IX International Conference “Heavy Machinery-HM 2017”, Zlatibor, 28 June – 1 July 2017, B.13 – B.18

Application of Multicriteria Decision Making in Selection of Optimal Toolpath

Aleksandra Petrović[1*], Slobodan Ivanović[2], Goran Miodragović[2], Vladan Grković[1]
[1]Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac (Serbia)
[2] High Technical Mechanical School Trstenik (Serbia)

Peripheral pocket or contour milling using flat end milling tool can be performed using different tool paths. Tool path determines radial and axial depth of cut, engagement angle, feed and feed rate profile. Each possible tool path will result with different machining characteristics: cutting force, tool life, process stability, machining time etc. Some of milling process characteristics are conflicting each other which makes difficult for technology designers to choose optimal tool path.

This paper presents using mulicriteria decision making in selection of optimal tool path. The program for calculating machining elements along the toolpath is developed and applied on one example of pocket machining for 10 different tool paths. Based on obtained machining parameters 10 criteria for selecting optimal tool path are formed. Using basic version of ELECTRE method for choosing optimal tool path, application of multicriteria decision making is shown.

Keywords: Multicriteria decision making, tool path, milling

1. INTRODUCTION

Most of mechanical parts consist of faces parallel or normal to a single plane and free form objects which require a 2.5D rough milling operation of the raw work piece [1]. In practice, classical methods of machining in one direction, in both directions and contour parallel milling are still commonly used. Recently, CAM programs developed applications that support HSM machining in terms of application spiral, trochoidal and D tool paths in order to meet high speed machining demands. Using CAM programs for creating tool path, technology designers face some choices which determine the final shape of tool path. They use their experience, knowledge and intuition to choose some of offered options, so that generated tool path still largely depend of individual judgement [2]. Figure 1. shows an example of diferent tool paths generated with the same CAM program for pocket machining.

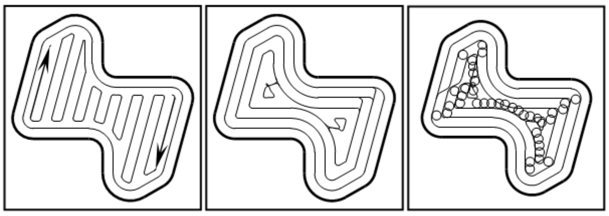


Figure1. Examples of typical tool paths generated by CAM program

This paper presents approach to choose one of offered tool paths using multicriteria decision making based on calculated elements of machining process.

For given pocket contour, using two CAM programs, 9 toolpaths and corresponding NC programs are generated, and one NC program is manually written. Radial and axial depth of cut along the tool path, feed rate profile, cutting force profile, machining time and tool path length are calculated using developed module for cutting elements monitoring. Based on obtained machining parameters 10 criteria for optimal tool path selection are established. ELECTRE multicriteria decision making method is used for selection of the best tool path among 10 available tool paths.

2. OPTIMIZATION PROBLEM

Tool path is generaly generated based on the shape of contour (pocket or island), tool diametar and given stepover so that the workpiece is completly machined. It is usually generated by contour offsetting inward or outward. Tool path determines cutting directions, path curvature, changes in cutting directions and nominal values of axial and radial cutting depth.

Actual radial cutting depth changes along the tool path during cutting direction changes, especially at sharp corners. Engagement angle variations are similar to radial cutting depth, except it depends on shape of machining surface: linear, concave or convex.

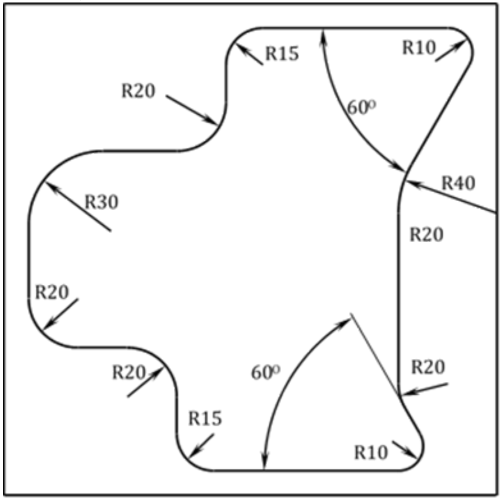
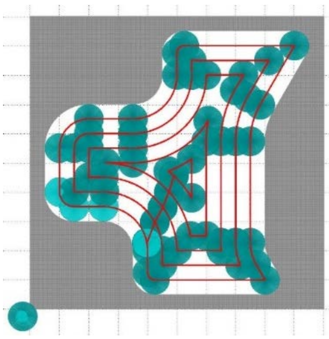


Figure2. Pocket counture example

It is clear that, as the tool is moving along the tool path, cutter engagement can drastically change, which causes the changes in the cutting loads too.

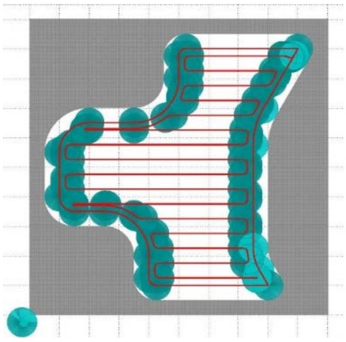
---

*Corresponding author: Dositejeva 19, 36000 Kraljevo, Serbia, petrovic.a@mfkv.rs



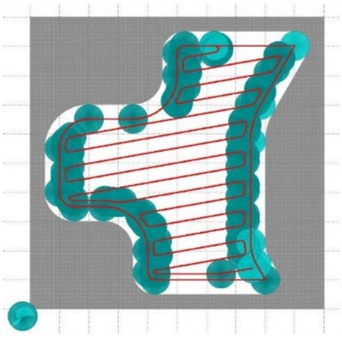
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. In-out
2. *Optimized concentric*
3. Without *r*

Alternative 1 (NC program 1011)



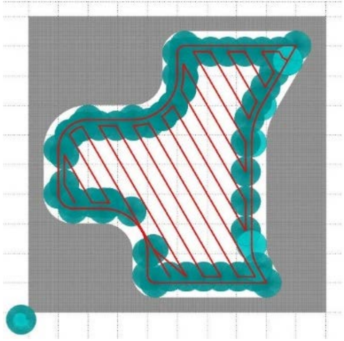
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. *Optimized lace*
2. Angle 0°
3. With *r*

Alternative 2 (NC program 1021)



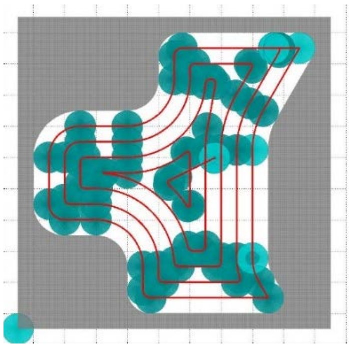
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. *Optimized lace*
2. Angle 10°
3. With *r*

Alternative 3 (NC program 1031)



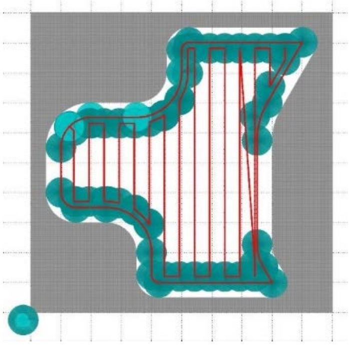
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. *Optimized lace*
2. Angle -60°
3. Without *r*

Alternative 4 (NC program 1031)



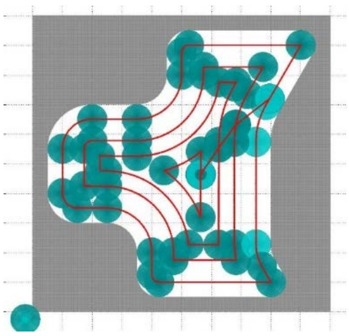
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. In-out
2. Optimized spiral
3. With *r*

Alternative 5 (NC program 1051)



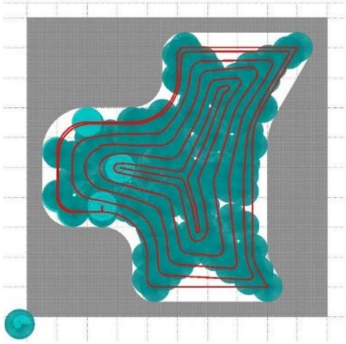
CAM system: *Edge CAM*
Tool: end mill diameter 20 mm
Stepover:10 mm
Options:
1. *Optimized lace*
2. Angle 90°
3. With *r*

Alternative 6 (NC program 1061)



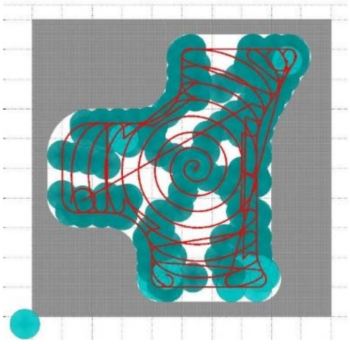
CAM system: *Inventor*
Tool: end mill diameter 20 mm
Stepover: maximum 19 mm
Options:
1. In-out
2. *2D Pocket*

Alternative 7 (NC program 1071)



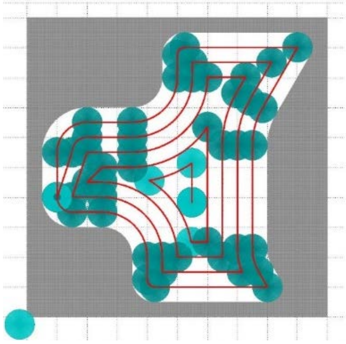
CAM system: *Inventor*
Tool: end mill diameter 20 mm
Stepover: maximum 19 mm
Options:
1. In-out
2. *2D Pocket*
3. *Use morphed spiral machining*

Alternative 8 (NC program 1081)



CAM system: *Inventor*
Tool: end mill diameter 20 mm
Stepover: maximum 12 mm
Options:
1. In-out
2. *2D Adaptive*
3.Min r 5 mm

Alternative 9 (NC program 1091)



Manual programing
Tool: end mill diameter 20 mm
Stepover: maximum 20 mm
Options:
1. Out-in

Alternative 10 (NC program 1101)

Figure3. 10 alternatives for pocket machining of given contour

A sudden increase in cutter engagement may result in dynamic instability, reduced tool life and even in tool breakage [3]. Therefore approaches to adapt or modify the tool path for achieving a constant load were studied recently ([4],[5],[6]).

Tool path shape determines it total length, too. Axial depth of cut can be changed by tool path when workpiece isn't prismatic or have some holes.

At each change of direction, the velocity has to be lowered to allow for the smooth change of the motion direction of the tool. How much lower, that depends on the angle between the two successive path segments ([7],[8]).

Accordingly, tool path determines axial and radial depth of cut, engagement angle, feed and feed rate profile. Knowledge of the above machining elements along the tool path gives us insight into the adequacy of the generated tool path from different aspects.

For a given pocket contour (Figure 2), we want to choose optimal tool path for milling operation. Using two CAM programs and different options which they offer, 9 tool paths and corresponding NC programs are generated. One program for pocket machining is written using manual programing. Tool paths and options used are presented in Figure 3.

NC code data for each tool path is imported into a database and processed. For each path segment the coordinates of start and end point, interpolation parameters, cutting conditions and geometric characteristics of the tool are obtained. Detailed description of used procedure is given in [9].

For evaluation of toolpaths it is necessary to determine radial and axial depth of cut along the tool path, feed rate profile, cutting force profile, machining time and tool path length.

Required elements of the cutting process can be calculated if, in addition to data contained in generated NC programs, geometric characteristics of blank and geometric and technological characteristics of the tool are defined.

Blank workpiece is imported in Matlab as a bitmap image representing view of blank from above, where each colour corresponds to an appropriate height of the blank, detailed description is given in [10].

Geometrical description of the tool is based on ASCII database in which diameter and shape of tool are written. Based on tool diameter d_t and radius r_t, as well as millimetre net division w_{mp} matrix of points on cylindrical tool net are calculated [11].

Then, according to the processed data from the NC program, tool path and the cutter location relative to the workpiece are generated at appropriate spatial intervals along a path.

Based on the cross-section of the cutting tool volume and the blank net, it is determined which section of the volume of the tool is in contact with the blank. In order to determine the angle of engagement and cutting depth in selected points of the tool path it is required to monitor section of the cutter half volume in the direction of the tool velocity in a bottom plane of tool, as well as at the axial depth of cut level. It is also necessary to subtract previously removed material from the blank before computation of these elements. Figure 3 shows tool positions at points in which it is changing motion direction.

Based on cross-section of cutting tool and blank network, values of radial depth of cut and cutting engagement angle are calculated at selected points of the tool path and diagrams of their variation along the tool path are generated.

Based on tool motion direction in junction points of tool path, optimal feed rate is determined using model described in [8]. Then the feedrate profile is determined according to model given in [7].

Applying of the linear model of cutting forces [2] and engagement angle and axial depth of cut, the value of the cutting force and its change along the tool path are determined.

Using module for milling parameters determination developed in [12], briefly described above, radial and axial depth of cut, feed rate profile, cutting force, milling type, machining time and tool path length are determined for all 10 tool paths. Obtained data is sorted in Tables 1-4 for purpose of tool path evaluating.

3. OPTIMIZATION CRITERIA

Tool path affect multiple characteristics of machining process. Criteria for tool path rating are developed based on: depth of cut, milling type, total tool path length and machining time and cutting force.

Table 1: Distribution of radial depth of cut in percentage

NC program	Radial depth of cut intervals $[mm]$																			
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
1011	4.64	1.03	0.73	0.6	0.96	0.58	0.41	0.49	12.01	42.11	5.37	2.86	3.46	2.12	2.84	1.69	1.69	2.24	2.09	12.08
1021	3.99	0.71	1.89	7.95	9.91	2.67	1.45	0.71	0.73	47.79	2.98	1.63	1.45	1.1	0.82	0.81	0.92	1.76	2.67	8.06
1031	1.97	0.17	0.98	8.66	5.46	3.55	3.43	2.3	1.55	26.53	24.92	2.19	1.38	1.13	1.09	1.02	1.38	1.48	1.8	9.01
1041	3.66	0.78	1.26	12.36	6.32	3.06	1.4	1.5	1.24	21.39	28.13	1.44	1.3	1.3	1.34	1.2	1.26	1.36	1.68	8.04
1051	1.1	0.38	0.16	0.41	0.38	0.63	0.52	0.45	14.7	41.36	6.53	3.33	4.01	2.27	2.63	2.93	2.03	2.14	2.81	11.23
1061	2.91	5.09	2.55	8.86	6.47	2.44	2.13	2.68	3.59	2	45.08	1.36	1.12	0.85	0.91	0.7	0.59	0.82	0.96	8.89
1071	4.49	1.01	0.81	0.71	0.66	0.74	1.14	1.04	0.91	10.6	10.93	6.22	3.86	8.88	17.83	3.48	4.31	2.66	3.27	16.44
1081	4.68	3.83	7.05	3.71	6	15.02	15.44	10.53	7.2	4.67	2.2	2.51	2.83	2.69	1.65	1.23	1.05	0.88	0.82	6.01
1091	41.85	1.72	1.17	1.15	1.03	0.92	2.07	1.13	1.03	1.19	1.03	6.75	37.78	0.73	0.31	0.01	0	0.01	0.01	0.11
1101	10.31	2.16	1.72	1.65	1.36	1.94	1.56	1.72	2.61	20.12	14.97	8.93	0.13	0.16	0.11	0.16	0.18	0.18	0.45	29.61

3.1. Depth of cut

Radial and axial depth of cut along with spindle speed determine stability lobe diagrams. In selected example, axial depth of cut and spindle speed are constant, therefore process stability estimation is based only on radial depth of cut. For given combination of workpiece and tool it is checked on stability lobe diagram which radial depths of cut ensure stable milling process.

For given example it is assumed: based on stability lobe diagrams it is determined that the process is stable for radial depth of cut below 18 mm; tool life is increasingly shorten for radial depth of cut smaller than 2 mm; preferable radial depth of cut is between 9 and 11 mm.

Criteria based on radial depth of cut are (Table 1):

- K1: Minimum contribution of radial depth of cut $a<2$ mm,
- K2: Maximum contribution of radial depth of cut $9<a<11$mm,
- K3: Minimum contribution of radial depth of cut $a>18$ mm.

3.2. Type of milling

In down milling (or climb milling) the cutting chips are carried downward by the tool. Rough machining can be performed faster because cutting forces are lighter and the thick-to-thin chip profile carries the heat away on the chip. Tool wear in down milling is less compare to the up milling, due to the cutter rotate with the feed and therefore tool life is longer. The cutting chips fall down behind the tool which gives better surface finish.

Following criteria based on milling type are adopted (Table 2):

- K4: Minimum contribution of combined milling,
- K5: Minimum contribution of up milling,
- K6: Minimum contribution of idle time.

In high speed machining, too small radial depth of cut causes excessive heating in shearing zone shortening the tool life. Also, small part of tool diameter engaged in machining process leads to tool deflection.

It is preferable that radial depth of cut corresponds to the given stepover which is previously determined as optimal value for given combination of workpiece and tool.

Table 2: Contribution of milling type in total tool path in percentage

NC program	Up milling	Down milling	Combined milling	Idle time
1011	0	61.78	37.28	0.94
1021	27.6	48.76	22.83	0.81
1031	15.16	37.8	46.08	0.96
1041	13.13	37.35	48.64	0.88
1051	0.02	58.87	40.62	0.49
1061	7.36	30.58	61.85	0.21
1071	0	19.99	78.72	1.29
1081	0	76.54	22.4	1.06
1091	0	17.73	47.15	35.12
1101	1.11	31.72	61.57	5.59

3.3. Total tool path length and machining time

For a long time total tool path length is used as basis criterion for tool path evaluation. With high speed machining development and inclusion of machining dynamics, total machining time become more significant indicator of machining process speed.

Based on tool path length and machining time (Table 3), the following criteria are adopted:

- K7: Minimum total tool path length and
- K8: Minimum total machining time.

Table 3: Tool path and machining time

NC program	Total		Rapid		With feed rate		Machining	
	Tool path length [mm]	Time[min]	Tool path length [mm]	Time[min]	Tool path length [mm]	Time[min]	Tool path length [mm]	Time[min]
1011	2024.32	3.143	148.77	0.00297	1875.54	3.140	1858.54	3.110
1021	2341.74	3.628	168.32	0.00336	2173.41	3.624	2156.41	3.595
1031	2257.13	3.491	167.32	0.00334	2089.80	3.488	2070.71	3.455
1041	2279.22	3.662	94.86	0.00189	2184.36	3.660	2167.36	3.631
1051	2016.93	3.019	209.86	0.00419	1807.07	3.014	1798.21	2.998
1061	2555.01	3.848	258.74	0.00517	2296.26	3.843	2292.06	3.835
1071	1752.79	2.665	161.08	0.00322	1591.71	2.662	1572.27	2.629
1081	2837.97	4.518	132.05	0.00264	2705.92	4.516	2677.77	4.467
1091	3550.25	4.782	244.66	0.00489	3305.58	4.777	2101.67	3.506
1101	1904.48	3.026	96.6	0.00193	1807.88	3.024	1708.61	2.851

3.4. Cutting force

With increase of cutting force, tool wear is increasing and tool life is shortening. Cutting force variations affect stability of milling process as well. The goal is to reduce mean value of cutting force as well as cutting force deviation.

Based on cutting force (Table 4), the following criteria are adopted:

- K9: Minimum cutting force for when feed rate is used,
- K10: Minimum deviation of cutting force

Using multicriteria decision making the optimal tool path can be selected for defined criteria.

Table 4: Mean value of cutting force Fsr and mean absolute deviation of cutting force Fod

NC program	Fsr (with feed rate) [*N*]	Fod (with feed rate) [*N*]	Fsr (machining) [*N*]	Fod (machining) [*N*]
1011	591.047	83.713	596.659	75.31
1021	425.71	169.519	429.168	168.19
1031	443.644	166.811	447.937	164.796
1041	431.934	168.354	435.767	166.76
1051	605.364	61.183	608.341	56.751
1061	432.163	154.262	433.069	153.901
1071	597.825	86.212	605.66	73.391
1081	369.46	182.693	373.371	180.805
1091	355.526	287.178	547.516	149.488
1101	511.285	188.942	541.218	155.999

4. MULTICRITERIA DECISION MAKING

Multiple-criteria decision-making (MCDM) is a procedure that combines the performance of decision alternatives across several, contradicting, qualitative and/or quantitative criteria and results in a compromise solution [13]. A typical MCDM problem can be defined as a ranking aid to arrange a finite number of decision alternatives, each of which is clearly described in terms of different characteristics. These characteristics are also often called attributes or decision criteria [14].

In this paper ELECTRE I method is used for selecting optimal tool path, since it is found to be best suited for selection problems.

4.1. ELECTRE method

The ELECTRE (Elimination and Choice Translating algorithm) family was introduced by Benayoun, Roy and Sussman in 1968. The method was later developed by Bernard Roy. This family includes ELECTRE I, II, III, IV, IS and TRI methods [14].

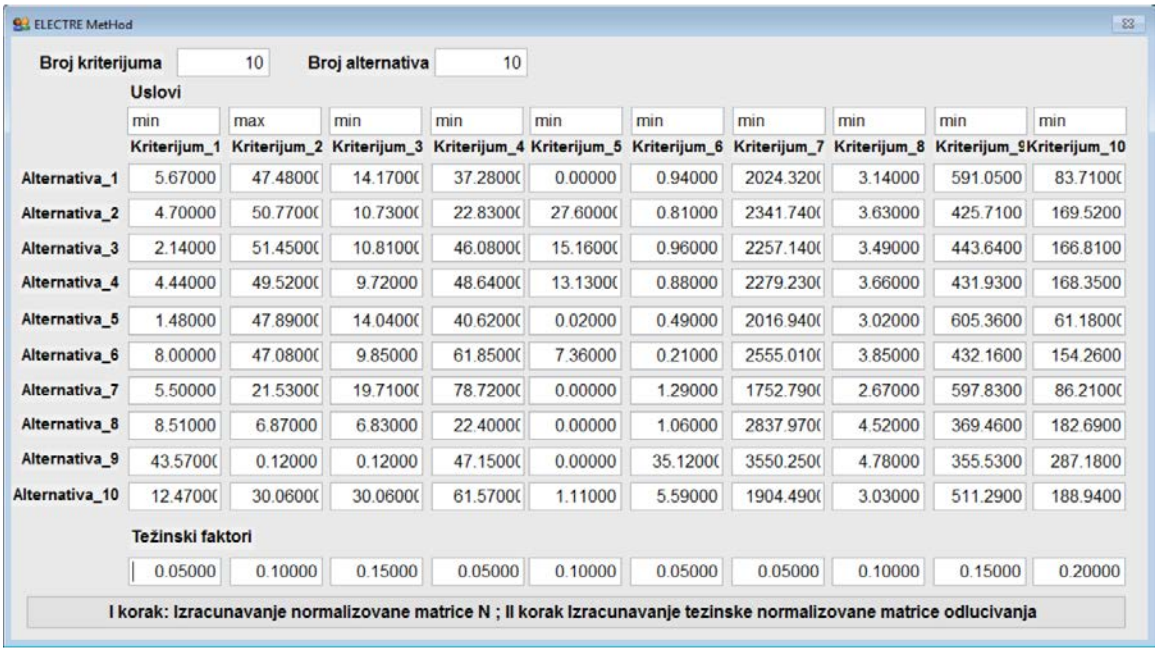
The basic concept of the ELECTRE method is to deal with "outranking relations" by using pairwise comparisons among alternatives under each one of the criteria separately. The organization of the ELECTRE method is best illustrated in the following steps [15]:

- *Normalizing the Decision Matrix:* This procedure transforms various units in the decision matrix into dimensionless comparable units.
- *Weighting the Normalized Decision Matrix:* The column of the matrix is then multiplied by its associated weights which were assigned to the criteria by the decision maker.
- *Determine the Concordance and Discordance Sets:* The concordance set of two alternatives is defined as the set of all criteria for which one alternative is preferred to other. The complementary subset is called the discordance set.
- *Construct the Concordance and Discordance Matrices:* The relative value of the elements in the concordance matrix is calculated by means of the concordance index. The concordance index is the sum of the weights associated with the criteria contained in the concordance set. The concordance index indicates the relative importance of one alternative with respect to other alternative.
- *Determine the Concordance and Discordance Dominance Matrices:* The concordance dominance matrix is constructed by means of a threshold value for the concordance index.
- *Determine the Aggregate Dominance Matrix.*
- *Eliminate the Less Favorable Alternatives.*

4.2. Application of ELECTRE I method in selecting optimal tool path

Based on criteria defined in section 3 decision matrix is formed (Figure 4).

According to steps briefly described in previous subsection (detailed description of steps given in [15]), program for ELECTRE application is created [12] .



Broj kriterijuma 10 **Broj alternativa** 10

Uslovi

	Kriterijum_1	Kriterijum_2	Kriterijum_3	Kriterijum_4	Kriterijum_5	Kriterijum_6	Kriterijum_7	Kriterijum_8	Kriterijum_9	Kriterijum_10
Uslovi	min	max	min	min	min	min	min	min	min	min
Alternativa_1	5.67000	47.4800(	14.1700(	37.2800(	0.00000	0.94000	2024.320(	3.14000	591.0500	83.7100(
Alternativa_2	4.70000	50.7700(	10.7300(	22.8300(	27.6000(	0.81000	2341.740(	3.63000	425.7100	169.5200
Alternativa_3	2.14000	51.4500(	10.8100(	46.0800(	15.1600(	0.96000	2257.140(	3.49000	443.6400	166.8100
Alternativa_4	4.44000	49.5200(	9.72000	48.6400(	13.1300(	0.88000	2279.230(	3.66000	431.9300	168.3500
Alternativa_5	1.48000	47.8900(	14.0400(	40.6200(	0.02000	0.49000	2016.940(	3.02000	605.3600	61.1800(
Alternativa_6	8.00000	47.0800(	9.85000	61.8500(	7.36000	0.21000	2555.010(	3.85000	432.1600	154.2600
Alternativa_7	5.50000	21.5300(	19.7100(	78.7200(	0.00000	1.29000	1752.790(	2.67000	597.8300	86.2100(
Alternativa_8	8.51000	6.87000	6.83000	22.4000(	0.00000	1.06000	2837.970(	4.52000	369.4600	182.6900
Alternativa_9	43.5700(	0.12000	0.12000	47.1500(	0.00000	35.1200(	3550.250(	4.78000	355.5300	287.1800
Alternativa_10	12.4700(	30.0600(	30.0600(	61.5700(	1.11000	5.59000	1904.490(	3.03000	511.2900	188.9400
Težinski faktori	0.05000	0.10000	0.15000	0.05000	0.10000	0.05000	0.05000	0.10000	0.15000	0.20000

Figure 4. Decision matrix

Final result is that Alternative 5 (NC program 1051) absolutely dominate over other alternatives.

Using individually criteria following results are obtained:

- According to criteria K1- alternative 5,
- According to criteria K2- alternative 2,
- According to criteria K3- alternative 9,
- According to criteria K4- alternative 8,
- According to criteria K5- alternatives 1, 7, 8 and 9,
- According to criteria K6- alternative 6,
- According to criteria K7- alternative 7,
- According to criteria K8- alternative 7,
- According to criteria K9- alternative 9 and
- According to criteria K10- alternative 5.

It is clear that for solving problem of selecting optimal tool path, using multicriteria decision making gives more comprehensive solution.

5. CONCLUSION

In this paper, application of multicriteria decision making is presented on example of selecting optimal tool path for pocket milling.

CAM software offer multiple options for generation of tool path, in addition using same options in different software will result with different tool paths. Therefore, final decision depends largely on technology designer’s experience.

Using module for milling parameters determination developed in [12], data necessary for tool path evaluating is obtained for 10 different tool paths for pocket milling of given contour. Several criteria for tool path rating are established. ELECTRE multicriteria decision making method is implemented, which result in selection of Alternative 5 as optimal tool path.

Presented approach helps technology designers in choosing options for NC program generation.

Some other criteria are to be added in future work, such as maximum productivity and its minimum variation along the tool path.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Ministry of Education and Science of the Republic of Serbia for their support to this research through the project TR37020.

REFERENCES

[1] Sandeep DHANIK, “NC Tool Path Evaluator and Generator for High Speed Milling,” vol. 4533. ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, Lausanne, Switzerland, p. 201, 2009.

[2] A. Petrović, S. Ivanović, and L. Lukić, “NC Tool Path and Its Influence on Cutting Force in Peripheral Milling Analyses,” *IMK -14–- Res. Dev. Heavy Mach.*, vol. 21, pp. 41–46, 2015.

[3] S. K. Gupta, S. K. Saini, B. W. Spranklin, and Z. Yao, “Geometric algorithms for computing cutter engagement functions in 2.5D milling operations,” *Comput. Des.*, vol. 37, no. 14, pp. 1469–1480, Dec. 2005.

[4] M. S. Uddin, S. Ibaraki, A. Matsubara, S. Nishida, and Y. Kakino, “A Tool Path Modification Approach to Cutting Engagement Regulation for the Improvement of Machining Accuracy in 2D Milling With a Straight End Mill,” *J. Manuf. Sci. Eng.*, vol. 129, no. 6, p. 1069, Dec. 2007.

[5] H. Wang, P. Jang, and J. A. Stori, “A Metric-Based Approach to Two-Dimensional (2D) Tool-Path Optimization for High-Speed Machining,” *J. Manuf. Sci. Eng.*, vol. 127, no. 1, p. 33, Feb. 2005.

[6] J. . Stori and P. . Wright, “Constant engagement tool path generation for convex geometries,” *J. Manuf. Syst.*, vol. 19, no. 3, pp. 172–184, Jan. 2000.

[7] N. Nesic, “Modeling and Simulation of Energy Efficient Milling Process Plans for Prismatic Parts,” ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, 2012.

[8] B. H. Kim and B. K. Choi, “Machining efficiency comparison direction-parallel tool path with contour-parallel tool path,” *Comput. Des.*, vol. 34, no. 2, pp. 89–95, Feb. 2002.

[9] A. Petrović, S. Ivanović, and L. Lukić, “Generating Parametres from the NC Code Needed for Defining the Optimal Tool Path,” in *MMA 2015 - FLEXIBLE TEHNOLOGIES*, 2015, pp. 157–160.

[10] S. Ivanović, A. Petrović, and L. Lukić, “Matrix blank description as part of module for machining parameters generation along the tool path for peripheral milling,” *IMK-14 – Res. Dev. Heavy Mach.*, vol. 21, no. 4, pp. EN119–124, 2015.

[11] Petrovic A, Lukic Lj, Ivanovic S, Pavlovic A, „Optimisation of tool path for wood machining on CNC machines“, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, (2016)

[12] A. Petrović, “Optimizacija putanje glodala pri konturnoj obradi velikim brzinama rezanja”, PhD Thesis, University of Kragujevac, Serbia, 2016.

[13] A. Dadda, I. Ouhbi, “ A decision support system for renewable energy plant projects”, In Proceedings of the 2014 Fifth International Conference on Next Generation Networks and Services (NGNS), Casablanca, Morocco, 28–30 May 2014.

[14] Mary, S. and Suganya, G. (2016) Multi-Criteria Decision Making Using ELECTRE. *Circuits and Systems*, **7**, 1008-1020.

[15] E. Triantaphyllou, B. Shu, S. Nieto Sanchez, and T. Ray,” Multi-Criteria Decision Making: An Operations Research Approach” Encyclopedia of Electrical and Electronics Engineering, John Wiley & Sons, New York, NY, Vol. 15, pp. 175-186, (1998).