QUANTITATIVE EVALUATION OF CAM FINISHING STRATEGIES FOR COMPLEX FREEFORM SURFACES USING A DIMENSIONLESS EFFICIENCY INDEX

Milen Pavlov Dunkov
Technical College – Sofia, Technical University of Sofia, Sofia, Bulgaria, EU,
E-mail(s): milen.dunkov@tu-sofia.bg (✉)

Abstract - This study presents a quantitative evaluation of finishing strategies applied to complex freeform surfaces using Autodesk Inventor CAM. The investigation focuses on the influence of toolpath generation algorithms on machining performance, particularly in terms of residual material distribution and machining time. A representative freeform geometry was modelled and multiple finishing strategies—including Contour, Parallel, Scallop, Spiral, Morphed Spiral, and Ramp, as well as hybrid approaches incorporating Swarf machining—were analysed under identical technological conditions. The evaluation is based on CAM simulation data, including machined volume and machining time, enabling a consistent comparison of different strategies without the need for physical experiments. As the central contribution of this study, a dimensionless efficiency index is proposed, integrating geometric accuracy, expressed through residual material, and productivity, represented by machining time, into a unified performance metric. The results demonstrate that toolpath strategy selection has a significant impact on machining performance. Curvature-adaptive strategies improve geometric accuracy, while continuous toolpaths reduce machining time. Hybrid strategies exhibit the highest efficiency, indicating the benefits of combining different toolpath generation principles. The proposed methodology provides a practical framework for objective selection of finishing strategies and can support optimization of CAM processes for complex geometries.

Keywords: High-Speed Machining (HSM), Autodesk Inventor CAM, finishing strategies, freeform surfaces, residual material, toolpath optimization, machining efficiency, CAM simulation, dimensionless efficiency index

1. Introduction

In modern manufacturing, driven by the principles of Industry 4.0, the demand for high precision, productivity, and process optimization has significantly increased. This is particularly evident in the machining of complex freeform surfaces, widely used in mould and die production, aerospace components, and advanced tooling systems. High-Speed Machining (HSM) plays a key role in achieving these objectives, enabling efficient material removal, improved surface integrity, and enhanced process stability. [1], [2], [3], [4].

HSM should not be understood merely as an increase in spindle speed or feed rate, but rather as a comprehensive technological approach aimed at reducing cutting forces, minimizing thermal effects, and improving overall machining performance.

In parallel, modern Computer-Aided Manufacturing (CAM) systems provide advanced capabilities for generating optimized and intelligent toolpaths, allowing accurate approximation of complex geometries and stable machining performance [5], [6], [7], [8].

A critical stage in the machining process is the finishing operation, where the final geometry and surface quality of the component are established. Numerous studies have demonstrated that the selection of toolpath strategy significantly influences machining time, surface accuracy, and residual material distribution. In particular, the relationship between toolpath patterns, scallop height, and geometric deviation has been extensively investigated [9], [10], [11], [12]. These findings highlight the importance of selecting appropriate finishing strategies, especially when machining freeform surfaces with varying curvature.

dx.doi.org/10.17683/ijomam/issue25/v2.20

In addition, recent research has emphasized the need for systematic approaches in process design and optimization, particularly in applications requiring high reliability, where the interaction between technological parameters and operational performance must be carefully controlled [13]. Parallel studies focusing on material behaviour and process control further underline the importance of parameter optimization in achieving desired mechanical and structural properties [14]. These works collectively demonstrate the necessity of integrated evaluation methods combining process efficiency with product quality.

Comparative investigations of CAM systems confirm that both the software environment and the selected toolpath strategy have a significant impact on machining performance. For example, the study by [15] shows that differences between CAM platforms such as TopSolid'CAM and ESPRIT lead to measurable variations in machining time and process efficiency when manufacturing mould components. Similar conclusions have been reported in experimental and optimization-based studies, where toolpath strategies significantly influence surface quality, geometric accuracy, and machining efficiency when processing freeform surfaces [16], [17], [18].

It should also be noted that the investigated component in the present study is directly related to tooling used in polymer processing technologies. Specifically, the analysed geometry corresponds to an electrode used in Electrical Discharge Machining (EDM) for the fabrication of mould cavities applied in blow-moulding processes, such as the production of PET bottle bottoms. In such applications, the final geometry of the mould is strongly dependent on the accuracy of the electrode, which is manufactured through CNC machining. Studies reported in [19], [20] demonstrate that the geometry of the preform and process parameters significantly influence the final shape of blow-moulded products. Consequently, deviations introduced during electrode machining directly propagate into the mould geometry and affect the quality of the final product, establishing a strong link between machining accuracy and functional performance.

Despite these developments, most existing approaches evaluate machining performance using individual indicators, such as machining time or surface roughness, without providing an integrated and quantitative framework for comparison. This limitation restricts objective decision-making, particularly when multiple toolpath strategies must be evaluated under identical machining conditions [21], [22].

Multi-criteria evaluation approaches can provide a structured framework for machining strategy selection by combining several performance indicators through weighting or decision-support procedures. However, their application commonly requires the definition of criterion weights or additional decision parameters. In the present study, a direct dimensionless efficiency index is adopted to provide a transparent comparison based on geometric accuracy and machining productivity without predefined weighting coefficients.

At the same time, CAM-based simulation has become a widely accepted tool for virtual process analysis, enabling detailed evaluation of material removal, tool engagement, and machining efficiency without the need for physical experimentation [23], [24], [25], [26]. However, despite its widespread industrial application, the use of simulation data for systematic and quantitative comparison of finishing strategies remains limited.

In this context, the present study proposes a quantitative methodology for evaluating CAM finishing strategies based on a unified, dimensionless efficiency index. The proposed approach integrates geometric accuracy, expressed through residual material, and productivity, represented by machining time, into a single performance metric. This enables objective and reproducible comparison between different toolpath strategies under identical machining conditions.

The methodology is applied to a complex freeform geometry using Autodesk Inventor CAM, where multiple finishing strategies are analysed and compared. The results provide insight into the relationship between toolpath generation algorithms and machining efficiency, offering a practical framework for decision-making in industrial CAM programming.

The main contributions of this study can be summarized as follows:

- development of a unified, dimensionless efficiency index integrating geometric accuracy and machining productivity;
- systematic comparison of multiple CAM finishing strategies under identical conditions using simulation data;
- demonstration of the effectiveness of hybrid toolpath strategies for improving machining performance.

These contributions establish a practical and scalable framework for objective evaluation and selection of optimal finishing strategies in CAM-based machining of complex freeform geometries.

2. Methodology

2.1 CAD Model and Geometry

A complex freeform geometry was selected as a representative case study, corresponding to an electrode used in Electrical Discharge Machining (EDM) for the fabrication of mould cavities applied in polymer processing technologies. Such components are characterized by nonlinear surface topology and continuous curvature variation, making them suitable for evaluating the performance of different finishing strategies.

The CAD model was developed in Autodesk Inventor using parametric solid modelling techniques, ensuring precise control over geometric features and surface continuity.

The resulting model, together with the defined workpiece, is shown in Figure 1, where the relationship between the final geometry and the initial stock is illustrated.

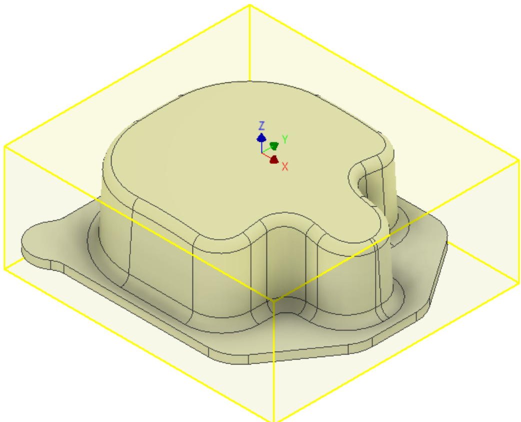

Figure 1: CAD model of the investigated component (1) and corresponding workpiece definition with technological allowances (2)

2.2 Workpiece Definition and Technological Allowances

A prismatic workpiece was defined based on the final geometry, incorporating technological allowances required for machining operations.

A uniform allowance of 1 mm was applied to the upper and peripheral surfaces, ensuring sufficient material for finishing operations and enabling the achievement of the required surface quality and dimensional accuracy.

Additionally, a base allowance of 10 mm was introduced, serving as a technological support element to ensure stable clamping and sufficient rigidity during machining, as illustrated in Figure 1(2).

2.3. Rough Machining Strategy

Due to the complex spatial configuration and the presence of nonlinear surfaces, a 3-axis rough machining strategy (Adaptive Clearing) was applied. This strategy enables efficient bulk material removal while maintaining stable cutting conditions and minimizing tool load variations.

The selected tool was a flat end mill with a corner radius (Sandvik Coromant 1K334-2000-100-XD 1730).

The generated toolpath for the rough machining stage is presented in Figure 2, where the adaptive trajectory ensures uniform material removal and controlled engagement.

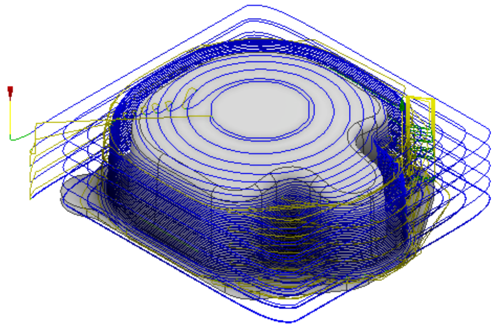

Figure 2: Toolpath generated using the Adaptive Clearing strategy for rough machining

2.4 Finishing Strategies Selection

The Autodesk Inventor CAM system provides a wide range of finishing strategies for machining complex freeform surfaces. In the present study, a representative set of strategies was selected for comparative analysis, including Contour, Parallel, Scallop, Spiral, Morphed Spiral, and Ramp.

These strategies differ in their toolpath generation principles, ranging from direction-based approaches (Contour, Parallel) to curvature-adaptive and constant scallop height methods (Scallop, Spiral).

The generated toolpaths for each strategy are illustrated in Figure 3, where the differences in trajectory structure and coverage can be clearly observed.

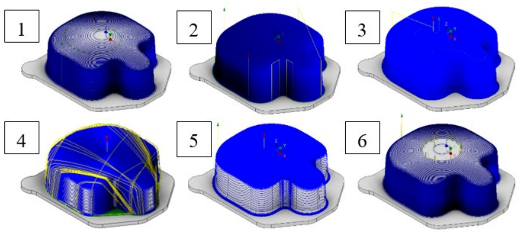

Figure 3: Selected CAM finishing strategies for the investigated freeform surfaces

Strategies such as Pencil, Radial, Project, Morph, and Flow were excluded due to their limited applicability to the investigated geometry.

The machining area was restricted exclusively to the freeform surfaces in order to ensure a consistent and focused comparison.

2.5. Tool Selection and Machining Parameters

Finishing operations were performed using a ball-end milling tool (Sandvik Coromant 2B320-0500-NG H10F), selected due to its suitability for machining complex freeform geometries.

The spherical geometry of the tool enables continuous contact with the surface, resulting in smooth surface generation during multi-axis motion.

The cutting parameters used in the finishing operations are presented in Figure 4, including spindle speed, feed rate, and step parameters.

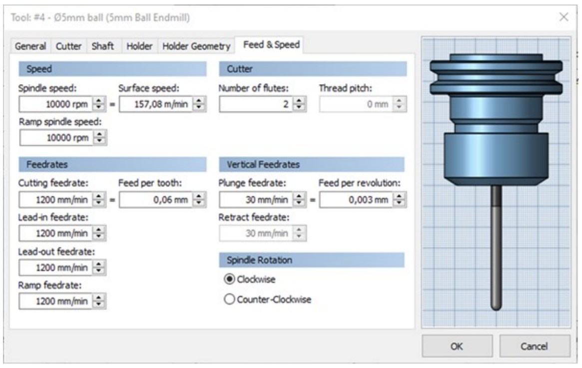

Figure 4: Cutting parameters applied during finishing operations

Although individual finishing strategies may require strategy-specific parameter optimization, identical machining parameters were intentionally applied to establish a consistent basis for comparative evaluation. This approach minimizes the influence of variations in cutting conditions and allows the observed differences to be attributed primarily to the characteristics of the investigated toolpath strategies.

Compared with conventional weighted scoring or more complex multi-criteria decision-making approaches, the proposed index provides a transparent and computationally simple measure for the direct comparison of CAM finishing strategies using parameters obtained directly from the simulation, without requiring predefined weighting coefficients.

2.6. Hybrid Strategy with Swarf Machining

In addition to conventional 3-axis finishing strategies, a hybrid machining approach incorporating a 5-axis Swarf strategy was analysed.

Swarf machining utilizes the lateral surface of the tool, enabling efficient machining of inclined surfaces and improving surface quality in specific regions.

Due to the geometric characteristics of the investigated component, the Swarf strategy was applied in combination with standard finishing strategies, resulting in hybrid toolpath configurations.

The corresponding trajectories are shown in Figure 5, where the combined strategies demonstrate different approaches to surface coverage and tool engagement.

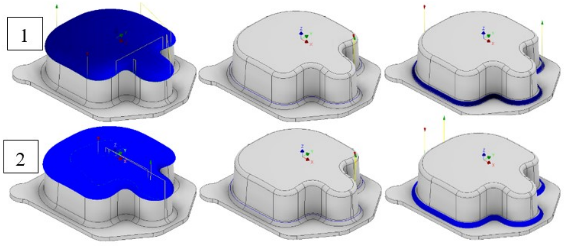

Figure 5: Hybrid toolpaths: (1) Parallel + Swarf + Contour; (2) Scallop + Swarf + Scallop

2.7. Simulation and Data Extraction

The machining process was analysed using CAM-based simulation tools integrated within Autodesk Inventor. The simulation environment provides detailed visualization of material removal and enables verification of toolpath execution.

The simulation includes:

- stock removal visualization
- tool engagement tracking
- comparison with the original CAD geometry
- numerical verification of machining results

The following quantitative parameters were extracted from the simulation:

- final machined volume
- residual material
- machining time

These data serve as the basis for the quantitative evaluation of finishing strategies presented in the subsequent sections.

2.8. Efficiency Evaluation Method

In order to enable a quantitative and objective comparison between the investigated finishing strategies, a dimensionless efficiency index is introduced. The proposed approach integrates geometric accuracy and machining productivity into a single performance metric.

- Part-based efficiency:

$$\eta_p = \frac{1}{\varepsilon \cdot T} \tag{1}$$

where:

- $\eta_p x10^{-3}$ – part-based efficiency index [-];
- $\varepsilon\ x10^{-4}$– normalized residual material error [-];
- T – total machining time [min].

Normalized residual error:

$$\varepsilon = \frac{V_{res}}{V_{CAD}} \tag{2}$$

where:
- V_{res} – residual material volume after machining [mm^3];
- V_{CAD} – nominal volume of the CAD model (final part geometry) [mm^3].

Residual material definition:

$$V_{res} = V_{machined} - V_{CAD} \tag{3}$$

where:
- $V_{machined}$ – volume of the machined part obtained from CAM simulation [mm^3].

The residual material represents the deviation between the machined geometry and the nominal CAD model, and is used as an indicator of geometric accuracy.

Stock-based efficiency:

$$\eta_s = \frac{1}{\varepsilon \cdot T} \tag{4}$$

Normalized residual error (stock-based):

$$\varepsilon = \frac{V_{res}}{V_{stok}} \tag{5}$$

where:
- V_{stock} – initial volume of the workpiece (stock) [mm^3].

The stock-based formulation provides an alternative efficiency perspective by relating the residual material to the total available material volume, thus reflecting the overall material removal effectiveness.

Higher values of the efficiency index correspond to lower residual material and shorter machining time, representing improved geometric accuracy and higher machining productivity, respectively. Consequently, higher values of η indicate improved overall performance with respect to both evaluation criteria.

The proposed formulation allows direct comparison between strategies independently of part size under controlled machining conditions.

The multiplicative structure of the proposed efficiency index was selected to provide a simple dimensionless measure in which geometric accuracy and machining productivity contribute simultaneously to the overall evaluation. In contrast to weighted additive formulations, the proposed form does not require predefined weighting coefficients, which would introduce an additional subjective assumption regarding the relative importance of accuracy and productivity. The inverse-product formulation therefore provides a consistent comparative measure under the controlled machining conditions adopted in this study, while preserving the simultaneous influence of both performance criteria.

3. Results

Following the definition and implementation of all machining operations and finishing strategies, the complete process was evaluated using CAM-based simulation within Autodesk Inventor.

The purpose of this stage is to obtain reliable quantitative data describing the machining performance under identical technological conditions for all investigated strategies. This ensures that the observed differences in the results are directly related to the toolpath generation method rather than external factors.

3.1. Numerical Verification of Machining Process

The CAM system provides a numerical verification module that enables validation of the machining process prior to physical execution. This module includes collision detection, volumetric analysis, and comparison between the machined geometry and the original CAD model.

In addition to validation, the simulation provides quantitative data regarding the volume of the machined part and the initial stock. An example of the verification output is presented in Figure 6, where both the machined volume and the initial workpiece volume are displayed. These simulation outputs provide the quantitative basis for the subsequent calculation and comparative evaluation of the investigated finishing strategies.

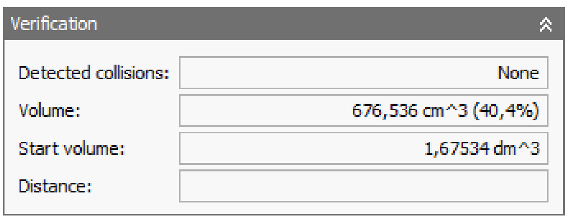

Figure 6: Numerical verification results obtained from CAM simulation, including machined volume and initial stock volume.

3.2. Machining Time and Volume Analysis

The primary quantitative results extracted from the simulation include the final machined volume and the total machining time for each finishing strategy. These values are summarized in Table 1.

In contrast, the machining time exhibits significant variation between strategies. For example, the Parallel strategy results in the longest machining time, reflecting the layered and direction-based nature of the toolpath, which increases tool movement and reduces trajectory efficiency.

Strategies such as Spiral and Morphed Spiral demonstrate shorter machining times due to smoother and more continuous toolpaths, which reduce non-productive movements and improve overall machining efficiency.

Table 1. Machined volume and machining time for the investigated finishing strategies

Strategy	Volume after machining (mm^3)	Time (h:mm:sec)
Contour	676536	1:29:14
Parallel	675674	3:27:39
Scallop	675621	2:15:02
Spiral	676204	1:22:12
Morphed Spiral	676216	1:46:38
Ramp	677233	1:28:09
Parallel, Swarf and Contour	675456	2:08:48
Scallop, Swarf and Scallop	675490	1:18:47

3.3. Performance Indicators Based on Simulation Data

In order to facilitate a structured comparison between the investigated strategies, the simulation data were further processed using the efficiency formulation described in Section 2.8.

The calculated part-based efficiency values are presented in Table 2 and Figure 7, where the variation in performance between different strategies can be clearly observed.

Similarly, the stock-based efficiency values are shown in Table 3 and Figure 8, providing an alternative evaluation perspective based on the initial workpiece volume.

This representation reflects the relationship between the total material removal and machining time, offering additional insight into the overall efficiency of the machining process under the investigated CAM conditions.

Table 2. Part-based efficiency indicators for the investigated finishing strategies

Str.	Part Volume (mm^3)	Mach. Vol. (mm^3)	Res. Vol. (mm^3)	Error ε [-]x10^{-4}	Time (min)	Eff. η
1	675170.8	676536	1365.20	20.22008	89.2333	5.542
2	675170.8	675674	503.201	7.45294	207.65	6.462
3	675170.8	675621	450.201	6.66796	135.0333	11.10 62
4	675170.8	676204	1033.20	15.30281	82.2	7.949
5	675170.8	676216	1045.20	15.48054	106.6333	6.057 9
6	675170.8	677233	2062.20	30.54340	88.15	3.714 2
7	675170.8	675456	285.201	4.22413	128.8	18.38
8	675170.8	675490	319.201	4.72771	78.7833	26.85

1- Contour, 2- Parallel, 3 -Scallop, 4-Spiral, 5-Morphed Spiral, 6-Ramp, 7- Parallel, Swarf and Contour, 8- Scallop, Swarf and Scallop.

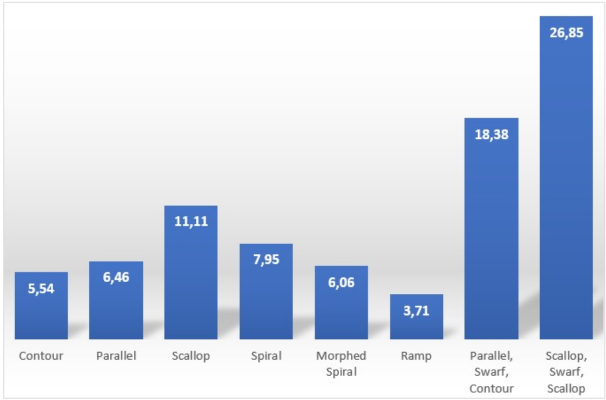

Figure 7: Part-based efficiency index (η_p) for the investigated finishing strategies

Table 3. Stock-based efficiency indicators for the investigated finishing strategies

Str.	Stock Volume (mm^3)	Mach. Vol. (mm^3)	Res. Vol. (mm^3)	Error ε [-]x10^{-4}	Time (min)	Eff. η [-]x10^{-3}
1	1675344	676536	998808	5961.81	89.23	18.7973
2	1675344	675674	999670	5966.95	207.7	8.0708
3	1675344	675621	999723	5967.27	135.0 333	12.4103
4	1675344	676204	999140	5963.79	82.2	20.3989
5	1675344	676216	999128	5963.72	106.6 333	15.7250
6	1675344	677233	998111	5957.65	88.15	19.0416
7	1675344	675456	999888	5968.25	128.8	13.0088
8	1675344	675490	999854	5968.05	78.78	21.2683

1- Contour, 2- Parallel, 3 -Scallop, 4-Spiral, 5-Morphed Spiral, 6-Ramp, 7- Parallel, Swarf and Contour, 8- Scallop, Swarf and Scallop.

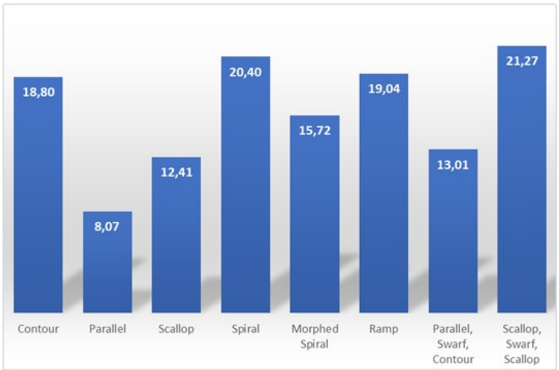

Figure 8: Stock-based efficiency index (η_s) for the investigated finishing strategies.

4. Discussion

The results obtained from the simulation-based analysis demonstrate that the selection of toolpath strategy has a direct and measurable influence on machining performance, affecting both geometric accuracy and machining time.

The observed differences between strategies are primarily related to the underlying principles of toolpath generation, including trajectory continuity, tool engagement, and adaptation to the geometric characteristics of the surface.

4.1. Influence of Toolpath Strategy on Geometric Accuracy

The results indicate that curvature-adaptive strategies, such as Scallop, achieve lower residual material values compared to direction-based approaches.

This behaviour is associated with the ability of such strategies to maintain a relatively constant scallop height over the surface, resulting in more uniform material removal and improved geometric conformity to the CAD model.

In contrast, strategies such as Parallel and Contour, which rely on predefined tool movement directions, tend to produce non-uniform surface coverage. This leads to increased residual material, particularly in regions with complex curvature transitions or varying surface orientation.

These findings confirm that the geometric characteristics of the toolpath play a critical role in determining the accuracy of the final machined surface.

4.2. Influence on Machining Time

Significant differences are also observed in machining time, which is strongly influenced by toolpath density and trajectory structure.

The Parallel strategy exhibits the highest machining time, due to the repetitive nature of the tool motion and the increased number of passes required to cover the surface. This results in a higher proportion of non-productive movements and reduced process efficiency.

In contrast, Spiral and Morphed Spiral strategies demonstrate improved performance, as their continuous toolpaths reduce tool retractions and ensure smoother transitions between machining segments.

These results highlight the importance of trajectory continuity in minimizing machining time and improving overall process performance.

4.3. Performance of Hybrid Strategies

The hybrid strategies combining conventional 3-axis finishing approaches with Swarf machining demonstrate the highest efficiency values among all investigated configurations.

This improved performance can be attributed to the complementary nature of the combined strategies. While the 3-axis toolpaths ensure accurate surface finishing, the Swarf strategy enables efficient machining of inclined surfaces using the lateral surface of the tool.

This combination reduces unnecessary tool movements and enhances surface coverage, leading to a more favourable balance between machining time and geometric accuracy.

The results indicate that hybrid strategies can effectively overcome the limitations of individual toolpath approaches and provide a more flexible solution for machining complex geometries.

4.4. Evaluation Using the Efficiency Index

The efficiency index introduced in Section 2.8 provides a unified framework for evaluating machining strategies by combining geometric accuracy and productivity into a single performance metric.

The calculated efficiency values show that strategies achieving both low residual material and reduced machining time obtain the highest performance ratings.

This combined assessment enables performance differences that may not be evident from machining time or geometric accuracy considered separately to be identified within a single quantitative measure.

In particular, the hybrid strategies demonstrate superior efficiency, confirming that combining different toolpath generation principles leads to improved overall performance.

This approach allows direct and objective comparison between strategies and can support decision-making in CAM programming and process optimization.

4.5. Practical Implications

From an industrial perspective, the results highlight the importance of selecting toolpath strategies according to the specific requirements of the machining task.

For applications where high geometric accuracy is critical, curvature-adaptive strategies such as Scallop are more suitable.

When productivity is a primary concern, strategies with continuous trajectories, such as Spiral, provide better performance due to reduced machining time.

Hybrid strategies represent an effective compromise, offering both acceptable accuracy and improved efficiency, and are therefore particularly suitable for high-performance machining of complex freeform components.

In the specific case investigated in this study, these findings are directly relevant to the manufacturing of EDM electrodes used for producing mould cavities in blow-moulding applications. Since geometric deviations introduced during electrode machining can be transferred to the resulting mould geometry, the selection of an appropriate finishing strategy is particularly important. The proposed efficiency index provides a quantitative basis for balancing machining productivity and geometric accuracy when selecting CAM strategies for such applications.

4.6. Limitations and Future Work

The present study is based exclusively on CAM simulation data obtained under controlled conditions. Consequently, the proposed methodology does not explicitly account for real machining phenomena such as machine tool dynamics, cutter deflection, thermal effects, tool wear, and actual surface roughness. These factors may influence the experimentally observed machining accuracy and productivity and should therefore be considered when transferring the proposed efficiency index to industrial machining conditions.

Future work will focus on experimental validation of the proposed methodology, as well as the inclusion of additional performance indicators such as surface roughness and tool life.

Furthermore, the proposed efficiency framework can be extended to multi-axis machining environments and integrated into intelligent CAM systems for automated strategy selection.

4.7. Sensitivity Analysis of the Efficiency Index

In order to further evaluate the robustness of the proposed efficiency formulation, a qualitative sensitivity analysis was performed to assess the influence of machining time and residual material on the efficiency index.

The efficiency index is defined as the inverse product of normalized residual material and machining time, which implies that both parameters contribute simultaneously to the final performance evaluation. However, their relative influence is not identical.

From the formulation, it can be observed that the efficiency index exhibits an inverse proportionality to machining time. This indicates that even moderate increases in machining time result in a noticeable reduction in efficiency, making productivity a dominant factor in the evaluation.

In contrast, the influence of residual material becomes more significant in cases where geometric deviations increase beyond a certain threshold. For strategies producing similar machining times, even small differences in residual material lead to measurable changes in efficiency, highlighting the importance of geometric accuracy in high-precision applications.

The normalization of residual material with respect to the CAD model and stock volume ensures that the proposed formulation remains independent of part size, enabling consistent comparison across different machining scenarios.

Overall, the sensitivity analysis confirms that the efficiency index provides a balanced evaluation framework, where machining time dominates in productivity-driven cases, while residual material becomes critical in accuracy-sensitive applications.

5. Conclusions

This study presents a systematic and quantitative evaluation of finishing strategies applied to complex freeform surfaces using Autodesk Inventor CAM.

A unified efficiency framework was developed, integrating geometric accuracy and machining productivity through a dimensionless performance index. This approach enables objective comparison between different toolpath strategies under identical machining conditions.

The results demonstrate that the choice of finishing strategy has a significant influence on machining performance. Curvature-adaptive strategies provide improved geometric accuracy, while continuous toolpath strategies reduce machining time.

The highest efficiency values were obtained for hybrid strategies combining 3-axis finishing and Swarf machining, indicating that the integration of different toolpath generation principles leads to improved overall performance.

The proposed methodology provides a practical tool for selecting optimal finishing strategies and can support decision-making in CAM programming for complex geometries.

The approach is general and can be extended to other machining applications, including multi-axis environments and advanced manufacturing systems.

Acknowledgement

The author would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

References

[1] Msaddek, E. B., Bouaziz, Z., Baili, M. (2026). Smoothing of CAM cutting methods for HSM milling. *International Journal on Interactive Design and Manufacturing*, 20(3), 1687–1707. https://doi.org/10.1007/s12008-025-02456-7

[2] Guo, S., Lu, S., Zhang, B., & Cheung, C. F. (2022). Surface integrity and material removal mechanisms in high-speed grinding of Al/SiCp metal matrix composites. *International Journal of Machine Tools and Manufacture*, Volume 178, id. 103906. https://doi.org/10.1016/j.ijmachtools.2022.103906

[3] Sun, L., Huang, X., Zhao, J., Wang, X., Ma, M. (2025). An intelligent chatter detection method for high-speed milling under variable tool–workpiece systems and cutting parameters. *Mechanical Systems and Signal Processing*, 224, id. 111960. https://doi.org/10.1016/j.ymssp.2024.111960

[4] Jain, A., Bajpai, V. (2020). Chapter 1 - Introduction to high-speed machining (HSM). In: *High Speed Machining* (pp. 1–25). Academic Press. https://doi.org/10.1016/B978-0-12-815020-7.00001-1

[5] Simonič, M., Palčič, I., Klančnik, S. (2025). Advancing intelligent toolpath generation: A systematic review of CAD–CAM integration in Industry 4.0 and 5.0. *Strojniški vestnik – Journal of Mechanical Engineering*, 71(9-10), 328–336. https://doi.org/10.5545/sv-jme.2025.1370

[6] Zhang, K., Xiao, W., Fan, X., Zhao, G. (2025). CAM as a Service with dynamic toolpath generation ability for process optimization in STEP-NC compliant CNC machining. *Journal of Manufacturing Systems*, 80(3), 294–308. https://doi.org/10.1016/j.jmsy.2025.03.004

[7] Hou, M., Faddis, T. N. (2007). Automatic tool path generation of a feature-based CAD/CAPP/CAM integrated system. *International Journal of Computer Integrated Manufacturing*, 19(4), 350–358. https://doi.org/10.1080/09511920500504354

[8] Xu, T., Chen, Z., Li, J., Yan, X. (2015). Automatic tool path generation from structuralized machining process integrated with CAD/CAPP/CAM system. *The International Journal of Advanced Manufacturing Technology*, Volume 80(5), 1097–1111. https://doi.org/10.1007/s00170-015-7067-5

[9] Li, Y. F., Li, J. R., Xie, H. L., Wang, Q. H. (2024). The generation of supplementary toolpaths for surface machining based on rapid prediction of scallop height distributions. *The International Journal of Advanced Manufacturing Technology*, 135(3), 1205–1220. https://doi.org/10.1007/s00170-024-14415-9

[10] Vavruska, P., Kasik, F., Lomicka, J., Cermak, A. (2025). Adaptive toolpath setup to reduce machining time when milling complex shape parts. *The International Journal of Advanced Manufacturing Technology*, 139(5), 2977–2995. https://doi.org/10.1007/s00170-025-16038-0

[11] Cai, X. L., Yang, W. A., Yang, X., You, Y. P. (2026). Spiral tool path generation for high-speed milling of multi-connected surface based on quasi-conformal theory. *The International Journal of Advanced Manufacturing Technology*, 142, 1–22. https://doi.org/10.1007/s00170-025-17184-1

[12] Wang, L., Han, J., Tang, Z., Zhang, Y., Wang, D., Li, X. (2025). Geometric accuracy design of high performance CNC machine tools: modeling, analysis, and optimization. *Chinese Journal of Mechanical Engineering*, 38(1), 87. https://doi.org/10.1186/s10033-025-01258-y

[13] Dimitrov, V., Dimitrova, V. K., Zdravcheva, G. S. (2025). Investigation and optimization of process parameters for electrochemical rifling of firearm barrels. *International Journal of Mechatronics and Applied Mechanics*, 21 (1), 40–48. https://dx.doi.org/10.17683/ijomam/issue21.4

[14] Dimitrova, V. K. (2025). Microstructural evolution and mechanical properties of cold-drawn 1566 steel wire subjected to heat treatment recrystallization annealing. *International Journal of Mechatronics and Applied Mechanics,* 20(1), 95–102. https://doi.org/10.17683/ijomam/issue20.9.

[15] Panayotov, D., Dimitrov, V., Kalev, K. (2016). Comparative analysis of the processes for machining of mold element with using TopSolid CAM and ESPRIT. *International Journal of Mechanical Engineering and Technology*, 7(2), 01–10.

[16] Zhang, X. F., Xie, J., Xie, H. F., Li, L. H. (2012). Experimental investigation on various tool path strategies influencing surface quality and form accuracy of CNC milled complex freeform surface. *The International Journal of Advanced Manufacturing Technology*, 59(5), 647-654. https://doi.org/10.1007/s00170-011-3515-z

[17] Vila, C., Ayabaca, C., Torres, R., Gutiérrez, S. C., Meseguer, A., Yang, X. (2019). Analysis of different tool path strategies for free form machining with computer aided surface milling operations. *Procedia Manufacturing*, 41, 843-850. https://doi.org/10.1016/j.promfg.2019.10.006

[18] Li, L., Deng, X., Zhao, J., Zhao, F., Sutherland, J. W. (2018). Multi-objective optimization of tool path considering efficiency, energy-saving and carbon-emission for free-form surface milling. *Journal of Cleaner Production*, 172, 3311-3322. https://doi.org/10.1016/J.JCLEPRO.2017.07.219

[19] Dimitrova, V. K., Dimitrov, V. P. (2025). Design and thermal simulation of pet bottle and moulding tool for injection stretch blow moulding. *International Journal of Mechatronics and Applied Mechanics*, 20(1). https://doi.org/10.17683/ijomam/issue20.21

[20] Bozherikov, S. (2026). Parametric Modeling Of Bolted Assembly And Its Components For Industrial Design And Application. Journal of Applied Engineering Science, 24(1), 188-202. https://doi.org/10.5937/jaes0-58641

[21] Celent, L., Mladineo, M., Gjeldum, N., & Crnjac Zizic, M. (2022). Multi-criteria decision support system for smart and sustainable machining process. *Energies*, 15(3), 772. https://doi.org/10.3390/en15030772

[22] Sun, W., Zhang, Y., Luo, M., Zhang, Z., & Zhang, D. (2022). A multi-criteria decision-making system for selecting cutting parameters in milling process. *Journal of Manufacturing Systems*, 65, 498-509. https://doi.org/10.1016/j.jmsy.2022.10.008

[23] Lauwers, B., Plakhotnik, D. (2012). Five-axis milling tool path generation with dynamic step-over calculation based on integrated material removal simulation. *CIRP annals*, *61*(1), 139-142. https://doi.org/10.1016/j.cirp.2012.03.090

[24] Takeva-Beberova, I., Bozherikov, S., & Draganov, G. (2026). Functional design of an eco-efficient parking lot for electric vehicles with photovoltaic panel integration and charging stations. *Int. J. Mechatron. Appl. Mech*, 227-240. https://doi.org/10.17683/ijomam/issue23.21

[25] Wang, X., Wei, Z., Zhang, T., Liu, Y., & Zhang, D. (2026). A transitional tool path planning method for changing large diameter tools in impeller plunge milling. *The International Journal of Advanced Manufacturing Technology*, 142(3), 1333-1347. https://doi.org/ 10.1007/s00170-025-16909-6

[26] Li, S. C., Ma, H. Y., Zhang, B. W., & Shen, L. Y. (2026). End-to-End Tool Path Generation for Triangular Mesh Surfaces in Five-Axis CNC Machining. *AppliedMath*, 6(3), 35. https://doi.org/10.3390/appliedmath6030035