APEM journal

Advances in Production Engineering & Management
Volume 10 | Number 1 | March 2015 | pp 18–26
http://dx.doi.org/10.14743/apem2015.1.189

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Tool selection for rough and finish CNC milling operations based on tool-path generation and machining optimisation

Mwinuka, T.E.[a,*], **Mgwatu, M.I.**[a]

[a]University of Dar es Salaam, Department of Mechanical and Industrial Engineering, Dar es Salaam, Tanzania

A B S T R A C T

Most of CAD/CAM systems lack fully-automated process planning capabilities and depend on semi-automatic capabilities that necessitate the traditional selection of tools and cutting parameters. This paper attempts to determine proper combinations of cutting tools through the generation of tool paths and optimisation of machining parameters using an example of the CNC milling process. Several machining simulations with different combinations of tool sizes were performed using MasterCAM software. Based on these simulations, substantial variations in tool paths were observed for different tool combinations and as such the optimum tool combination could only be obtained arbitrarily. The tool paths derived from machining simulations were used to optimise machining parameters, that is, cutting speed, feed rate and depth of cut with the objective of minimising production time. In this case, an optimisation model was developed as a nonlinear programming problem and solved using extended LINGO nonlinear software. The results show that the subjectivity when selecting cutting tools can be avoided when appropriate tools are chosen alongside with the generation of a tool path within a CAD/CAM system using optimised machining parameters. As a consequence, CNC machine tools could be effectively utilised and the productivity significantly improved at shorter production time and cost.

A R T I C L E I N F O

Keywords:
CAD/CAM
Milling operations
Machining optimisation
Nonlinear programming
Tool-path generation
Tool selection

**Corresponding author:*
tmwinuka@udsm.ac.tz
(Mwinuka, T.E.)

Article history:
Received 30 December 2013
Revised 26 December 2014
Accepted 25 January 2015

1. Introduction

Numerical Control (NC) technology has mainly contributed towards the automation of manufacturing processes specifically in metal cutting processes. In NC technology, numerical data are used to control operations of machine tools, material handling systems and inspection equipment in manufacturing of different products. The control is achieved through feeding the part program into the machine control unit (MCU). The accuracy and precision of components produced on NC machine tools is less dependent on skills of the operator but on the instructions contained in the part program. Actually, a computer numerical control (CNC) machine tool is accompanied with a computer where a part program can be prepared, stored and edited. MCU reads the instructions in the part program and interprets to allow the required movement of the worktable and spindle of the machine tools.

Part programming can be done manually or with the aid of the computer. Manual part programming is time consuming, error prone and limited to simple geometry. In computer-assisted part programming, much of tedious computation tasks inherent in manual part programming are performed using high-level programming languages. Automatically Programmed Tools (APT) was one of the common languages employed to describe part geometry and specify tool motions. However, such programming systems are no longer common due to emerging of CAD/CAM systems which are more convenient in defining part geometries and specifying tool paths. A CAD/CAM system has a platform where a component can be modelled in CAD and its geometric data is accessed by a CAM system to generate tool paths achieving the requirements of NC programming. Several CAD/CAM systems are available in the market such as MasterCAM, Bob CADCAM, KELLER SYMPlus and EDGECAM.

In order to accomplish a complete NC part program for application in a CNC machine tool, process planning activities should be integrated in the CAD/CAM system. Activities of process planning includes: (1) interpretation of product design data, (2) selection of machining operations, (3) sequencing of machining operations, (4) planning of work-holding, (5) selection of machine tools, (6) selection of cutting tools, (7) determination of optimal cutting parameters, and (8) determination of product routing. However, the literature shows that many of CAD/CAM systems lack fully-automated process planning capabilities but depend on semi-automatic applications which need several inputs from the user for feature identification, tool selection and determination of optimal cutting parameters. In other words, most of decisions in process planning are done manually with the assistance of a computer [1-4]. For example, most of the available CADCAM systems often do not generate optimum toolpath in CNC machining operations [5]. As a result, a full CAD/CAM integration has not yet been achieved.

A number of researchers have worked on process planning for metal cutting operations in different details. An algorithm was developed in [6] for determining the biggest possible cutter for 2D milling operation for achieving highest production rate. The algorithm is centred on the tools ability to cover target region. For any point on a target region, there must be a permissible location for a cutter such that an area covered by a cutter is fully contained in a target region. The algorithm however did not deal with minimising production cost. The study by [7] addressed the problem of selecting a sequence of end milling cutters to machine a 2.5D pocket with the goal of incurring the minimum combined cost of tool wear and machining time. A two-dimensional contour offset approach was used to find accessible areas for various tools. The accessible areas were defined as the region within the 2D contour in that the tool can reach without gouging the boundary. The decomposition of the pocket into sub-pockets was carried out based on the accessible areas of various tools. All possible sequences can be represented as a directed graph. In the graph, the nodes represented the state of the stock after the tool named in the node has accomplished the machining operation. Upstream nodes in the graph have tools of larger diameter compared to downstream nodes. Edges were weighted with the cost of machining starting from one state of the stock to another.

The research reported in [8] described a method for determining the optimal combination of cutting tool for 3D volumes or 2D profiles. Optimal tools were selected by considering residual materials that are inaccessible to oversized cutters and the relative clearance rates of cutters that can access these regions of the selected machining features. They used machining features and set of tool diameters to calculate tool access volumes and ultimately determine residual volumes. Researchers of [9] presented a method of selecting optimal tools from a set of feasible tools, considered global residual (due to presence of neck or island) and local residue (due to smallest concave radius in the pocket). They argued that the high number of tools is associated with pockets with global residue and is less than four. It was pointed out that the key factor in determining the number of tools in the optimal combinations is the ratio of the pocket area to the local residue area. When the pocket area is much larger than the local residue area, a roughing tool must be used to remove the main area of the pocket first. Some types of uncut area can occur in pocket milling but are not related to the two categories referred to by [9]. These may be caused by using large radial depth of cut, up to the size of tool diameter. The solution around this problem can be to reduce radial depth of cut or using tool paths with compensation for uncut regions as described in [10]. The tool compensation can allow radial depth of cut up to the size of tool diameter. In another attempt to avoid uncut areas especially at corners of the part, the tool may be offset by tool radius to create the first tool path, and then the remaining tool paths can be obtained by offsetting the previous tool paths by a distance of 0.85 multiplied by the diameter of the tool [11]. Researchers in [12] developed an optimised cutting tool selection model as an input to CADCAM system to automatically machine recognised features based on ISO STEP format that enables information exchange within CADCAM software. In their work, a Rule-Based Knowledge and Decision System generates the cutter and inserts; then selects the cutting conditions from Sandvic Coromant database for each manufacturing feature.

The optimisation of tool selection proposed by [13] used Artificial Intelligence whereby tool paths were considered alongside with tool selection method. In this work, tool paths were determined within Matlab environment and the optimisation problem was solved using Genetic Algorithm. However, the effect of machining strategy was not addressed. Previous work [14] showed that Genetic Algorithm has been the most widely used optimisation procedure for various objectives including reduction of cost, tool changing time and tool travel path, and minimising machining time. Other methods are Particle Swarm optimization (PSO), Artificial Neural Networks (ANN), Ant Colony Optimization (ACO) and Artificial Immune System (AIS).

Although nowadays process planning can be achieved by using computer-aided process planning (CAPP) systems, the linkage of CAPP to CAD/CAM systems is still not well established. Much of the research work is yet to contribute into efficient commercial CAD/CAPP/CAM system with a reason that CADCAM systems (or NC generating software) still require a lot of user input especially in process planning. The optimum set of tools is specific for a particular geometry of a machining feature. Bigger tools can remove material from the work-part much faster but leave larger residual material and operate at higher production cost or time. The use of more than one tool may or may not necessarily lead to reduction in production cost or time. In such as situation, the use of optimisation procedure that is not implemented within CADCAM systems is inevitable. The major contribution of this study is based on the selection of cutting tools for CNC milling operations through tool-path generation and machining parameter optimisation. Specifically, the study is intended to create a geometric feature and perform extensive machining simulations on different sets of cutting tools to reveal the economics of CNC milling process in terms of production time.

2. Methodology

Trial machining simulations for CNC milling operations were conducted on MasterCAM system. This system is commonly used in industries and has the capability of creating part geometries as well as generating tool paths and associated NC codes. Before simulations were done on MasterCAM, a test component was selected. The selected component was a side plate of a sugar-cane crusher. This component is geometrically complex with intricate pockets and islands as shown in Fig. 1(a) and Fig 1(b).

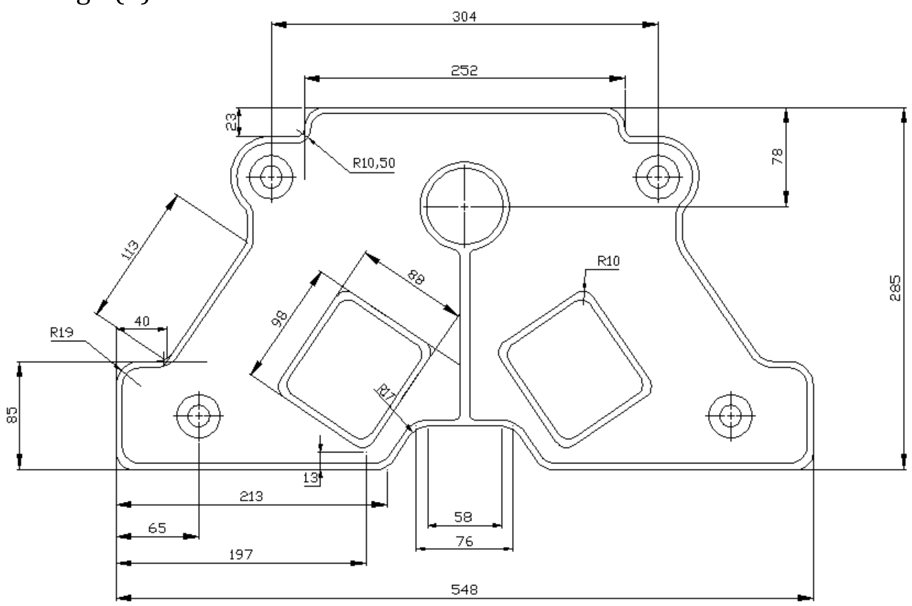

Fig. 1(a) A side plate of sugar-cane crusher in orthographic view

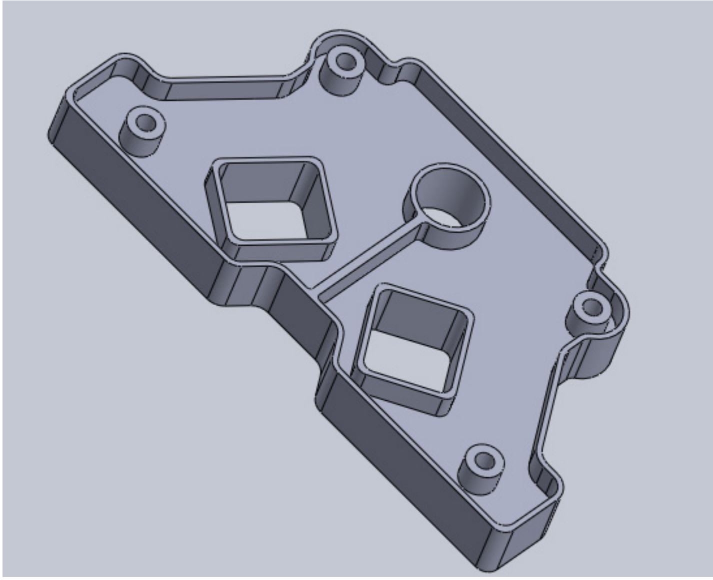

Fig. 1(b) A side plate of sugar-cane crusher in 3D view

Tool combinations were selected in such a manner that bigger sets of tools can at least gouge the pocket of the work-piece and smaller sets of tools can pass through the smaller constrictions within the pockets.

The following tool combinations were tried out: Single tools, two-tool combinations and three-tool combinations. For each simulation trial, the total length of the tool path for each tool was recorded. A radial width of cut equal to 0.85 of tool diameter was selected to avoid the existence of uncut regions. Since it is known that the length of the tool path and the corresponding machining time depends on the tool path strategy, e.g. spiral, zigzag, one way etc. [5, 15], the zigzag strategy was used throughout the machining tests. Previous works [16] shows that zigzag tool path is more favourable than any other strategy in terms of cycle time in rough machining of pockets. From simulations, it can be clearly noted whether or not there is any residual materials left on the work-piece. In order to obtain a comprehensive process plan, tool paths derived from machining simulations were used to optimise the machining parameters such as cutting speed, feed rate and depth of cut for CNC milling operations. The optimisation of machining parameters is conducted to achieve the best performance of the machine tool in terms of production time. The optimisation model for minimising production time needed for both rough and finish CNC milling operations can be formulated as follows:

$$\text{Minimise } t_p = \sum_{i=1}^{N}\left(\frac{\pi D_i L_i}{1000 v_i f_i Z_i} + \frac{\pi D_i^{1-w_T} L_i W_i^{\delta_T} Z_i^{\lambda_T - 1}}{1000 E_T} v_i^{\alpha_T - 1} f_i^{\beta_T - 1} d_i^{\gamma_T} t_r\right) \tag{1}$$

Subject to:

$$v_i^L \le v_i \le v_i^U, \forall i \tag{2}$$

$$f_i^L \le f_i \le f_i^U, \forall i \tag{3}$$

$$d_i^L \le d_i \le d_i^U, \forall i \tag{4}$$

$$E_F D_i^{\omega_F} v_i^{\alpha_F} f_i^{\beta_F} d_i^{\gamma_F} W_i Z_i \le F_{max,} \, \forall i \tag{5}$$

$$E_P D_i^{\omega_P} v_i^{\alpha_P} f_i^{\beta_P} d_i^{\gamma_P} W_i Z_i \le P_{max,} \, \forall i \tag{6}$$

Where: t_p is the production time; v_i the cutting speed; f_i the feed rate; and d_i the depth of cut. The developed model is a nonlinear programming problem containing the nonlinear objective function as well as linear and nonlinear constraints. This model can easily be solved with extended LINGO software to achieve the optimal cutting speed, feed rate and depth of cut and yet meeting the minimum production time. Various methods can also be used to solve the model including particle swarm optimisation (PSO), artificial neural networks (ANN), ant colony optimisation (ACO) and artificial immune system (AIS). The selection of LINGO software was based on the fact that it is capable of solving unlimited size of linear and nonlinear constraints and unlimited number of integer, nonlinear and global variables [17]. The first term of the objection function in Eq. 1 defines the machining time while the second term of the equation defines the tool replacement time. Constraints (2), (3), and (4) express the allowable limits of the minimum and maximum cutting speed, feed rate, and depth of cut, respectively. The cutting force and cutting power are restricted by maximum limits in constraints (5) and (6), respectively.

3. Results and discussion

Trials of machining simulations with different combinations of tool sizes were performed using MasterCAM software with the intention of selecting the optimum combinations of tool size. On conducting the simulations, a stock size was selected based on prismatic bounding box of the component with allowances of 5 mm in all the three machining axes. Tool paths were automatically generated as shown in pictorial view (Fig. 2).

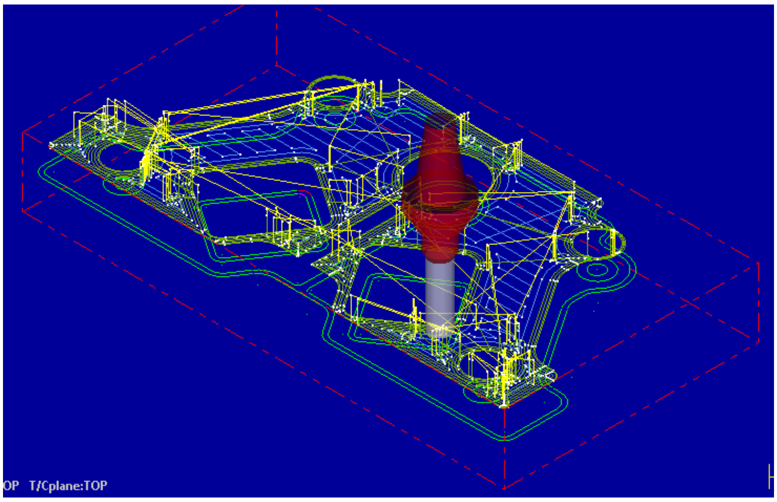

Fig. 2 Tool path generated in MasterCAM

Four single tools were tried out to generate tool paths. As shown in Table 1, the tool with a diameter D = 6 mm provides the minimum length of tool path (L = 30269 mm) without any island left in the pockets. In Table 2, seven sets of two-tool combinations were tried out in the simulation of tool path. The results show that tools with diameters of 40 mm and 5 mm in combination provide the minimum length of tool path (L = 32801 mm) without islands. Table 3 shows the simulation results for three-tool combinations whereby tools with diameters of 40 mm, 20 mm and 5 mm provide the minimum length of the tool path (L = 25873 mm) without islands. By comparison of all trial simulations with single tool, two-tool combinations and three-tool combinations, it is observed that a set of three tools with diameters of 40 mm, 20 mm and 5 mm is optimum as it provides the minimum length of tool path. However, this reason alone may not necessarily lead to the minimum production time because other machining parameters such as cutting speed, feed rate and depth of cut are not considered. In this case, further analysis is to be performed using the formulated optimisation model to determine the optimum machining parameters in order to determine the appropriate tool combination which provides the minimum production time. Additional data for the model is given in Tables 1, 2 and 3. These include number of tool teeth z; radial depth of cut W (mm); limits of machining parameters v^L (m/min), v^U (m/min), f^L (mm/tooth), f^U (mm/tooth), d^L (mm), d^U (mm). Tool life constants are given as α_T = 3.03, β_T = 1.51, γ_T = 1.51, λ_T = 0.3, δ_T = 0.3, ω_T = 1.36, E_T = 148880 whereas cutting force and power constants are given as ω_F = -0.86, α_F = 0, β_F = 0.72, γ_F = 0.86, ω_P = -0.86, α_P = 1, β_P = 0.72, γ_P = 0.86, E_F = 0.642, E_P = 0.0107, F_{max} = 0.8 kN , P_{max} = 1.5 kW [18, 19].

Table 1 Generated tool path L (mm) with a single tool

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
1	6	30269	2	5.1	9	30	0.063	0.127	1	4
2	5	34593	2	4.25	9	30	0.063	0.127	1	4
3	4	42788	2	3.4	9	30	0.063	0.127	1	4
4	3	57553	2	2.55	9	30	0.063	0.127	1	4

Table 2 Generated tool path L (mm) with a combination of two tools

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
1	40	2784	6	34	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
2	35	3460	6	29.75	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
3	30	4507	6	25.5	60	120	0.063	0.152	2	8
	5	30018	2	4.25	9	30	0.063	0.127	1	4
4	25	5360	4	21.25	60	120	0.063	0.152	2	8
	5	30017	2	4.25	9	30	0.063	0.127	1	4
5	20	6947	4	17	9	30	0.063	0.127	1	4
	5	30017	2	4.25	9	30	0.063	0.127	1	4
6	15	9877	4	12.75	9	30	0.063	0.127	1	4
	5	30018	2	4.25	9	30	0.063	0.127	1	4
7	10	14780	2	8.5	9	30	0.063	0.127	1	4
	5	30474	2	4.25	9	30	0.063	0.127	1	4

Table 3 Generated tool path L (mm) with a combination of three tools

S/N	D	L	z	W	v^L	v^U	f^L	f^U	d^L	d^U
	40	2784	6	34	60	120	0.063	0.152	2	8
1	20	10990	4	17	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	40	2784	6	34	60	120	0.063	0.152	2	8
2	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	35	3460	6	29.75	60	120	0.063	0.152	2	8
3	20	10990	4	17	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	35	3460	6	29.75	60	120	0.063	0.152	2	8
4	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4
	30	4507	6	25.5	60	120	0.063	0.152	2	8
5	10	20823	2	8.5	9	30	0.063	0.127	1	4
	5	12099	2	4.25	9	30	0.063	0.127	1	4

Based on the optimisation results in Tables 4, 5 and 6, a single tool with a diameter D = 3 mm provides the minimum production time (t_p = 70.7 min) while two tools with diameters of 40 mm and 5 mm in combination provide the minimum production time (t_p = 65.4 min) and three tools with diameters of 40 mm, 20 mm and 5 mm in combination provide the minimum length of the tool path (t_p = 73.6 min).

Table 4 Tool path and machining parameters with single tool

S/N	D	L	z	W	v_{opt}	f_{opt}	d_{opt}	t_p
1	6	30269	2	5.1	30	0.127	1	76.0
2	5	34593	2	4.25	30	0.127	1	71.4
3	4	42788	2	3.4	30	0.127	1	70.7
4	3	57553	2	2.55	30	0.127	1	71.4

Table 5 Tool path and machining parameters with two tools

S/N	D	L	Z	W	v_{opt}	f_{opt}	d_{opt}	t_p
1	40	2784	6	34	120	0.152	2	65.4
	5	30017	2	4.25	30	0.127	1	
2	35	3460	6	29.75	120	0.152	2	65.8
	5	30017	2	4.25	30	0.127	1	
3	30	4507	6	25.5	120	0.152	2	66.3
	5	30018	2	4.25	30	0.127	1	
4	25	5360	4	21.25	120	0.152	2	68.4
	5	30017	2	4.25	30	0.127	1	
5	20	6947	4	17	30	0.127	1	90.6
	5	30017	2	4.25	30	0.127	1	
6	15	9877	4	12.75	30	0.127	1	92.6
	5	30018	2	4.25	30	0.127	1	
7	10	14780	2	8.5	30	0.127	1	123.9
	5	30474	2	4.25	30	0.127	1	

Table 6 Tool path and machining parameters with three tools

S/N	D	L	Z	W	v_{opt}	f_{opt}	d_{opt}	t_p
1	40	2784	6	34	120	0.157	2	73.6
	20	10990	4	17	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
2	40	2784	6	34	120	0.157	2	114.2
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
3	35	3460	6	29.75	120	0.157	2	74
	20	10990	4	17	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
4	35	3460	6	29.75	120	0.157	2	114.6
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	
5	30	4507	6	25.5	120	0.157	2	115.1
	10	20823	2	8.5	30	0.127	1	
	5	12099	2	4.25	30	0.127	1	

By comparison of tool paths and machining parameters for single tool, two-tool combinations and three-tool combinations, it is observed that a set of two tools with diameters of 40 mm and 5 mm is optimum as it provides the minimum production time (t_p = 65.4 min). As noted, this observation is different from the previous findings where a set of three tools with diameters of 40 mm, 20 mm and 5 mm provided the minimum length of the tool path (L = 25873 mm), but without considering other variables such as machining parameters.

The set of two tools providing the minimum production time can be operated efficiently using the following machining parameters: v_{opt} = 120 m/min, f_{opt} = 0.152 mm/tooth, d_{opt} = 2 mm for 40 mm tool in rough milling operation; and v_{opt} = 30 m/min, f_{opt} = 0.127 mm/tooth, d_{opt} = 1 mm for 5 mm tool in finish milling operation. The consideration of two selected tools and efficient machining parameters in milling operations is reasonable for application to the manufacturing shop floor. This fact is supported by the work of [9] which concluded that for pockets with global residuals, the optimum number of tool combination is less than four while for pockets with local residuals the optimum number of tools may be one or two.

4. Conclusion

The main function of CAD/CAM systems such as MasterCAM is to integrate the design and manufacturing activities using computer technology by creating geometric features and generating automatic NC codes for application on CNC machining operations in one platform. However, the selection of cutting tools and optimisation of machining parameters is difficult to achieve in CAD/CAM systems due to their limitation to fully automate the process planning. In reality, some of the process-planning activities are not linked into CAD/CAM systems. This paper has come up with a method whereby the selection of cutting tools for CNC milling operations is done using the generated tool path and the optimised machining parameters. In this manner, the arbitrary choice of tools can be avoided and the performance of the machine tool can be improved. Several trials of machining simulations with different combinations of tool sizes were performed using MasterCAM software. The results have shown that there are substantial variations on tool paths for different tool combinations, and a subjective way of obtaining the optimum tool combination can be avoided by optimising the cutting conditions to achieve time or cost effective production of parts. This approach is a step towards automating process planning in CADCAM systems. Its main advantage is that the optimum selection of tools can be achieved using already existing algorithms and software tools. However, interfacing different software modules may pose a major drawback and hence the need for future research.

Acknowledgement

The authors would like to express their thanks to the anonymous reviewers for noteworthy comments which helped to improve the manuscript.

References

[1] ElMaraghy, H.A. (1993). Evolution and future perspectives of CAPP, *CIRP Annals – Manufacturing Technology*, Vol. 42, No. 2, 739-751, doi: 10.1016/S0007-8506(07)62537-2.

[2] Ahmad, N., Haque, A.F.M., Hasin, A.A. (2001). Current trend in computer aided process planning, In: *Proceedings of the 7th Annual Paper Meet and 2nd International Conference*, The Institution of Engineers, Bangladesh Mechanical Engineering Division, Dhaka, Bangladesh, 81-92.

[3] Tolouei-Rad, M., Payeganeh, G. (2006). A hybrid approach to automatic generation of NC programs, *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 14, No. 1-2, 83-89.

[4] Hou, M., Faddis, T.N. (2006). Automatic tool path generation of a feature-based CAD/CAPP/CAM integrated system, *International Journal of Computer Integrated Manufacturing*, Vol. 19, No. 4, 350-358, doi: 10.1080/09511920500504354.

[5] Prajapati, R., Rajurkar, A., Chaudhary, V. (2013). Tool path optimization of contouring operation and machining strategies for turbo machinery blades, *International Journal of Engineering Trends and Technology*, Vol. 4, No. 5, 1731-1737.

[6] Yao, Z., Gupta, S.K., Nau, D.S. (2001). A Geometric algorithm for finding the largest milling cutter, *Journal of Manufacturing Processes,* Vol. 3, No. 1, 1-16, doi: 10.1016/S1526-6125(01)70029-1.
[7] D'Souza, R., Wringt, P., Séquin, C. (2001). Automated microplanning for 2.5-D pocket machining, *Journal of Manufacturing Systems*, Vol. 20, No. 4, 228-296, doi: 10.1016/S0278-6125(01)80048-0.
[8] Lim, T., Corney, J., Ritchie, M., Clark, D.E.R. (2001). Optimizing tool selection, *International Journal of Production Research*, Vol. 39, No. 6, 1239-1256, doi: 10.1080/00207540010020063.
[9] You, C.F., Sheen, B.T., Lin, T.K. (2007). Selecting optimal tools for arbitrarily shaped pockets, *The International Journal of Advanced Manufacturing Technology*, Vol. 32, No. 1-2, 132-138, doi: 10.1007/s00170-005-0320-6.
[10] Mansor, M.S.A., Hinduja, S., Owodunni, O. (2006). Voronoi diagram-based tool path compensations for removing uncut material in 2½D pocket machining, *Computer-Aided Design*, Vol. 38, No. 3, 194-209, doi: 10.1016/j.cad.2005.09.001.
[11] Lee, K., Kim, T.J., Hong, S.E. (1994). Generation of toolpath with selection of proper tools for rough cutting process, *Computer-Aided Design*, Vol. 26, No. 11, 822-831, doi: 10.1016/0010-4485(94)90096-5.
[12] Elmesbahi, A., Rechia, A., Jaider, O. (2014). Optimized-automated choice of cutting tool machining manufacturing features in milling process, In: *Proceedings of the 11th World Congress on Computational Mechanics*, Barcelona, Spain, 1747-1761.
[13] Gjelaj, A., Balič, J., Ficko, M. (2013). Intelligent optimal tool selections for CNC programming of machine tools, *Transactions of Famena*, Vol. 38, No. 3, 31-40.
[14] Narooei, K.D., Ramli, R. (2014). Application of artificial intelligence methods of tool path optimization in CNC machines: A review, *Research Journal of Applied Sciences, Engineering and Technology,* Vol. 8, No. 6, 746-754.
[15] Daneshmand, S., Mirabdolhosayni, M., Aghanajafi, C. (2013). Sifting through the optimal strategies of time-based tools path machining in software CAD-CAM, *Middle-East Journal of Scientific Research*, Vol. 13, No.7, 844-849.
[16] Kariuki, L.W., Ikua, B.W., Nyakoe, G.N. (2014). Generation and optimization of pocket milling tool paths – A review, In: *Proceedings of 2014 International Conference on Sustainable Research and Innovation*, Nairobi, Kenya, Vol. 5, 129-133.
[17] LINDO Systems Inc. (2008). *LINDO User's Guide*, Chicago, Illinois, USA.
[18] Shunmugam, M.S., Reddy, S.V.B., Narendran, T.T. (2000). Selection of optimal conditions in multi-pass face-milling using a genetic algorithm, *International Journal of Machine Tools and Manufacture*, Vol. 40, No. 3, 401-414, doi: 10.1016/S0890-6955(99)00063-2.
[19] Wang, P., Liang, M. (2005). An integrated approach to tolerance synthesis, process selection and machining parameter optimization problems, *International Journal of Production Research*, Vol. 43, No. 11, 2237-2262, doi: 10.1080/00207540500050063.