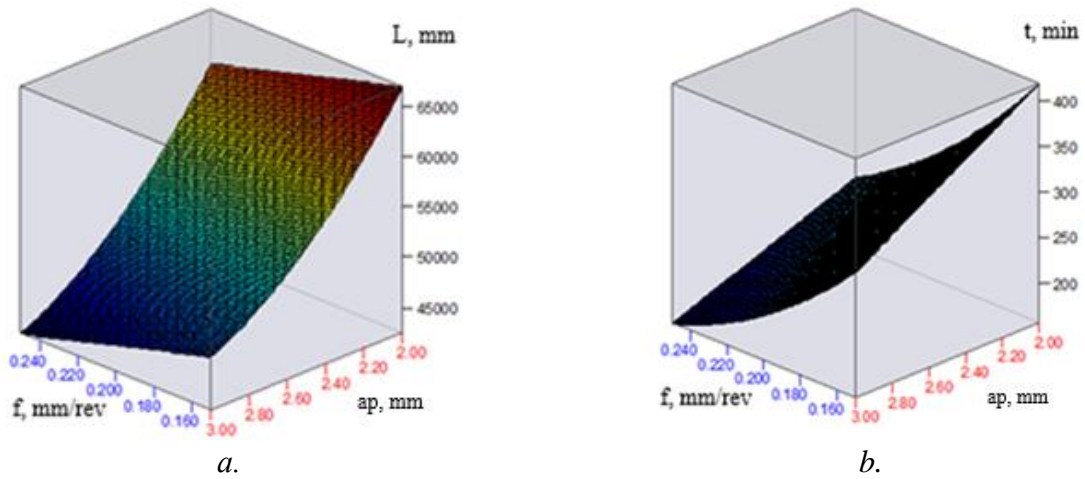


Fig. 3.6. Durability and productivity at $V_c^*=180$ m/min

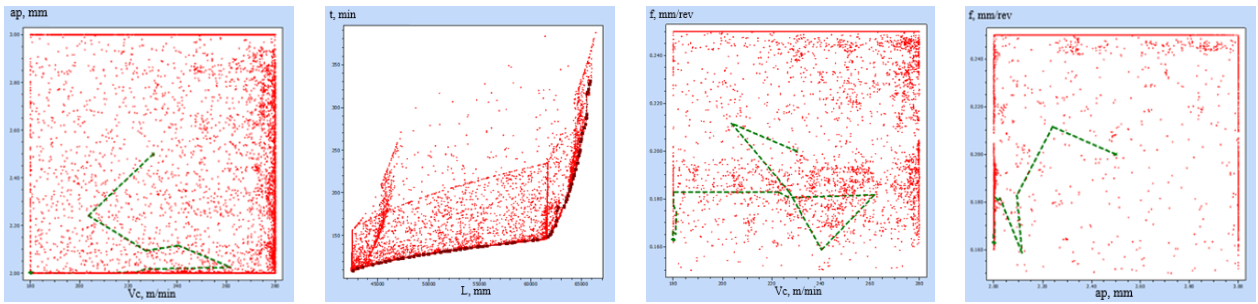


Fig. 3.7. Visualization of determining the optimal cutting mode for the best combination of maximum durability and maximum productivity

3.4.2. Multi-objective process optimization using the generalized utility function method

3.4.2.1 Modeling a generalized utility function

Multi-objective optimization in this case is reduced to determining the cutting conditions - cutting speed V_c^* (m/min), feed f^* (mm/rev) and cutting depth a_p^* (mm), which provide a combination of maximum tool life and maximum process productivity. The general form of the models, adopted based on the analysis of the influence of cutting speed, feed and cutting depth on process productivity and cutting tool life, is:

$$\Phi_{A_i} = B_0 + B_1 V_c + B_2 a_p + B_3 f + B_{11} V_c^2 + B_{22} a_p^2 + B_{33} f^2 + B_{12} V_c a_p + B_{23} a_p V_c + B_{13} V_c f. \quad (3.9)$$

The models (3.9) are built based on the experimentally determined values of durability and productivity, presented in Table 2.11.

The experiment plan with the values of the generalized arithmetic mean utility functions with weighting coefficients Φ_{A1} and Φ_{A2} , determined in accordance with dependencies (3.4) and (3.5), as well as the studied parameters of the turning process (path L from the tool along the machined surface until reaching roughness $Rak=2.0 \mu m$ and machining time t) are presented in Table 3.8.

The values of the weighting coefficients of the generalized arithmetic mean utility function are respectively: for Φ_{A1} - $w_1=0.2$ (for the target parameter durability Li); $w_2=0.8$ (for the target parameter processing time tj); for Φ_{A2} - $w_1=0.8$ (for the target parameter durability Li); $w_2=0.2$ (for the target parameter processing time tj).

In the first case, higher productivity of the turning process is ensured by reducing the unit time, and in the second case, greater durability of the cutting tool.

Table 3.8. Experimental data and generalized utility function

Control factors			CNC turning process parameters		Utility coefficients		Utility coefficients	
x_1	x_2	x_3	L (mm)	t (min)	η_1	η_2	Φ_{A1}	Φ_{A2}
-1	-1	-1	67 742	427.92	1	0	0.2	0.8
1	-1	-1	65 170	266	0.899	0.498	0.578	0.819
-1	1	-1	47 547	295.17	0.208	0.408	0.368	0.248
1	1	-1	46 312	187.5	0.160	0.74	0.624	0.276
-1	-1	1	61 740	234	0.765	0.597	0.631	0.731
1	-1	1	61 225	148.75	0.744	0.859	0.836	0.767
-1	1	1	42 237	159.6	0	0.826	0.661	0.165
1	1	1	42 360	102.9	0.005	1	0.801	0.204
-1	0	0	52 170	246.67	0.389	0.558	0.524	0.423
1	0	0	51 465	158.17	0.362	0.83	0.736	0.456
0	-1	0	63 455	234.33	0.832	0.596	0.643	0.785
0	1	0	45 077	164.25	0.111	0.811	0.671	0.251
0	0	-1	53 439	265.3	0.265	0.500	0.453	0.312
0	0	1	50 055	147.92	0.307	0.861	0.750	0.418
0	0	0	51 888	190.13	0.378	0.732	0.661	0.449

When determining the utility functions Φ_{A1} and Φ_{A2} , the values of the most useless result and the utility limits of the turning process parameters are (table 2.11): for tool life - $L_u=42\ 237$ mm; $L_g=67\ 742$ mm; $L_l=42\ 237$ mm; for machining time - $t_u=427.92$ min; $t_g=427.92$ min; $t_l=102.9$ min.

After statistical analysis of the experimental results by applying the regression analysis method and the QstatLab software product, experimental models were built for the generalized arithmetic mean utility functions Φ_{A1} and Φ_{A2} (table 3.9).

Table 3.9. Experimental models of generalized utility functions and statistical characteristics of the models

Experimental models	Student's criterion	Fisher's criterion		Coefficient of determination
	$t_{\alpha/2, \nu}$	\hat{F}	F_{α, ν_1, ν_2}	\hat{R}^2
$\Phi_1 = -3,2604 + 0,0076 \cdot V_c + 0,4815 \cdot a_p + 18,061 \cdot f - 22,72 \cdot f^2 - 0,001 \cdot V_c \cdot a_p - 1,095 \cdot a_p \cdot f - 0,0145 \cdot f^2$	2,365	163.975	3.787	0.988
$\Phi_2 = 3,8723 + 0,0003 \cdot V_c + 2,7545 \cdot a_p + 6,5171 \cdot f + 0,4406 \cdot a_p^2 - 17,1429 \cdot f^2$	2,262	94.011	3.482	0.971

The models are adequate, since the condition $F > F_{(\alpha, \nu_1, \nu_2)}$ is fulfilled with a 95% confidence probability. The calculated \hat{F} and tabulated $F_{(\alpha, \nu_1, \nu_2)}$ values of the Fisher test ($\alpha=0.05$; $\nu_1=k-1$ and $\nu_2=N-k$ are degrees of freedom) for each of the regression models are presented in Table 3.8.

The experimental models describe with high accuracy the relationships between the generalized utility functions Φ_{A1} and Φ_{A2} and the control factors. The values of the coefficients of determination are $R^2=0.971 \div 0.988$ (table 3.9). The influence of cutting conditions on the generalized utility functions Φ_{A1} and Φ_{A2} is graphically presented in Fig. 3.8 and 3.9, respectively. In order to determine the degree of influence of the control factors on Φ_{A1} and Φ_{A2} , the analysis of variance (ANOVA) was performed using QStatLab.

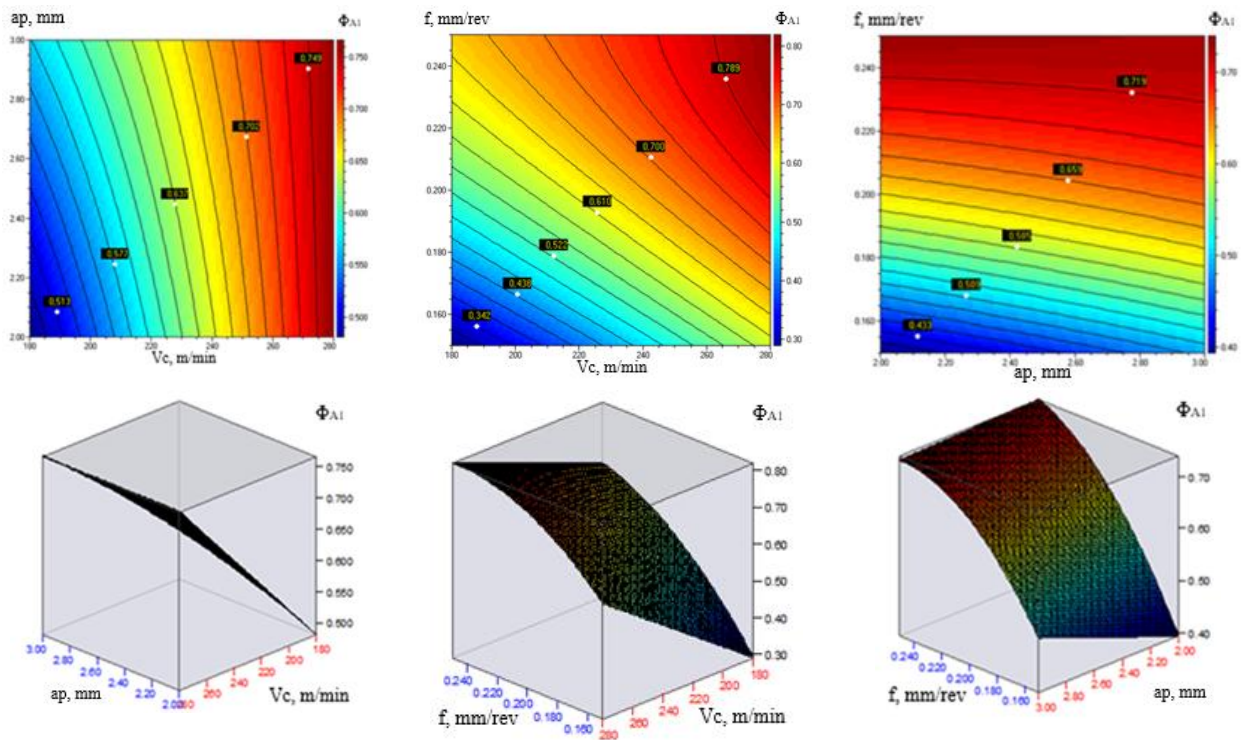


Fig. 3.8 Graphical visualization of the models of the arithmetic mean generalized utility function for Φ_{A1} for CNC lathes with weighting factors $W_1 = 0.2$ and $W_2 = 0.8$

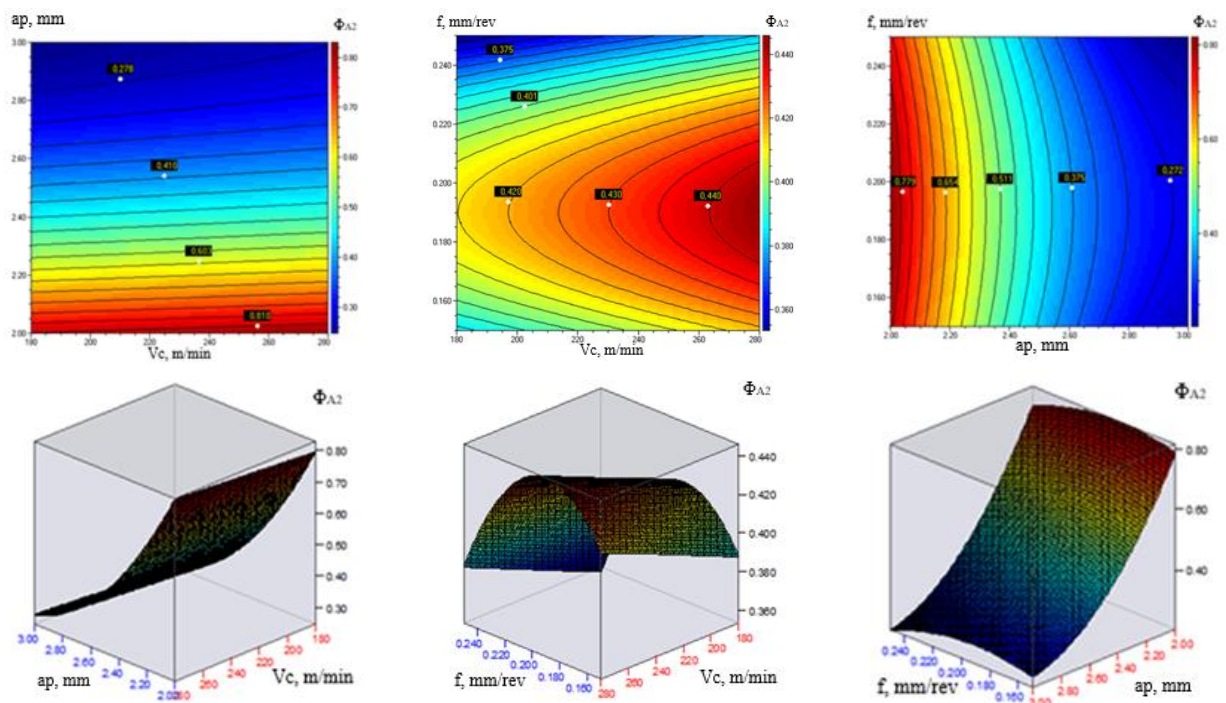


Fig.3.9. Graphical visualization of the models of the arithmetic mean generalized utility function Φ_{A1} for CNC lathes with weighting coefficients $W_1 = 0.8$ r $W_2 = 0.2$

3.4.2.2. Determination of the optimal cutting modes

The optimization problem is solved by applying a genetic algorithm and using the software product QStatLab. The optimal cutting conditions (cutting speed V_c^* , feed f^* and cutting depth a_p^*) are those at which the generalized arithmetic mean utility functions Φ_{A1} and Φ_{A2} have a maximum (table 3.10).

Table 3.10. Optimal cutting modes

Optimal cutting modes			Output variables		Generalized utility function	
V_c^* , m/min	a_p^* , mm	f^* , mm/rev	L, mm	t, min	Φ_{A1}	Φ_{A2}
280	2.0	0.25	61 543.575	145,962	0.8458	-
280	2.0	0.19	63 742.485	200,159	-	0.8319

The determined Pareto-optimal solutions guarantee the best combination of tool life and productivity when turning hardened steel 42CrMo4 on a CNC lathe with robotic feeding. The cutting conditions (V_c^* , a_p^* and f^*), at which the generalized arithmetic mean utility function Φ_{A1} has a maximum, provide higher productivity of the turning process, and those at which the generalized arithmetic mean utility function Φ_{A2} has a maximum - higher tool life. The experimentally determined values of the tool path L, as a parameter for assessing its life, and of the machining time t are presented in Table 3.10.

The influence of cutting conditions on the generalized utility function Φ_{A1} and Φ_{A2} at the optimal cutting speed $V_c^* = 280$ m/min is presented graphically in Fig. 3.11. Visualizations of determining the optimal cutting modes by applying the generalized arithmetic mean utility function method (Φ_{A1} and Φ_{A2}) are shown in Fig. 3.12 and Fig. 3.13, respectively.

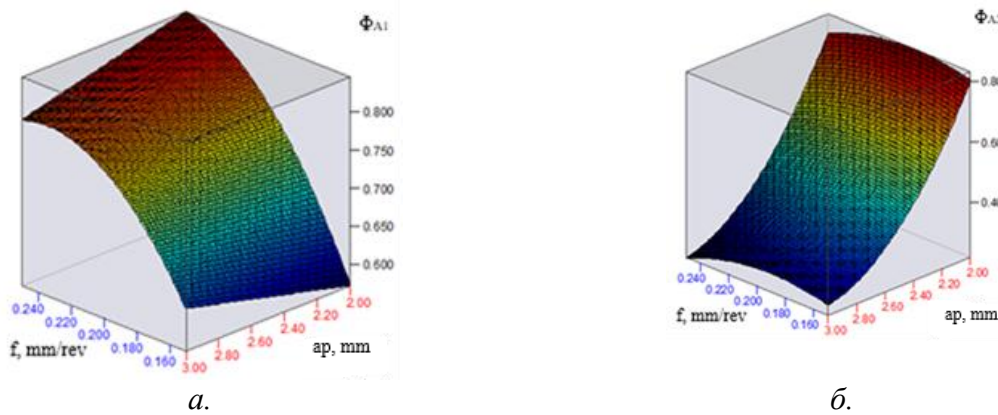


Fig. 3.11. Graphical visualization of the models of the arithmetic mean generalized utility functions Φ_A for CNC turning with weighting coefficients: a - $W_1 = 0.2$ and $W_2 = 0.8$; b - $W_1 = 0.8$ and $W_2 = 0.2$ at the optimal cutting mode $V_c^* = 280$ m/min

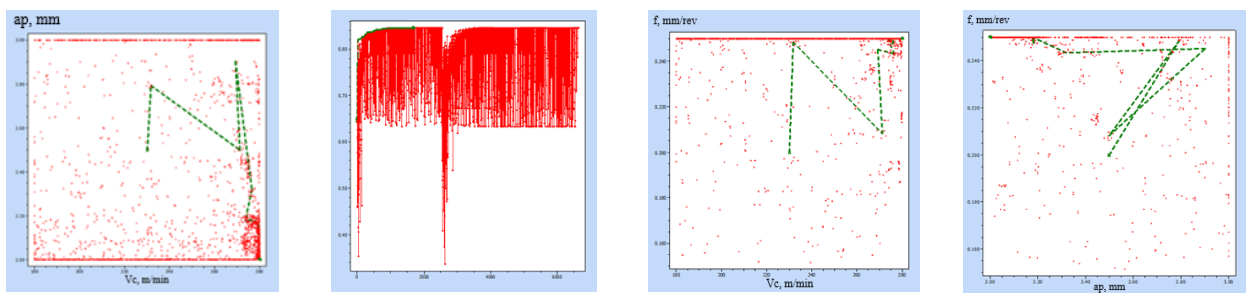


Fig. 3.12 Visualization of determining the optimal cutting mode for a generalized utility function Φ_{A1} with weighting coefficients $w_1=0.2$; $w_2=0.8$

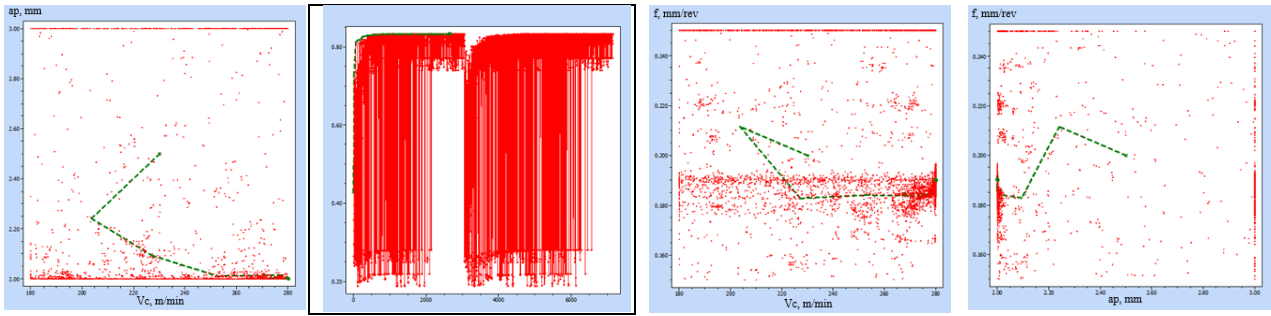


Fig. 3.13 Visualization of determining the optimal cutting mode for a generalized utility function Φ_{A2} with weighting coefficients $w_1=0.8$; $w_2=0.2$

Chapter Four: Determining the Number of Cutting Tools to Ensure a Continuous Work Cycle on CNC Lathes with Robotic Feed

4.1. Research tasks

To ensure a continuous work cycle when processing a given number of parts, it is necessary to:

1. Know the durability of the tools under specific cutting modes.
2. Calculate the capacity of the workpiece magazine (number of parts that can be processed with one charge).
3. Calculate the capacity of the tool magazine (turret head).
4. Create an algorithm for determining the minimum required number of tools for each transition, so that:
 - there are no unplanned stops due to exhaustion of durability;
 - the total number of tools for the operation does not exceed the magazine capacity;
 - the tool change is synchronized with the supply of the blank magazine and the change of the processed batch of parts.

Based on this, the development of a methodology for determining the required number of cutting tools, ensuring a continuous work cycle without unplanned stops for tool changes, is an important step towards the integration of CNC lathes with robotic feed into fully automated and intelligent production systems, typical of Industry 4.0.

The task of this chapter is to determine the required number of cutting tools in operations performed on CNC lathes with robotic feed, taking into account the specified tool life, the capacities of the workpiece magazine and the tool magazine, so as to guarantee a continuous work cycle of the machine when processing a specified number of parts.

4.2. Methodology for determining the number of cutting tools

In CNC lathes with robotic feeding, it is important for the control system to check, given the volume of the production batch N and the capacity of the workpiece feeder and the tool magazine, whether the tool life is sufficient to process the batch or whether additional tools must be activated for the individual transitions in the operation.

The number of parts processed with one tool in the i -th technological transition in the operation is:

$$N_{p,i} = \text{floor} \left(\frac{L_{t,i}}{L_{w,i}} \alpha \right), \quad (4.1)$$

where: $L_{t,i}$ - tool durability, expressed as the distance traveled to reach a given technological wear criterion, mm;

$L_{w,i}$ – length of the working stroke of the tool when processing the surface, mm;

α – safety factor ($\alpha = 0.8 \div 0.9$);

floor () – rounding to the nearest lower integer.

The required number of tools for the i technological transition in the operation $N_{t,i}$, is:

$$N_{t,i} = \text{ceil} \left(\frac{N}{N_{p,i}} \right), \quad (4.2)$$

where: $\text{ceil} ()$ - rounding to the nearest larger integer.

The specified number of tools for the individual transitions in the operation must not exceed the number of positions N_T of the tool magazine (turret head) – 4.3:

$$N_t = \sum_{i=1}^p N_{t,i} \leq N_T, \quad (4.3)$$

where: p - number of transitions in the operation.

In case $N_t > N_T$, the following solutions are possible:

- reducing the number of necessary tools by selecting cutting modes that ensure tool durability during individual transitions, sufficient to meet condition (4.3);
- selecting a machine with a tool magazine (turret head) with a number of positions meeting condition (4.3).

With condition (4.3) provided, the required number of power supplies m of the magazine (pallets) of the robotic station with blanks at a given volume of the production batch N is determined by expression 4.4:

$$m = \text{ceil} \left(\frac{N}{N_w} \right), \quad (4.4)$$

where: N_w - capacity of the feed magazine (pallet) for blanks.

The remaining number of blanks for the last feed is:

$$N_m = N - N_w \cdot \text{floor} \left(\frac{N}{N_w} \right). \quad (4.5)$$

Depending on the ratio of the number of parts processed with one tool $N_{p,i}$ and the volume of the production batch N , the following cases are possible:

1. $N_{p,i} \geq N$

In this case, no tool change is necessary when processing the production batch.

2. $N_{p,i} < N$.

The following options are possible:

2.1. The number of parts processed with one tool is greater than the capacity of the feed magazine (pallet) $N_{p,i} \geq N_w$.

In this case, the number of full magazine feeds with workpieces processed with the first tool m_i^l is:

$$m_i^l = \text{floor} \left(\frac{N_{p,i}}{N_W} \right), \quad (4.6)$$

And the number of processed parts until the tool life is exhausted, remaining for the next magazine feed, is determined by 4.7:

$$N_{p,r,i}^l = N_{p,i} - m_i^l N_W \quad (4.7)$$

After machining $N_{(p,r,i)}^l$ workpieces, it is necessary to replace the tool with an additional one from the tool magazine (turret head) of the machine, and the worn tool can be replaced with a new one the next time the magazine is powered.

For the following tools, it is necessary to determine:

- the total number of feedings of the magazine with blanks until the durability of the s_i -th tool is exhausted (where s_i is the serial number of the tool ($s_i=2 \div N_{t,i}$)) according to 4.8:

$$m_i^{s_i} = \text{floor} \left(\frac{\sum_{q=1}^{s_i} N_{p,i,q}}{N_W} \right); \quad (4.8)$$

- the remaining number of parts for the next feed $N_{p,r,i}^{s_i}$, after which the tool needs to be changed, is determined according to 4.9:

$$N_{p,r,i}^{s_i} = \sum_{q=1}^{s_i} N_{p,i,q} - m_i^{s_i} N_W. \quad (4.9)$$

For the last power supply of the store:

- if $N_{p,r,i}^{s_i} \geq N_m$ - no tool change is required;
- if $N_{p,r,i}^{s_i} < N_m$ - an additional tool is required after machining $N_{p,r,i}^{s_i}$ the workpiece.

2.2. The number of parts processed with one tool is less than the capacity of the feed magazine (pallet) - $N_{p,i} < N_W$

In this case, since the tool life cannot cover the capacity of the feed magazine (pallet), additional tools are required for each feed.

When the magazine is first loaded with blanks, after machining $N_{p,i}$ the workpiece, it is necessary to replace the tool with an additional one from the tool magazine (turret head).

The number of additional tools $N'_{t,i}$ for machining the remaining blanks in the magazine is:

$$N'_{t,i,1} = \text{ceil} \left(\frac{N_W}{N_{p,i}^t} - 1 \right). \quad (4.10)$$

The total number of processed parts with the first and additional tools is determined according to 4.11:

$$N_{p\Sigma,i,1} = N_{p,i} (1 + N'_{t,i,1}). \quad (4.11)$$

The number $N_{p,r,i}^l$ of parts remaining for the next magazine (pallets) feed until the life of the last tool is exhausted is:

$$N_{p,r,i}^l = N_{p\Sigma,i,1} - N_W \quad (4.12)$$

After machining $N_{p,r,i}^l$ the workpiece, it is necessary to replace the tool with an additional one from the tool magazine (turret head), and the worn tool can be replaced with a new one the next time the magazine is fed.

For subsequent magazine feeds ($j>1$, where j is the sequential number of magazine (pallet) feed with blanks ($j=1\div m$)), the required number of additional tools is determined as follows:

- if $N_{p,r,i}^{j-1} + N_{p,i} \geq N_W$, one additional tool is needed for the j^{th} feed ($N'_{t,i,j} = 1$);
- if $N_{p,r,i}^{j-1} + N_{p,i} < N_W$, the required number of additional tools is determined by expression

4.13:

$$N'_{t,i,j} = \text{ceil} \left(\frac{N_W - N_{p,r,i}^{j-1}}{N_{p,i}} \right). \quad (4.13)$$

The total number of processed parts is calculated with 4.14:

$$N_{p\Sigma,i,j} = N_{p,i} N'_{t,i,j} + N_{p,r,i}^{j-1}. \quad (4.14)$$

The number of parts $N_{p,r,i}^j$ remaining for the next magazine feed until the life of the last tool is exhausted, after which the tool needs to be changed, is determined by dependency 4.15:

$$N_{p,r,i}^j = N_{p\Sigma,i,j} - N_W \quad (4.15)$$

For the last store supply ($j=m$):

- if $N_{p,r,i}^{m-1} \geq N_m$, no tool change is required;
- if $N_{p,r,i}^{m-1} < N_m$, the required number of additional tools after machining the workpiece

$N_{p,r,i}^{m-1}$ is determined according to 4.16:

$$N'_{t,i,m} = \text{ceil} \left(\frac{N_m - N_{p,r,i}^{m-1}}{N_{p,i}} \right). \quad (4.16)$$

Based on the created methodology, a block diagram of an algorithm (Fig. 4.1) has been compiled, which can be used to create a software product for determining the required number of cutting tools for a given tool life, production batch volume, tool magazine (turret head) and feed mechanism capacities. The software product can be used to control the operation of CNC lathe machines with robotic feeding.

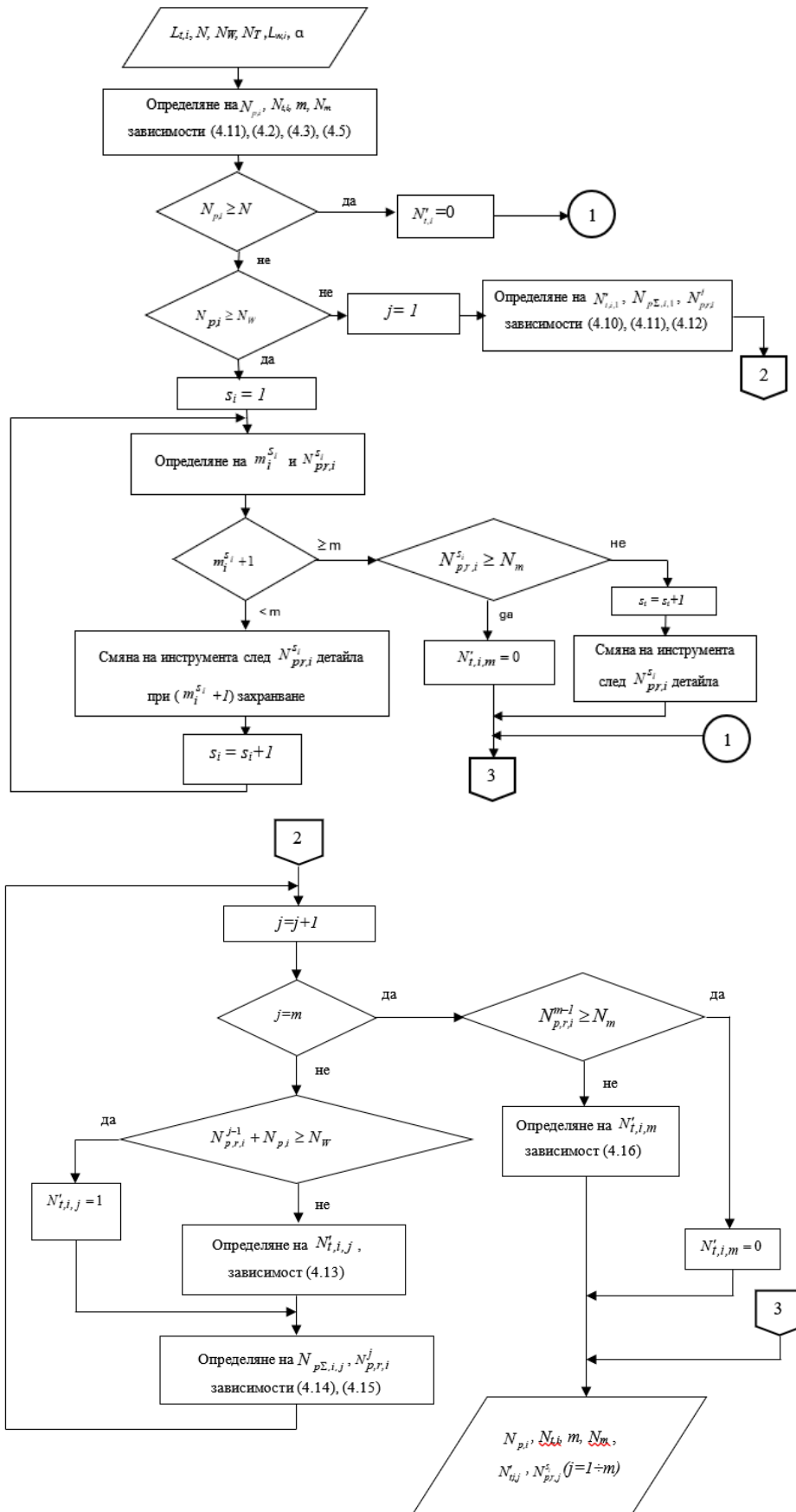


Fig.4.1. Flowchart of an algorithm for determining the required number of cutting tools for CNC machines with robotic feeding

4.3. Application of the methodology for determining the number of cutting tools

The developed methodology was applied to the machining of 42CrMo4 steel parts on a HARRIS C400 CNC lathe with a FANUC BOXI Raptor Auto Loader robotic feeding station. The machining is performed in one pass ($i=1$) with cutting tools with metal-ceramic indexable inserts CCMT09T304-F1 TP2501 from SECO. The experimental models for the durability of the inserts created in chapter two were used, reflecting the influence of the feed f and the cutting speed V_c (table 2.7), in which the durability of the cutting tool was determined by the distance traveled L_t (mm) by the tool along the machined surface until reaching a technological wear criterion – roughness $Ra_k=2.0 \mu\text{m}$. The length of the working stroke of the tool when machining the surface is $L_w = 37 \text{ mm}$. At cutting mode $f = 0.18 \text{ mm/tr}$ and $V_c=130 \text{ mm/min}$, the durability is $L_t = 18,661 \text{ mm}$ (Table 2.6).

With an assumed production batch volume of $N = 2000$ parts, the following are determined using dependencies (4.1) and (4.2):

- the number of parts processed with one tool: $N_p = 453$;

- the required number of tools: $N_t = 5$.

Two variants of billet magazines with capacities $N_W = 300$ and 900 pieces were considered, corresponding to the cases $N_{(p,i)} \geq N_W$ and $N_{(p,i)} < N_W$.

The safety factor is $\alpha = 0.9$.

Using dependencies (4.4) and (4.5), the following were obtained:

- the required number of magazine feeds: $m = 7$ at $N_W = 300$ pieces and $m=3$ at $N_W = 900$ pieces;

- the number of blanks at the last feed: $N_m = 200$.

The results obtained for the required additional tools and the remaining number of parts for the individual feeds, after which the tool needs to be changed, are given in Table 4.1.

Table 4.1. Number of additional tools and number of parts before tool change

j	$N_W = 300 (N_{p,i} \geq N_W)$							$N_W = 900 (N_{p,i} < N_W)$		
	1	2	3	4	5	6	7	1	2	3
Number of additional tools $N'_{t,j}$	-	1	-	1	1		1	1	2	1
Number of parts before tool change $N_{p,r}$	-	153	-	6	159	-	12	453	6	12

ANALYSIS AND CONCLUSIONS

Based on the results of the conducted research, the following main conclusions can be formulated:

1. The influence of the elements of the cutting mode on the technological parameters (productivity, durability of the cutting tools and roughness of the machined surfaces) of the turning process on CNC turning machines with two types of stations with robotic feeding when machining parts made of 42CrMo4 steel has been studied and adequate experimental models with high accuracy have been obtained. Cutting tools with different replaceable cermet inserts have been used.

2. It has been established that the influence of the elements of the cutting mode on the technological parameters of the CNC turning process depends on the type of robotic station and the cutting tools used:

- When machining with a Fanuc LR Mate 200iD/7L robotic station, the cutting speed has the strongest influence on the durability of the tools, with the highest durability shown by the inserts of the company SECO. The increase in the cutting speed and feed lead to a corresponding increase in the roughness of the machined surfaces, with the lowest roughness being obtained when machining with the inserts of the company SECO. The feed and cutting speed have approximately the same influence on the productivity, with the influence being most pronounced when machining with inserts of the company PALBIT.

- When machining with a Mitsubishi RV-8CRL robotic station, the greatest influence on the durability of the cutting tools is the feed, and on the productivity - the depth of cut. The cutting speed has a stronger influence on the productivity, as it increases with its increase. The decrease in durability with increasing speed in the studied range is minimal.

3. A methodology for multi-objective compromise optimization of the turning process on CNC machines with robotic feed has been developed using two methods: determination of a compromise optimal region; optimization using the generalized arithmetic mean utility function with weighting coefficients. By applying it, the optimal cutting modes have been determined, providing the best combination of technological parameters (productivity, durability of cutting tools and roughness of machined surfaces) of the CNC turning process with two types of robotic feed stations (Fanuc LR Mate 200iD/7L and Mitsubishi RV-8CRL) when machining parts made of 42CrMo4 steel with cutting tools from SECO, PALBIT and ISCAR companies (tables 3.1, 3.2 and 3.10).

4. A comparative analysis of the technological parameters of the process has been made with the determined optimal cutting modes using the two optimization methods (tables 3.6 and 3.11). It has been established that:

- when using a Fanuc LR Mate 200iD/7L robotic station, the following results are obtained: higher productivity when working with the modes determined by the generalized utility function method, with the largest difference when processing with SECO inserts (up to 40%); comparable durability of cutting tools at the optimal cutting modes determined by both methods, with the difference ranging from 0.77 to 4%; lower roughness when working with cutting modes determined by the compromise optimal area method, with the largest difference when processing with PALBIT inserts (up to 16.4%);

- when using a Mitsubishi RV-8CRL robotic station, the following results are obtained: higher productivity when working with the modes determined by the generalized utility function method, with the difference ranging from 48.3% to 57.3% depending on the optimal feed value; comparable durability at the optimal cutting modes determined by both methods, with the difference ranging from 3.9% to 5.7%.

5. A methodology has been developed for determining the required number of cutting tools in operations performed on CNC lathes with robotic feed, depending on their durability in a certain cutting mode, the capacities of the tool magazine and the feed mechanism, and the volume of the production batch. The methodology allows for predicting the number of processed parts at which a given tool becomes obsolete, which necessitates the activation of additional tools.

6. In accordance with the methodology for determining the required number of cutting tools, an algorithm has been developed that can be used to create a software product for managing the operation of CNC lathes with robotic feed and ensuring a continuous work cycle when processing a given batch of parts.

CONTRIBUTIONS OF THE DISSERTATION

A. Scientific and applied

- Experimental models of the parameter Ra of roughness, productivity and durability of cutting tools when machining on CNC turning machines with two types of robotic feeding stations.
- Methodology for multi-objective compromise optimization of the CNC turning process with robotic feeding.
- Methodology for determining the number of cutting tools to ensure a continuous work process depending on the durability of the tools, the capacity of the tool magazine and the feeding mechanism and the volume of the production program.

B. Applied

- Optimal cutting modes when turning improved steel 42CrMo4 on CNC lathes with robotic stations.
- Algorithm for a software product for controlling the operation of CNC lathes with robotic feeding, ensuring a continuous production process for a given batch of parts.

DOCTORAL PUBLICATIONS

1. **Kolev N.**, Aleksandrova I., Metev H., Investigation of roughness in machining of 42CrMo4+QT steel on robot-feed CNC machines. International Scientific Conference UNITECH 2023, Gabrovo, Bulgaria, Proceedings, 17-18 November 2023, pp. II80 - II85, ISSN 1313-230X.

2. **Kolev N.**, Technological capabilities and application of robots for feeding CNC machines. International Scientific Conference UNITECH 2024, Gabrovo, Bulgaria, Proceedings, 21-22 November 2024, ISSN 1313-230X.

3. **Kolev N.**, Aleksandrova I., Metev H., Investigating and modeling the durability and performance of metal cutting tools when machining rotary workpieces on robotically powered CNC lathes. International Scientific Conference UNITECH 2024, Gabrovo, Bulgaria, Proceedings, 21-22 November 2024, ISSN 1313-230X.

4. H. Metev, I. Aleksandrova, **N. Kolev**. Investigation of The Machinability of 42CrMo4+QT Steel in Tool Turning with Carbide Inserts on CNC Machines With Robotic Power Supply. Environment. Technology. Resources. Proceedings of the 16th International Scientific and Practical Conference. Rezekne, Latvia, 2025, vol. IV pp. 225 - 233. <https://doi.org/10.17770/etr2025vol4.8414>, ISSN 2256-070X. (Scopus).

5. H. Metev, I. Aleksandrova, **N. Kolev**. Multi-Objective Optimization of Cutting Parameters for CNC Turning 42CrMo4 Hardened Steel Using Utility Function. Environment. Technology. Resources. Proceedings of the 16th International Scientific and Practical Conference. Rezekne, Latvia, 2025, vol. IV. pp. 217 - 223. <https://doi.org/10.17770/etr2025vol4.8413>, ISSN 2256-070X. (Scopus).

6. Aleksandrova, H. Metev, **N. Kolev**. Multi-Purpose Optimization of the Turning Process on CNC Machines with Robotic Loading. International Conference AUTOMATICS AND INFORMATICS`2025, October 09 - 11, 2025, Varna, Bulgaria (ICAI'25). DOI: [10.1109/ICAI67591.2025.11324854](https://doi.org/10.1109/ICAI67591.2025.11324854).

7. Aleksandrova, H. Metev, **N. Kolev**. Determining the Number of Cutting Tools, Ensuring a Continuous Work Cycle in CNC Turning Machines with Robotic Loading. International Conference AUTOMATICS AND INFORMATICS`2025, October 09 - 11, 2025, Varna, Bulgaria (ICAI'25). DOI: [10.1109/ICAI67591.2025.11324509](https://doi.org/10.1109/ICAI67591.2025.11324509).

TITLE: OPTIMIZATION OF TECHNOLOGICAL PROCESSES FOR PART PROCESSING ON CNC MACHINES WITH ROBOTIC FEEDING

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ABSTRACT: *For the manufacture of critical parts in mechanical engineering, operating in conditions requiring a combination of high static strength and hardness with high impact toughness, such as parts of compressors, turbines, working elements of heavy ground and underground equipment, parts for agricultural machinery, etc., heat-treated (hardened and high-temperature annealed) steel 42CrMo4 is used. The optimal cutting modes for its processing specified and recommended in the literature are valid only for certain cutting tools and metal-cutting machines. However, there is no information on the machinability of this steel on CNC lathes in conditions of robotic feeding. In this regard, the aim of the dissertation work is to optimize the CNC turning process with robotic feeding according to the criteria of productivity, durability of cutting tools and roughness of the machined surfaces and ensuring a continuous work cycle when processing heat-treated (hardened and high-temperature tempered) steel 42CrMo4.*

In the research process, two robotic loading stations Fanuc LR Mate 200iD/7L and Mitsubishi RV-8CRL were used. The technological processes of turning on CNC machines with robotic feeding were studied and modeled. Multi-objective optimization of the studied technological processes was carried out. A methodology was developed for determining the number of cutting tools ensuring a continuous work cycle when turning on CNC machines with robotic feeding.

Keywords: *CNC turning; robotic stations; mathematical models; multi-objective optimization; continuous duty cycle*